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ORIGINAL ARTICLE

Development of a system to assess vulnerability of flooding from water in karst aquifers induced by mining

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Abstract

Flooding from water in karst aquifers that are mining-induced poses a threat to coal mining in North China. In this study, a new geographic information system (GIS)-based assessment model is proposed and developed to assess flooding from water in karst aquifers induced by mining. Microsoft Excel and ArcGIS Engine 9.3 are used to build a GIS-based multi-criteria decision making system, which is developed by using the C Sharp programming language. The decision matrix which contains the criteria that determine the vulnerability of flooding is constructed by considering the geological conditions and mining activity. The weight vectors of the criteria are calculated by using an information entropy model. Then, a flooding vulnerability index is constructed in accordance with the overall criteria. The flooding vulnerability index is validated with data from the Xinqiao Coal mine in Henan Province, China. The results indicate that the multi-criteria decision making system can realistically assess flooding from water in karst aquifers induced by mining, and is a good technological support for determining the safety of underground mining.

Keywords Multi-criteria decision making · System development · Flooding · Karst aquifers · Geographic information system · Vulnerability index

Introduction

Karsts are widely found throughout China, and these formations affect the water supply, mining activities, water conservancy and hydropower construction projects, city and road construction projects, and daily life activities. There are nearly 3.25 million km^2 of carbonate rocks in China, with about 1.25 million km^2 of denudated karst areas and about 2 million km^2 of buried karsts (Li and Zhou 2006; Yu 1994). Unfortunately, coal seams are usually mined between, over, or below karst aquifers in North China (Wang and Park 2003; Zhang and Shen 2004). Therefore, more than 30 coalfields in North China are under the threat of flooding from water in karst aquifers which is induced by mining (Li and Zhou 2006). Most coal mines contain numerous karst formations, and the karst water has a pumping rate of over 60 m^3/min (Table 1). Therefore, an assessment of the vulnerability of flooding from water in karst aquifers induced by mining is very important for mining safely over or below karst aquifers.

In recent years, the assessment of the vulnerability of flooding from water in karst aquifers induced by mining has been the focus of many researchers, and many geographic information system (GIS)-based methods have been proposed to address the problem (see for e.g., Gui and Lin 2016; Wu et al. 2011). A model that couples the Bayesian network and GIS to assess water-inrush was proposed by Dong et al. (2012). Li and Chen (2016) proposed an analytic hierarchy process (AHP) model with a gray relational analysis to evaluate the risks of mining on aquifers. Li et al. (2015) provided an AHP model based on attribute mathematics which was used to assess flooding from water in mining. Models based on fuzzy mathematics have also been used to evaluate the

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Table 1 Cases of flooding from water in karst aquifers induced by mining in North China

Mine	Date	Maximum water inrush volume (m^3/min)
Zibo	1935.05.13	443
Linxi	1950s	71.8
Yanmazhuang	1979.03.09	240
	1985.05.17	320
Fangezhuang	1984.06.02	2053
Renlou	1996.03.04	576
Dongpang	2003.04.12	1167
Luotuoshan	2010.03.01	1083

risk of flooding from water (see for e.g., Wang et al. 2012; Yang et al. 2017). A vulnerability index which combines GIS and an artificial neural network was proposed in Wu and Zhou (2008) to assess the vulnerability of flooding in karst aquifers induced by coal mining.

A large volume of interrelated spatial data of the geological and hydrogeological conditions, drainage conditions and chemistry, and mining technical conditions (Bu et al. 2001; Cui et al. 2015) can be obtained from underground mines with karsts. Flooding in water and the vulnerability of karst coal mines to flooding in water are affected by many factors, the geological and hydrogeological environment, mining methods, and the geological and mechanical characteristics of the lower layers of the aquifers (Liu 2009; State Administration of Coal Mine Safety 2009; Wang et al. 2012; Wu et al. 2015). The complex problems that are found in underground coal mines can be addressed by using multiple criteria decision making methods and applications. Hence, an assessment of the vulnerability of coal mines with karsts to flooding in water can be carried out with a multi-criteria decision making method.

Spatial decision problems of underground mines with karst formations usually involve decision making information, and the spatial position of local resources and the local environment. Spatial multi-criteria decision making is defined as the use of multi-criteria decision analysis in the spatial domain, in which the alternatives, criteria, and other factors related to the decision problem are assessed (Densham and Goodchild 1989; Lu et al. 2014). The GIS promptly emerged as a new information processing tool that provides the unique ability to automate, manage, and analyze a variety of spatial data in the early 1980s (Goodchild 1989; Harris and Batty 1993; Jankowski 1995). Information for decision making could be obtained from geographic data which are then processed by using different processes and applications in GIS. GIS-based multi-criteria decision making is the process of coupling GIS with multi-criteria decision making that transforms geographic data and preferences to obtain information for informing decision making (Kitsiou et al. 2002; Malczewski 1999, 2000, 2006, 2011). Figure 1 shows the GIS-based multi-criteria decision making model (Boroushaki and Malczewski 2008, 2010; Fang et al. 2014; Wiecek et al. 2008).

In this paper, a GIS-based multi-criteria decision making method is proposed to assess the vulnerability of flooding from water in karst aquifers induced by mining, and a realistic system is developed for ease of viewing the results. The developed method simultaneously analyzes the hydrogeological, geological engineering and mining data collected from karst areas in mines. A case study for the Xinqiao Coal mine in Henan Province, China, is carried out. Then, the validity of the developed method is evaluated by taking into consideration the information contained in the criteria related to the decision problem.

The work here has been undertaken with the following objectives.

The first objective is to establish the criteria that contribute to the vulnerability of flooding from water in karst aquifers induced by mining. The second objective is to formulate a vulnerability index to quantitatively analyze the possibility of flooding from water in karst aquifers induced by mining. The third objective is to develop a system that can visualize and expedite the assessment process of the vulnerability of flooding. It is anticipated that this system is a good form of technological support for determining the safety of underground mining.

Method

GIS-based assessment of vulnerability model

Information entropy is one of the most commonly used methods for GIS-based decision making, and applied here to formulate a model that assesses the vulnerability of flooding from water in karst aquifers induced by mining along with a GIS. Figure 2 is a schematic of the work process to derive the model, and the steps of the work process are elaborated below.

1. The evaluation criteria are selected.

Based on the geological and hydrogeological environment as well as the mining activities, the criteria that influence the vulnerability of flooding from water in karst aquifers induced by mining are identified. The criteria are obtained through drilling, geophysical exploration and in situ measurements.

2. The GIS maps are established, and criteria values are normalized.

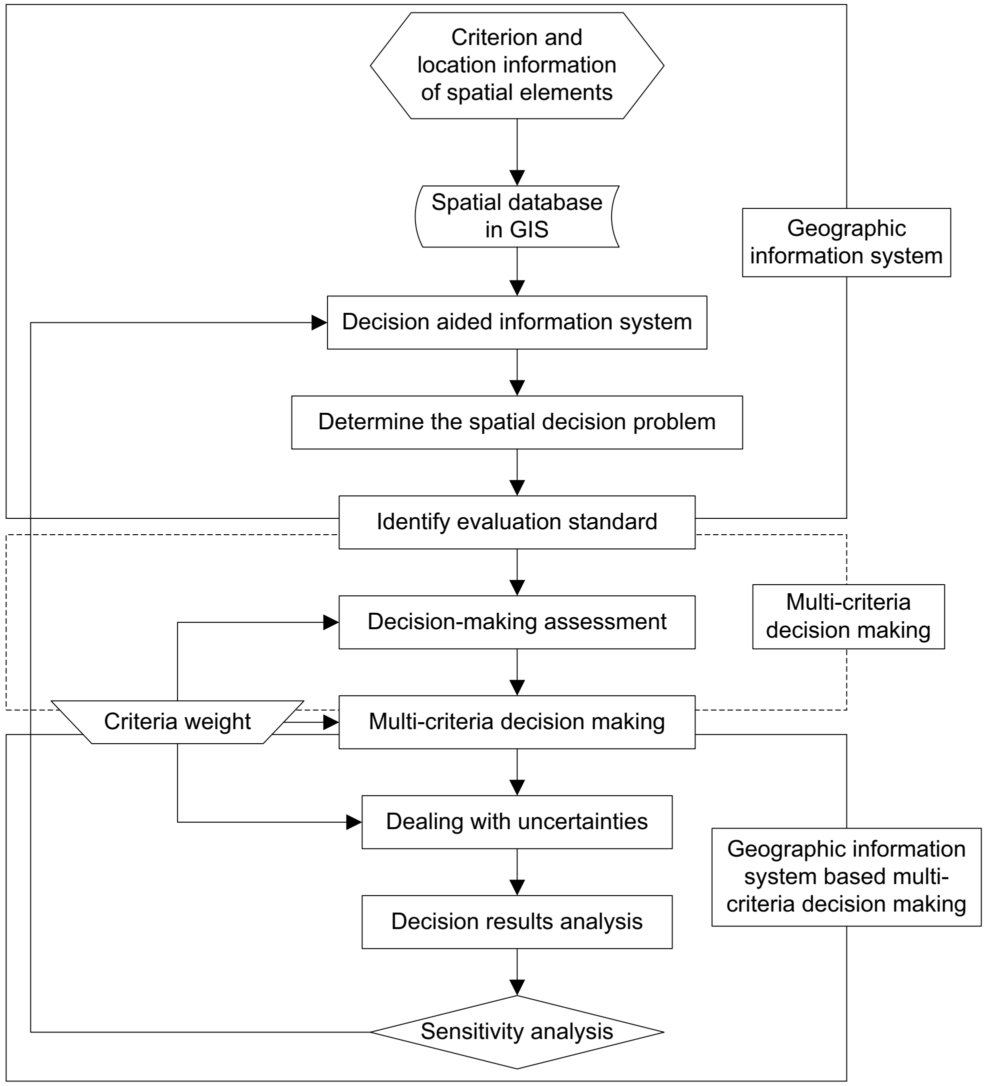

Fig. 1 GIS and multi-criteria decision making coupled model

The GIS mapping of the criteria is established through ordinary kriging (Krige 1981) with ArcGIS.

First, a second-order stationary random function is defined as:

$$Z^*(x) = \sum_{i=1}^{n} \lambda_i Z(x_i) \tag{1}$$

where λ_i is the weight coefficient, which denotes the contribution of the observation $Z(x_i)$ at each space sample point to the estimated value $Z^*(x)$.

The covariance function is defined as:

$$\sigma^2 = c(x,x) - 2\sum_{i=1}^{n} \lambda_i c(x_i,x) + \sum_{i=1}^{n}\sum_{j=1}^{n} \lambda_i \lambda_j c(x_i,x_j) \tag{2}$$

A spherical model is used as the variogram model which is a commonly used model theoretically. The spherical variogram model is defined as:

$$\gamma(h) = \begin{cases} 0 \quad h = 0 \\ C_0 + C\left(\frac{3}{2}\cdot\frac{h}{a} - \frac{1}{2}\cdot\frac{h^3}{a^3}\right) \quad 0 < h \le a \\ C_0 + C\, h > a \end{cases} \tag{3}$$

where C_0 is a nugget constant, a is the variable range, and $C_0 + C$ is the partial sill.

In accordance with the relationship between the covariance function and variogram: $c(h) = c(0) - \gamma(h)$, the kriging equations can be defined as:

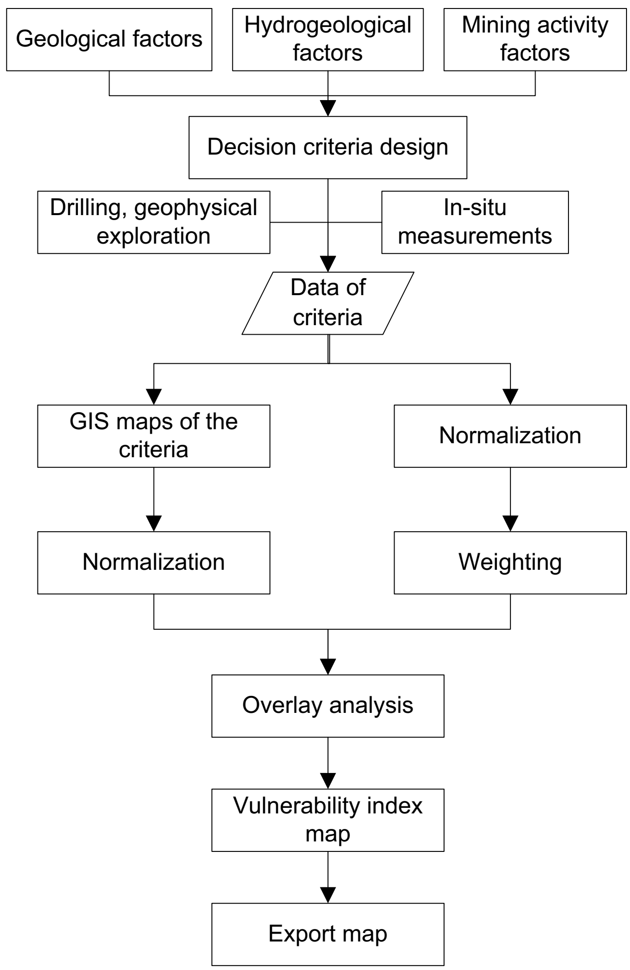

Fig. 2 Schematic of work process to derive model

$$\begin{cases} K\lambda = D \\ K = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1n} & 1 \\ c_{21} & c_{22} & \cdots & c_{2n} & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ c_{n1} & c_{n2} & \cdots & c_{nn} & 1 \\ 1 & 1 & \cdots & 1 & 0 \end{bmatrix}, \lambda = \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \vdots \\ \lambda_n \\ -\mu \end{bmatrix}, D = \begin{bmatrix} c(x_1, x) \\ c(x_2, x) \\ \vdots \\ c(x_n, x) \\ 1 \end{bmatrix} \end{cases} \tag{4}$$

The weight coefficient λ_i is calculated in accordance with the Lagrange multiplier principle and the estimated value $Z^*(x)$ at each space point can then be calculated in the GIS.

In general, there are two types of criteria in multi-criteria decision making: positive and negative criteria. Positive and negative criteria are positively and negatively related to the vulnerability of flooding from water in karst aquifers induced by mining, respectively. Equation 5 is used to normalize the positive criteria, whereas the negative criteria are normalized by using Eq. 6 (Liu and Qiu 1998).

$$y_{ij} = \frac{x_{ij} - \min\limits_i \{x_{ij}\}}{\max\limits_i \{x_{ij}\} - \min\limits_i \{x_{ij}\}}, i = 1, 2, \ldots, n \tag{5}$$

$$y_{ij} = \frac{\max\limits_i \{x_{ij}\} - x_{ij}}{\max\limits_i \{x_{ij}\} - \min\limits_i \{x_{ij}\}}, i = 1, 2, \ldots, n \tag{6}$$

Here, y_{ij} is the normalized value of the criteria, and x_{ij} is the initial value of the criteria.

3. The weight vectors are determined.

The information entropy model is used to calculate the weight vectors of the criteria. Based on the normalized values of the criteria, the normalized decision matrix is defined as:

$$Y = \begin{bmatrix} y_{11} & y_{12} & \cdots & y_{1n} \\ y_{21} & y_{22} & \cdots & y_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ y_{m1} & y_{m2} & \cdots & y_{mn} \end{bmatrix} \tag{7}$$

The ratio of the jth criteria is:

$$p_{ij} = \frac{y_{ij}}{\sum_{i=1}^{m} y_{ij}}, (i = 1, 2 \cdots m; \quad j = 1, 2 \ldots n) \tag{8}$$

The information entropy of the jth criteria is:

$$e_j = -k \sum_{i=1}^{m} p_{ij} \ln(p_{ij}), k > 0, k = \frac{1}{\ln(n)}, e_j \geq 0 \tag{9}$$

The coefficient of variation of the jth criteria is:

$$g_j = \frac{1 - e_j}{m - E_e}, E_e = \sum_{j=1}^{n} e_j, 0 \leq g_j \leq 1, \sum_{j=1}^{n} g_j = 1 \tag{10}$$

The weight vectors of the criteria are:

$$w = (w_1, w_2, \ldots, w_n)^T, w_j = \frac{g_j}{\sum_{j=1}^{n} g_j} (1 \leq j \leq n) \tag{11}$$

4. The vulnerability index of flooding from water in karst aquifers induced by mining is then formulated.

The weighted linear combination (WLC) model is one of the most widely used decision rules to derive composite maps in the GIS environment (Eastman 1999; Heywood et al. 1995; Hopkins 1977). Based on the weighted linear combination (Malczewski 2000, 2011), $w = (w_1, w_2, \ldots, w_m)^T$

can be regarded as the weight vectors of the criteria, $w_j \geq 0$, $j = 1, 2, \ldots, m$.

$$VI = \sum_{j=1}^{m} w_j \cdot f_j(x, y) \tag{12}$$

where VI is the vulnerability index of flooding from water in karst aquifers induced by mining; w_j is a normalized weight for the *j*th criteria; f_j is the function for the *j*th criteria; and (x, y) are the coordinates of the criteria. The vulnerability zone map and vulnerability grades of flooding are obtained and classified by the natural breaks method (Jenks 1963).

Development of a GIS-based decision making system

Microsoft Excel and ArcGIS Engine 9.3 were used to build the GIS-based multi-criteria decision making system, which was developed by using the C Sharp programming language. The elements of the vulnerability index model are: "Single criteria," "Normalized," "Crate maps," and "Overlay analysis."

To address with substantial volume of geospatial data in this study, ArcGIS Engine, a widely used GIS platform developed by ESRI, is used as the platform. Applications for different purposes can be developed by using the ArcGIS controls along with other control commands that are developed by the user. Desktop, web, and mobile applications can be developed by using a Microsoft-integrated development environment called Visual Studio.NET. Visual Studio 2008 and C# are used in this study as the development tool and programming language, respectively.

Data acquisition, processing, and display are required to construct the database. The data were based on the geological and hydrogeological conditions, and collected from drilling, geophysical prospecting and mining activities in the course of excavation and exploration work. The data were first inputted into Excel for data acquisition. The processed data and results were stored in Excel and displayed with a grid map. Components that contained some common GIS functions were linked to the database. The functions were listed on the left of the main interface, with which the criteria system that affects flooding in water was constructed. Figure 3 shows the main interface of this system which implements the assessment model that determines the vulnerability of flooding from water in karst aquifers induced by mining.

The results of the multi-criteria decision making system in this study are intuitively validated by coupling them with GIS visualization. The data, including information on the in situ measurements and drilling, were entered into Excel. Normalization of the mapping of the criteria was carried out by selecting the "Single criteria," "Normalized," and "Crate Maps" fields. The weight vectors of the criteria were calculated by selecting the "Calculation

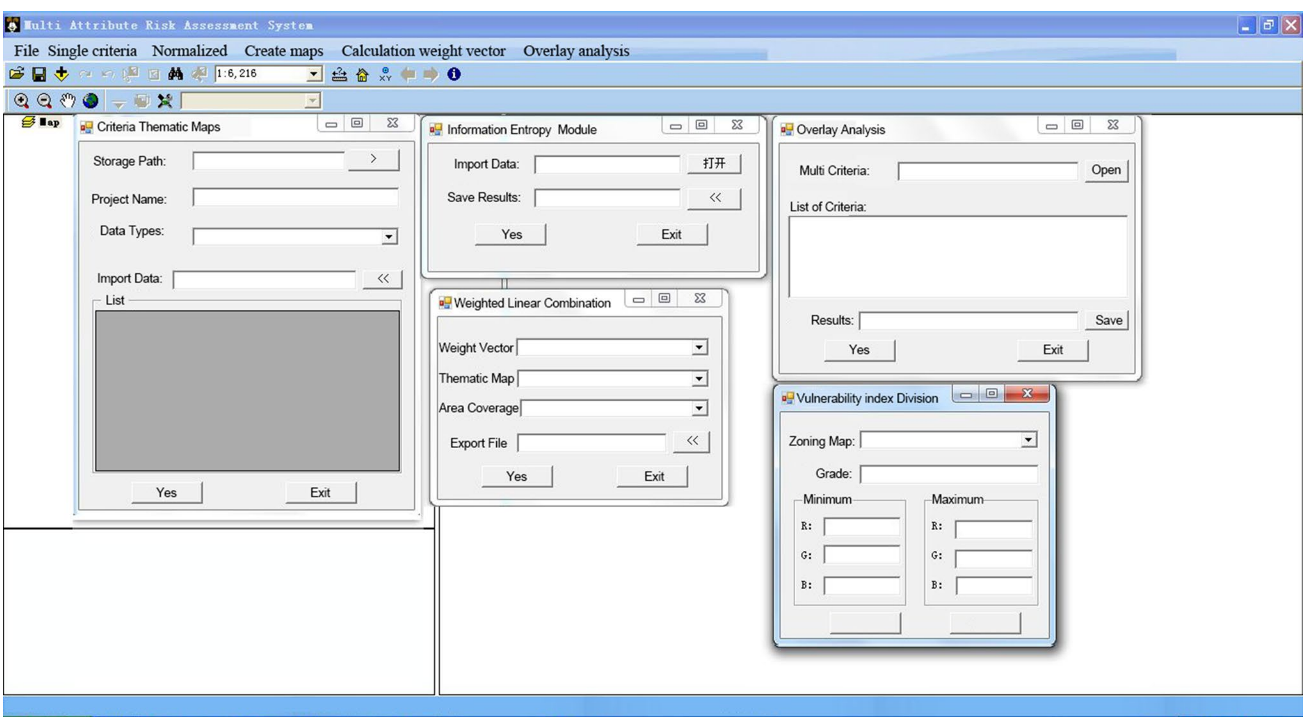

Fig. 3 Main user interface of system

Weight Vector" field, and the data were saved into an Excel database. The classification of the grades of vulnerability was obtained by selecting the "Overlay analysis" field. The vulnerability zone map used R (red), G (green), and B (blue) to grade the vulnerable zones of underground coal mines. The generated maps were then exported as images by using the "Export Map" field which is found under the "File" tab.

Fig. 4 Location of Xinqiao Coal mine

Case study

Xinqiao coal mine

The Xinqiao Coal mine is located in the junction of the Xinqiao, Maqiao, and Shuangqiao towns, 16 km southwest of Yongcheng city in Henan, China (Fig. 4) with an area of 35.0 km^2. The Xinqiao Coal mine is located in a monsoon-type climate area in the mid-latitude zone. The mean annual temperature is 14.3 °C. The average annual rainfall is 850.65 mm, with a maximum of 1518.6 mm (1963) and a minimum of 543.7 mm (2011) from 1963 to 2017. More than 50 percent of the annual atmospheric rainfall is in July and August. Mining generally takes place at a depth between 300 m and 1000 m below sea level. Panel 2103 of the Xinqiao Coal mine is located in the first district (Fig. 5). The confined aquifers in the karsts threaten the safety of workers when they are mining the coal seam in the upper part of the Taiyuan formation. The average accumulated thickness of the limestone aquifers is 30.66 m. The water pressure of the confined limestone aquifer under the floor of Coal Seam II$_2$ is more than 4.75 MPa. The failure zone of the floor of the coal seam develops with mining, and the thickness of the aquiclude is reduced. There are three karst aquifers that underlie the exploitable Coal Seam II$_2$ as shown in Fig. 6a. Zhao and Chang (2007) categorized the properties of karst aquifers in the Fengfeng coalfield in Jiangxi, China, by using borehole pumping data, especially the water yield of the boreholes. Zheng (2015) categorized the extent of karst development and the void structure in three local collieries in Liuqiao, Hengyuan, and Wugou in Huaibei, China, based on the water yield and the volume of the grout for the borehole. In this study, the water yield and volume of the grout are also considered. Figure 6b shows the ninety-four boreholes drilled for grouting to reinforce the karst aquifers. The water yield and volume of the grout in Aquifers L_{10}, L_{11}, and L_{12} were determined during the drilling process. In this study, the water yield and volume of the grout for boreholes in karst aquifers based on geological and hydrogeological conditions as well as mining activities are used as the variables to depict the inherent strength of the karst formations and the void structure. Ten criteria that influence the vulnerability of flooding are constructed and listed in Table 2. The amount of water yield and volume of grout required for each aquifer are listed in Table 3. The distribution of the water yield for Aquifers L_{10}, L_{11}, and L_{12} is shown in Fig. 7c–e, while the volume of grout required for the three aquifers is shown in Fig. 7i–h, respectively. L_{11} and L_{12} are the two aquifers that primarily threaten the safety of the mine and therefore have to be grouted to lower the permeability. L_{10}

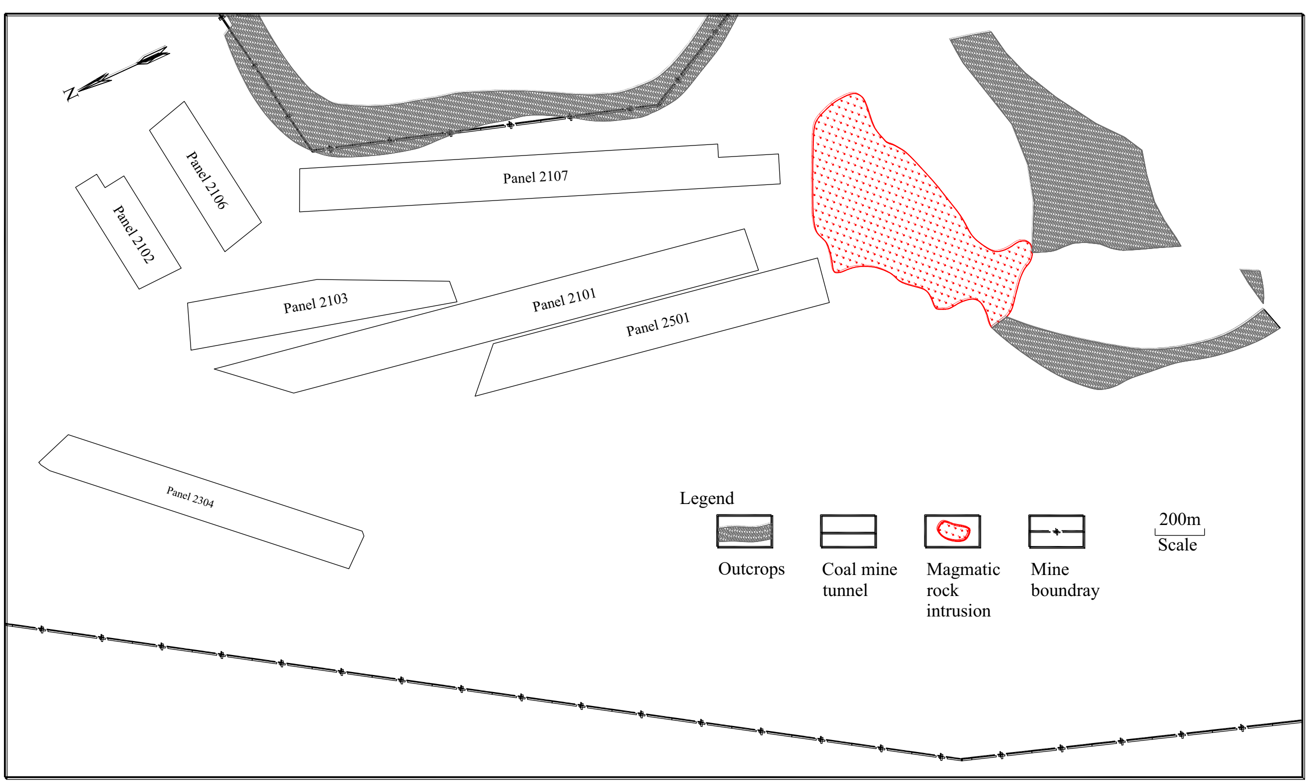

Fig. 5 Schematic geological map of Xinqiao Coal mine: layout of panels

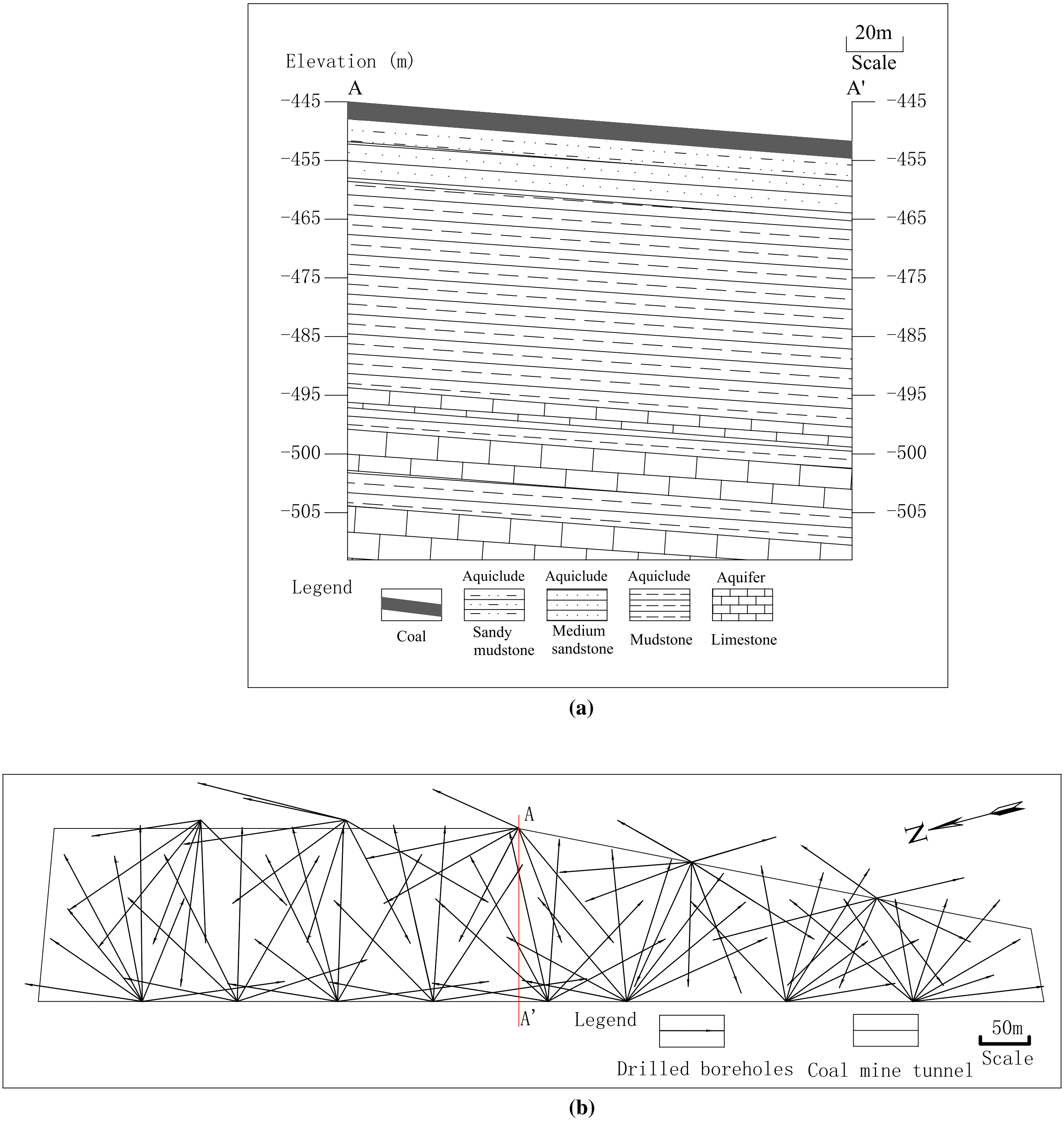

Fig. 6 Stratigraphic column and grouted boreholes in Panel 2103

and L_{11} contain a large volume of water and have developed karst fissures, so they recharge L_{12}.

Structurally, thirteen faults were found in the course of 3D seismic data and in situ measurements. Of these reported faults, there is one reverse fault, while the others are all normal faults, and their properties are listed in Table 4. The box-counting dimension is used to quantify the faults and defined as:

$$D = \dim_{\text{box}}(S) := \lim_{\varepsilon \to 0} \frac{\log N(\varepsilon)}{\log(1/\varepsilon)} \tag{13}$$

where $N(\varepsilon)$ are the number of boxes with a length ε of each side that are required to cover the set. D is the box-counting dimension for a fractal S.

Table 2 Decision making criteria with corresponding normalization method

Vulnerability of flooding from water in karst aquifers induced by mining	Criteria	Sub-criteria	Normalization
Vulnerability index	Geological conditions	Geological structures	Negative (Eq. 6)
		Thickness of aquiclude	Positive (Eq. 5)
	Hydrogeological conditions	Water yield of L_{10}	Negative (Eq. 6)
		Water yield of L_{11}	Negative (Eq. 6)
		Water yield of L_{12}	Negative (Eq. 6)
		Water pressure of confined limestone aquifers	Negative (Eq. 6)
		Volume of grout for L_{12}	Positive (Eq. 5)
		Volume of grout for L_{11}	Positive (Eq. 5)
		Volume of grout for L_{10}	Positive (Eq. 5)
	Mining activity	Depth of failure of floor of coal seam	Negative (Eq. 6)

Table 3 Water yield of aquifer and volume of grout required for each aquifer

Aquifer	Total water yield exposed by drilled holes (m^3/h)	Proportion of total yield (%)	Total volume of grout (tons)	Proportion of total volume of grout (%)
L_{10}	2033	81.81	5971	69.58
L_{11}	328	13.20	1707	19.89
L_{12}	124	4.99	904	10.53
Total	2485	100.00	8582	100.00

The criteria of the geological structures are quantified and normalized in Fig. 7a. The depth of the failure zone of the floor of the coal seam is calculated by using an empirical formula Eq. (14) in accordance with the "Regulations of Coal Mining and Protective Coal Pillar Design under Building, Water Body, Railway, Coal Mine & Roadway"(State Bureau of Coal Industry 2000).

$$h = 0.0085H + 0.1665a + 0.1079L - 4.3579 \quad (14)$$

where H denotes the depth of the mining, h is the depth of the failure zone of the floor of the coal seam, a denotes the dip angle, and L denotes the dip length of the panel. Then, the criteria for the depth of the failure of the floor of the coal seam are quantified and normalized; see Fig. 7j.

System implementation

The data of each criterion were collected during drilling, geophysical exploration, and in situ measurement surveys. Then, a criteria database was constructed, and the "Single criteria," "Normalized," and "Crate Maps" fields were selected to generate a normalized GIS layer for each criterion. As well, the GIS layer of each criterion was classified into five areas with different colors. Different colors were used to represent the degree of vulnerability of each criterion as an extension of the valuation by mapping each point in the input space for a value between 0 and 1. Furthermore, the weight vectors were calculated by selecting the "Calculation Weight Vector" field. The information entropy and weight were saved in the criteria database, which can be readily recalled. When the "Overlay analysis" field was selected, the vulnerability zone map and vulnerability grades of the panel can be obtained and exported as images by using the "Export Map" field which is under the "File" tab.

Results

The weight vectors of the evaluation criteria were taken as: (0.20, 0.19, 0.26, 0.10, and 0.25). Then, the overall value of all the criteria was obtained, and the vulnerability zone map of the vulnerability index was automatically generated, see Fig. 7 (Jenks 1963). The grades of the vulnerability of flooding from water in karst aquifers induced by mining are defined and listed in Table 5.

A vulnerability index of 99.6% in the area of Panel 2103 is classified as low to medium vulnerability. In the vulnerability zone map (Fig. 7k), very highly vulnerable areas have a thin aquiclude and high hydraulic pressure, and the limestone aquifers have a significant water yield. Flooding in water would therefore occur in this area. In order to prevent flooding from water in karst aquifers, more grouted boreholes are needed with a higher volume of grout.

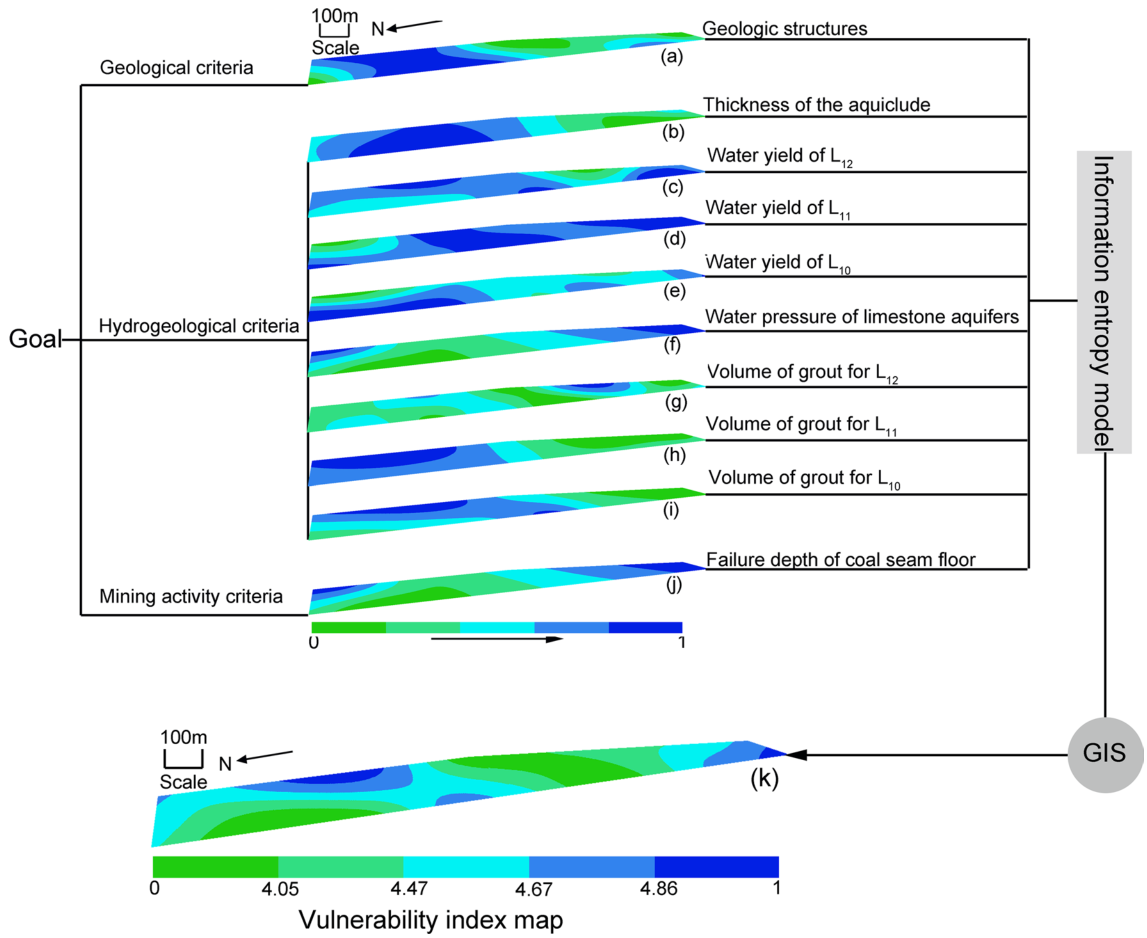

Fig. 7 Vulnerability zone map from vulnerability index

Table 4 Properties of faults of Panel 2103

Fault	Strike (°)	Dip direction (°)	Dip angle (°)	Fault throw (m)
F1-03-G1	164	74	60	1.1–2.0
F1-03-G2	48–159	21–115	58	2.0
F1-03-G3	108	18	85	0.8
F1-03-G4	150	240	43	2.1
F1-03-G5	243	153	35	2.1–4.0
F1-03-G6	195	285	60	1.4
F1-03-G7	181	91	40	4.3
F1-03-G8	285	195	52	2–2.4
F1-03-P1	133	43	57	2.5
F1-03-P2	104	194	65	2.7
F1-03-P3	89	359	60	2.0
F1-01-4	245	155	60	2.0
DSF63	67	157	70	0–2.0

Discussion

In real-life situations, measurement errors are usually the result of the uncertainty of the information available (Heuvelink et al. 1989). Therefore, the process of dealing with multi-criteria decision making problems in space should take into consideration the lack of complete information. The nature of external uncertainties is related to the decision making environment (Stewart 2004). Sensitivity analysis incorporates uncertainty into a multi-criteria decision analysis, through which the sensitive criteria that affect the model can be found, and the impact of these criteria on the object of decision can be determined (Lodwick et al. 1990). Sensitivity analysis can quantify the criteria of uncertainty and determine the impacts of uncertainty and the impacts of changes when modeling predictions (Crosetto and Tarantola 2001; Jovanović 1999). Sensitivity analysis comprises either global or local sensitivity analysis.

In GIS-based multi-criteria decision making, a local sensitivity analysis evaluates the local changes of each factor in the system. Different inputs for each separate element

Table 5 Grades of vulnerability of flooding from water in karst aquifers induced by mining

Grade of Vulnerability	Very low	Low	Medium	High	Very high
Vulnerability index	0 ≤ VI ≤ 0.2	0.2 < VI < 0.4	0.4 ≤ VI ≤ 0.6	0.6 < VI < 0.8	0.8 ≤ VI ≤ 1
Proportion (%)	2	82.4	15	0.5	0.1

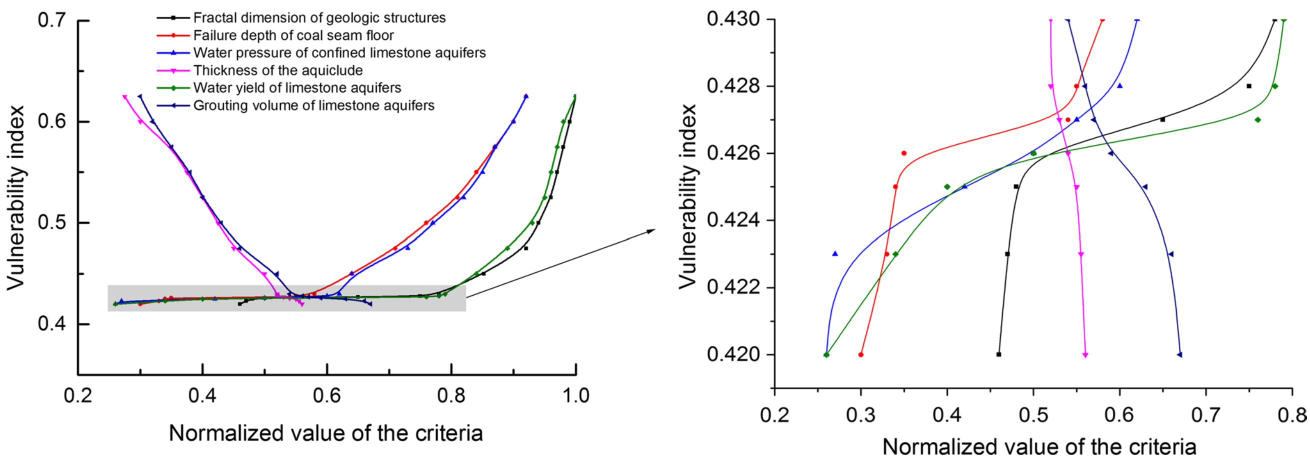

Fig. 8 Local sensitivity analysis of criteria

can be selected, and then the modeling is rerun. Finally, the corresponding changes in the results are recorded. This is the most common process (Lilburne and Tarantola 2009; Triantaphyllou and Sánchez 1997). The criteria that influence the outputs of the modeling are considered to be the most important. In this study, a local sensitivity analysis is used to determine how the selected criteria affect vulnerability to flooding in water and their sensitivity (Kiparissidis et al. 2013).

Figure 8 shows that the criteria selected are sensitive parameters that affect the vulnerability of flooding from water in karst aquifers induced by mining. The total water yield of the karst aquifers and volume of grout required for the karst aquifers are selected to represent the parameters of a karst aquifer. The geological structure has an insensitivity less than 0.085 in the vulnerability index. In other words, when geological structures have a high degree of complexity, the geological structure is a sensitive parameter. The vulnerability index decreases with increase in the thickness of the aquiclude. Aquifer water yield and water pressure are important characteristics of limestone aquifers, and therefore sensitive criteria.

Conclusions

Flooding from water in karst aquifers induced by mining is subjected to many criteria. In order to put into place an effective plan that prevents flooding from water in karst aquifers, a vulnerability assessment is essential. This paper therefore proposes a vulnerability index and establishes an advanced system that assesses the vulnerability of flooding from water in karst aquifers induced by mining. Subsequently, a GIS-based application program which simplifies the assessment process and promotes the management of the related data is developed.

The system is validated by examining a panel of the Xinqiao Coal mine which demonstrates that the newly established system provides objective and accurate assessments. The assessment system can be used to assess the vulnerability of flooding from water in karst aquifers with changing geological and hydrogeological conditions as well as mining activities. The vulnerability of flooding from water in karst aquifers is quantified in the assessment system. Therefore, the assessment procedure has been simplified. A spatiotemporal analysis of the criteria that control the vulnerability of flooding from water in karst aquifers induced by mining will need to be carried out in future work.

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