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Fuzzy comprehensive evaluation method of F statistics weighting in identifying mine water inrush source

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Abstract

In order to rapidly identify the source of water inrush in coal mine, and provide the theoretical basis for mine water damage prevention and control, fuzzy comprehensive evaluation model was established. The F statistics of water samples was normalized as the weight of fuzzy comprehensive evaluation for determining the source of water inrush in coal mine. The determination result of F statistics weighting method to 47 water samples was compared with that of over standard weighting method, and the former accuracy rate is 93.6%, the later accuracy rate is 74.5%. The result shows that F statistics reflects the identification ability of various indicators with higher accuracy than the common over standard weighting method. F statistics weighting method allocates weights according to the distinguish abilities of the evaluation factors, being more suitable for seeking an objective evaluation and discrimination from the differences of the statistical samples themselves.

Keywords: F statistics, fuzzy comprehensive evaluation, water inrush source, coal mine

1. Introduction

Mine water hazard issue has been in urgent need of study due to its impacts on safety of coal mine. It can cause the mine to stop production and huge economic loss, even mineworker death. For example, a major water inrush accident of Luotuoshan Coal Mine with the maximum water inflow 7200 m^3/h happened in Match 1, 2010, and 31 persons died in this accident. Now, there are two main aspects to research mine water hazard issue. One is the evaluation and prediction of the possibility of water inrush in advance (Wu et al. 2008), and the other is the discrimination of the water inrush source afterwards. Accurate and rapid discrimination of water inrush source is the basis of control measure and a key technique for coal mine safe production. In general, mine water hazard involves in fracture-karst aquifers. However, groundwater flow in these aquifers is always complex. And it is flowing in the hydro-geochemical cycle and takes water-rock interaction. It has the variation characteristics in space and time. Therefore, many researchers have done a lot of basic research works on groundwater in different aspects. For example, some studies involve in fracture-karst groundwater experiments (Zimmerman et al. 2002; Brush and Thomson, 2003; Qian et al. 2005; Qian et al. 2006; Qian et al. 2007; Zheng et al. 2008; Luo et al. 2009), and others on groundwater numerical simulation for assessment of groundwater resources (Qian et al. 2006; Qian et al. 2009). However, systemic survey on groundwater flow needed to conduct to assessment groundwater resource based on the above-mentioned studies. Now, an alternative method by chemical characteristic of groundwater to discriminate groundwater source obtains better application effects in mine water damage flood prevention and control. There are some commonly used methods to identify the source of water bursting in coal mines, such as fuzzy comprehensive evaluation method (Ben et al. 2005), Bayesian discrimination method (Chen et al. 2009; Song et al. 2005), gray correlation analysis method (Gao et al. 2007), artificial neural network (Wu et al. 2007), extension identification (Zhang et al. 2009), and so on. Among them, fuzzy comprehensive evaluation method due to good effect, simple calculation, has a wide range of application in identifying water inrush source.

To fuzzy comprehensive evaluation model, how to select an appropriate weight calculation method for your research fields for the model has been one of the difficulties. Commonly used weighting methods are over standard weighting method (Ma et al.

2009), biasing weighting method (Ben et al. 2006), analytic hierarchy process (AHP)(Liu et al. 2009) , and so on. Calculation weighting methods have a great impact on distinguishing the results.

F statistics is the ratio of mean square deviation between groups to mean square deviation in groups. It indicates the differences between groups and the differences inner groups, and its meaning is suit for the meaning of weight in the discrimination of water inrush source. So, in this paper, we tried to normalize F statistics as the weight, established fuzzy comprehensive evaluation model to determine the source of water bursting in coal mine.

2. Basic Theory

2.1 The basic theory and steps of fuzzy comprehensive evaluation: Fuzzy comprehensive evaluation method is a synthetical assessment method that applies fuzzy mathematical principles to evaluate things and phenomenon affected by variety of factors (Li et al. 2001). It regards evaluation objectives as a fuzzy set (named the Factor Set *U*) composed of variety of factors with different assessment levels selected. Another fuzzy set named the Evaluation Set *V* is employed to calculate the membership degree of each individual factor in the Evaluation Set to establish a fuzzy matrix. The quantitative evaluation value of each factor is finally determined by calculating the weight distribution of each factor in evaluation goal. It applies the fuzzy transformation theory and maximum membership degree law, and makes a comprehensive evaluation to various factors (Zhang et al. 1992). Specific steps are as follows:

- Determine the Factor Set of evaluation object, that is $U=\{u_1, u_2, \ldots, u_m\}$. It is a set composed of *m* kinds of evaluation factors.
- Determine the Evaluation Set, that is $V=\{v_1, v_2, \ldots, v_n\}$. It's a set composed of *n* kinds of evaluation standards.
- Construct single-factor evaluation matrix. Evaluate single-factor and then get vector R_i. A single-factor evaluation matrix R is constituted by numbers of single-factor evaluation vector put together. There are some commonly used membership degree calculation function of single-factor, such as "linearity lower semi-ladder-shaped" distribution function and so on.

$$R=\begin{bmatrix} R_1 \\ R_2 \\ \vdots \\ R_m \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} \tag{1}$$

In (1), *R* is a fuzzy relationship matrix composed of evaluation Factor Set *U* and the Evaluation Set *V*.

- Determine evaluation factors weight vector $E=\{e_1, e_2, \ldots, e_m\}$. There are many methods to calculate weight, such as over standard weighting method, analytic hierarchy process (AHP) and so on. Among them, over standard weighting method is commonly used in articles about all kinds of fuzzy comprehensive evaluation, which is calculated as follows:

$$e_i = x_i / a_i \tag{2}$$

In (2), x_i is the practice measure value of the *i* factor in distinguishing samples, and a_i states the statistical average value of the *i* factor in distinguishing standard. As the weight of fuzzy comprehensive evaluation method, it needs normalize, that is:

$$e_i = \left(x_i / a_i\right) / \sum_{i=1}^{m} \left(x_i / a_i\right) \tag{3}$$

- Comprehensive evaluation. The last results of comprehensive evaluation can be got by doing complex operations calculation between single factor weight vector *E* and fuzzy relationship matrix *R*, which is as follows.

$$B = E \cdot R = \{b_1, b_2, \ldots, b_m\} \tag{4}$$

In (4), b_i is the membership degree value of evaluation samples to each evaluation standard. The determination results are usually defined according to the maximum membership degree law.

2.2 *F statistics*: F statistics states the ratio of mean square deviation between groups to mean square deviation in groups, the ratio is higher, which indicates that the difference between groups is greater, and the difference inner groups is smaller. As the weight of fuzzy comprehensive evaluation, the value of F statistics is greater, which shows that there is bigger difference between various evaluation standards, and it is more concentrated distribution in each evaluation standards, the distinguishing ability is stronger. Therefore, in some areas, it is more conforms to the function and significance of weighting. The specific calculation is as follows.

$$F = \frac{S_A^2}{S_E^2} = \frac{Q_A/(r-1)}{Q_E/(n-r)} \tag{5}$$

In (5), the Q_A is deviation square sum in group, that is:

$$Q_A = \sum_{i=1}^{r} \sum_{j=1}^{n_i} \left(X_{ij} - \overline{X}_i \right)^2 \tag{6}$$

The Q_E is deviation square sum between the groups, that is:

$$Q_E = \sum_{i=1}^{r} n_i \left(\overline{X_i} - \overline{X}\right)^2 \tag{7}$$

In (5), (6) and (7), r is the level number of distinguishing factor, X_{ij} is the jth sample value under the ith level of distinguish factor. n_i is the sample number under the ith level of distinguish factor. $\overline{X_i}$ is average value of the ith distinguish gene, $\overline{X}$ is the total average value of distinguish factor, that is as follows.

$$\overline{X_i} = \frac{1}{n_i}\sum_{j=1}^{n_i} X_{ij}\ ,\ i = 1,2,...,r \tag{8}$$

$$\overline{X} = \frac{1}{n_i}\sum_{i=1}^{r}\sum_{j=1}^{n_i} X_{ij},\ n = \sum_{i=1}^{r} n_i \tag{9}$$

3. Application and Analysis

3.1 Fuzzy comprehensive evaluation model of over standard weighting method: For showing the feasible of F statistics as weight and analyzing its calculations effects, water inrush source discrimination of a coal mine was taken for example in this paper. The major aquifers of the mine are the Ordovician and Carboniferous limestone karst fracture aquifer (limestone water for short in the followed), coal measures sandstone fracture aquifer (coal measures water for short in the followed) and Cenozoic unconsolidated aquifer (Cenozoic water for short in the followed). There are 47 water samples of the three aquifers in Panyi Coal Mine, which are showed as Fig.1. Six common ions in groundwater are used as the evaluation factors, that is U = (Ca^{2+}, Mg^{2+}, K^{+}+Na^{+}, HCO_3^-, Cl^-, SO_4^{2-}), and the appraisal set V = (Cenozoic water, coal water, limestone water). According to 47 water samples of the mine, the statistical average values of aquifers' six ion indicators were calculated, which are also the background valuea of the three aquifers, shown in Table 1.

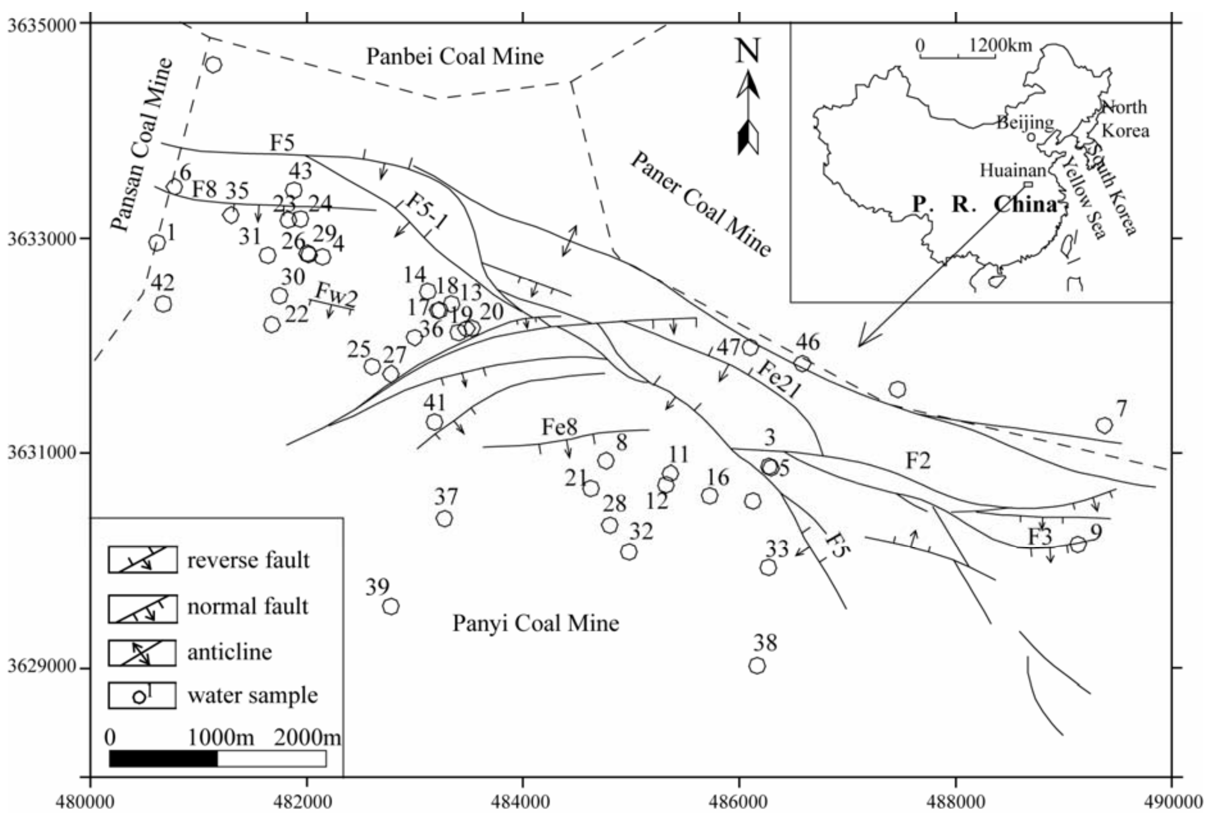

Figure 1. Water samples distribution of Panyi Coal Mine, China

Table 1. The average value of aquifers water quality indicators (mg / L)

Aquifers	**Ca^{2+}**	**Mg^{2+}**	**$K^{+}+Na^{+}$**	**HCO_3^{-}**	**Cl^{-}**	**SO_4^{2-}**
Cenozoic water	48.34	25.96	821.21	325.96	1041.96	260.18
Coal measures water	15.03	5.58	1038.19	973.68	947.42	69.30
limestone water	52.72	23.48	936.23	544.04	879.19	480.48

The 47 water samples were calculated by using fuzzy comprehensive evaluation model of over standard weighting method, and then every sample's aquifer was discriminated according the calculation result. The discrimination results (wrong discrimination part) are shown in Table 3, of which 12 samples are made a wrong distinguished, and the discrimination accuracy rate is 74.5%.

3.2 Fuzzy comprehensive evaluation model of F statistics weighting method: ANOVA of these three groups' 47 water samples was calculated in SPSS software. We obtained F statistics of the six ions, and then did normalization processing to F statistics for serving as the weight. F statistics and the normalized results are shown in Table 2. From the table we can seen that F-value of Mg^{2+} ion indicator is the largest, which shows that the aquifers identification ability is the strongest, so its weight value 0.37 is the largest weight in fuzzy comprehensive evaluation; SO_4^{2-} and Ca^{2+} take second place, whose identification abilities are strong, and the weights are 0.27 and 0.25; HCO_3^{-}, $K^{+}+Na^{+}$ and Cl^{-} the three ions' F values are small, which shows their identification abilities are weak, and the weights are respectively 0.06,0.04 and 0.02.

Table 2. F statistics and the normalized results

Indicators	Ca^{2+}	Mg^{2+}	$K^{+}+Na^{+}$	HCO_3^{-}	Cl^{-}	SO_4^{2-}
F statistics	20.48	29.85	2.90	4.90	1.28	22.23
Weights	0.25	0.37	0.04	0.06	0.02	0.27

Fuzzy comprehensive evaluation model of F statistics normalized results as the weight was constructed. The 47 water samples were also calculated by the model, and every sample's aquifer was indentified according to the calculation result. The result shows that there are three samples wrongly judged in total, and the accuracy rate is 93.6%, which is higher than the results of over standard weighting method. The comparison of the two methods discrimination results (wrong discrimination part) are shown in Table 3.

Table 3. Discrimination results by F method vs over standard weighting methods

Aqui-fers	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	$K^{+}+Na^{+}$ (mg/L)	HCO_3^{-} (mg/L)	Cl^{-} (mg/L)	SO_4^{2-} (mg/L)	F statistics weighting				Over standard weighting			
							1	*2*	*3*	*Results*	*1*	*2*	*3*	*Results*
1	52.91	17.14	821.79	306.92	1141.94	122.04	0.19	0.33	0.49	3	0.51	0.12	0.37	1
2	43.09	12.1	703.72	333.76	995.17	10.7	0.31	0.55	0.14	2	0.66	0.28	0.06	1
2	25.25	4.74	808.33	486.31	881.01	191.6	0.30	0.64	0.06	2	0.41	0.24	0.35	1
2	36.27	12.76	713.38	237.36	1020.34	58.45	0.27	0.59	0.15	2	0.63	0.30	0.07	1
2	29.86	10.09	714.07	234.92	1028.49	24.9	0.22	0.69	0.09	2	0.66	0.30	0.04	1
2	28.66	8.51	774.99	322.78	1013.96	93.84	0.24	0.70	0.06	2	0.62	0.36	0.02	1
2	25.85	5.72	759.59	302.03	1001.96	76.15	0.20	0.80	0.00	2	0.59	0.41	0.00	1
2	3.81	1.09	820.51	396.61	1004.74	37.04	0.09	0.89	0.02	2	0.68	0.25	0.07	1
2	25.65	7.42	790.17	328.88	1026.01	92.82	0.22	0.74	0.04	2	0.65	0.34	0.01	1
2	35.27	18.48	785.11	331.32	979.57	4.04	0.25	0.48	0.26	2	0.52	0.31	0.17	1
2	46.69	19.94	780.51	467.41	1047.19	34.57	0.31	0.36	0.33	2	0.65	0.08	0.27	1
3	12.63	8.75	1055.5	1379	875.1	1.65	0.00	0.92	0.08	2	0.00	0.80	0.20	2
3	67.01	36.65	864.23	357.76	1035.8	426.31	0.52	0.00	0.48	1	0.57	0.01	0.42	1

1 - Cenozoic water, 2 - coal measures water, 3 - limestone water

3.3 Comparative analysis of the two methods: From the above context, we can get that using F statistics normalized results as the weight in fuzzy comprehensive evaluation is feasible, and its discrimination effect is better than that of over standard weighting method. The reason is that the over standard weighting method is inclined to give bigger weight to the excess parts of the evaluation factors, and it is suitable for areas such as environmental assessment, in which the indicator factors of beyond the standard pollutants values give greater weights, thus emphasizing the seriousness of too high pollution. The F statistics is the ratio of mean square deviation between groups to mean square deviation in groups, and its value size directly reflects the distribution of the samples from the statistical samples themselves, and the weight values are allocated based on the distinguish abilities of the evaluation factors. Therefore, the application of F statistics weighting method more conforms to the reality significance of discriminating water inrush source and identifying the aquifers of water samples.

4. Conclusions

It is feasible that the normalized results of F statistics are introduced into fuzzy comprehensive evaluation as weight, and the result is better in water inrush source distinguish application of a coal mine. The accuracy rate is as high as 93.6%, which is higher than the accuracy rate of over standard weighting method. Compared with AHP methods, F statistics weighting method overcomes the interferences of artificial subjective factors, and is more in line with the objective reality. Compared with over standard weighting method, F statistics weighting method express the ratio of mean square deviation between groups to mean square deviation in groups, and the appropriate weight values are allocated according to the distinguish abilities of the evaluation factors, being more suitable for seeking an objective evaluation and discrimination from the differences of the statistical samples themselves. Therefore, in some domains, using F statistics weighting method may get better evaluate and discrimination effects.

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