**RESEARCH ARTICLE**

# Application of improved fuzzy comprehensive evaluation method in karst groundwater quality evaluation: a case study of Cengong county

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## Abstract

Groundwater quality is affected by various indexes, and the influence of each index on groundwater quality is fuzzy. Therefore, adopting a reasonable evaluation method can make the groundwater quality evaluation more accurate. Although fuzzy comprehensive evaluation method has great advantages in analyzing fuzzy problems, it has shortcomings in solving problems like weight calculation. The fuzzy comprehensive evaluation method was improved by combining with the entropy weight method in this study. On basis of this, a groundwater quality evaluation model was established. At the same time, by taking the groundwater aquifer of Cambrian Gaotai formation in Cengong County, Guizhou Province as a research object and based on the water quality monitoring data of 14 boreholes there, the model was adopted to evaluate the water quality of the aquifer by combining with GIS technology. The results demonstrated the feasibility and superiority of the improved fuzzy comprehensive theory in groundwater quality evaluation.

## Introduction

Groundwater resources are of great significance not only to the development of social economy, but also to the earth's ecosystem. In recent years, the increasing human engineering activities have brought a lot of negative effects on groundwater resources (Huang et al. 2016; Srinivas et al. 2014). Specifically, these effects are reflected in the decrease of groundwater quantity and the pollution of groundwater. Therefore, it is significant to make accurate assessment of groundwater quality so as to

protect the groundwater resources. As groundwater quality is a fuzzy system of multi-index interaction, groundwater quality indexes have attributes of uncertainty, randomness and fuzziness. To solve this, reasonable evaluation indexes and evaluation methods play an important role in the groundwater quality evaluation(GQE) (Zhang et al. 2015; El Moujabber et al. 2006; Bouderrala 2017).

Currently, there are mainly two assessment methods for GQE, which are single index assessment and multi-index comprehensive assessment (Ismai et al. 2018; Mao et al. 2014; Wu et al. 2018; Su et al. 2016). The former can highlight the impact of a single index on water quality, but it ignores the systematic of groundwater quality (Fei et al. 2015; Bouteraa et al. 2019), while the latter can comprehensively reflect the evaluation results (Huang et al. 2016). The most widely used multi-index comprehensive assessment methods include Improved Neural Networks (Xiao et al. 2019), Matter-Element Extension Method (Huang et al. 2016), Improved Set Pair Analysis (Su et al. 2016), Fuzzy-Grey (Liu et al. 2007), Multivariate Statistics (Atikul Islam et al. 2018; Bouteraa et al. 2019) and so on. Each of them has its own characteristics. Therefore, in the process of GQE, reasonable water quality evaluation methods should

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be selected according to the water quality characteristics of different research areas, so as to accurately evaluate the water quality of the region (Verma et al. 2019; Wang and Dang 2000). Groundwater in Cengong county of Guizhou province belongs to typical karst groundwater, and the influence of its pollution factors on water quality has obvious uncertainty, randomness and fuzziness. (Li et al. 2018a, b). To solve this, by adopting the fuzzy comprehensive evaluation method (FCEM), the concept of fuzzy set to weigh various factors in the fuzzy environment is used to accurately evaluate the advantages and disadvantages of the object, which is in line with the assessment process of karst groundwater quality. However, the influence of karst groundwater storage environment on groundwater quality could be easily neglected when only using FCEM. The reason is that linear weighted average was used in FCEM when obtaining the evaluation set, resulting in deviations in the evaluation results. In view of the above reasons, the entropy weight method (EWM) can determine the objective weight of each pollution factor according to the variation of pollution factors at each monitoring point in the study area. This method objectively measures the impact degree of each pollution factor on water quality, and comprehensively reflects the interaction between groundwater storage environment and water quality system. Therefore, an improved fuzzy comprehensive evaluation method (IFCEM) combined with EWM was proposed to establish an evaluation model to evaluate the groundwater quality in the typical study area of Cengong county, China. And the evaluation results were analyzed to prove the feasibility of the method, which can provide some reference and basis for related research.

## Modeling principle

The concept of fuzzy set is used to weigh various indexes in a fuzzy environment in FCEM and evaluates advantages, as well as disadvantages of objects comprehensively. (Zhao et al. 1993; Zhang et al. 2015; Su et al. 2016). Its assessment process includes two aspects: the evaluation indexes and the evaluation comments. Since the evaluation indexes and comments generally have fuzziness attributes, the fuzzy set and fuzzy relation is used to describe the indexes and comments, and then fuzzy conclusions are made based on the evaluation results through corresponding calculations in the evaluation process. However, each index weight is calculated by linear weighting in this method, thus the influence between indexes is neglected. EWM is an objective weighting method (Chen et al. 2008; Hou 2020). The objective weighting has the original information which takes root in objective indexes, so the influence of decision makers on indexes weights can be avoided, making evaluation results more objective (Liu et al.

2007). This method is basically used to determine the weight based on the difference of the evaluation indexes. Generally, if one index has a smaller entropy value, it's indicated that this index has a greater variation of its index value, and it offers more information, which plays a greater role in comprehensive evaluation and has a larger weight. On the contrary, if one index has a greater entropy value, it's indicated that this index has a smaller variation of its index value, and it offers less information, which plays a smaller role in comprehensive evaluation and has a smaller weight (Lin et al. 2002; Zheng et al. 2000). The calculation process of IFCEM is as follows:

### Calculation of membership function

Membership refers to the degree to which each evaluation index belongs to different evaluation grades. The linear membership function $r_{ij}$ is expressed as follows (Zhao et al. 1993; Luo et al. 2020):

$$r_{ij} \begin{cases} \frac{x_{ij}-s_0}{s_1-s_0} \ or \ \frac{s_1-x_{ij}}{s_1-s_0} & ,s_0 \leq x_{ij} \leq s_1 \\ 1 & ,x_{ij} \geq s_1 \\ 0 & ,x_{ij} \geq s_1 \end{cases} \qquad (1)$$

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1d} \\ r_{21} & r_{22} & \cdots & r_{2d} \\ \vdots & \vdots & \cdots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nd} \end{bmatrix} \qquad (2)$$

Where $s_0$ and $s_1$ are the adjacent standard values of the $j$-th index value of $i$-th evaluation unit. $R$ is the membership matrix of all grades of each sample. $x_{ij}$ are the value of the $j$-th evaluation index of the $i$-th evaluation unit. $n$ is the number of evaluation indexes. $d$ is the number of standard grades.

### Weight allocation of indexes

#### Calculation of the entropy weight

(1) The influencing factors are normalized, aiming to eliminate the influence of different dimensions of each factor on the evaluation result, making the data statistically significant and comparable. For groundwater quality evaluation index, each index is a negative index. The normalization formula (Chen et al. 2008; Hou 2020) of each index is as follows:

$$U_{nm} = \frac{x_{ij}-x\ min}{x\ max-x\ min} \cdot 3 \qquad (3)$$

**Fig. 1** Traffic and location of the study area
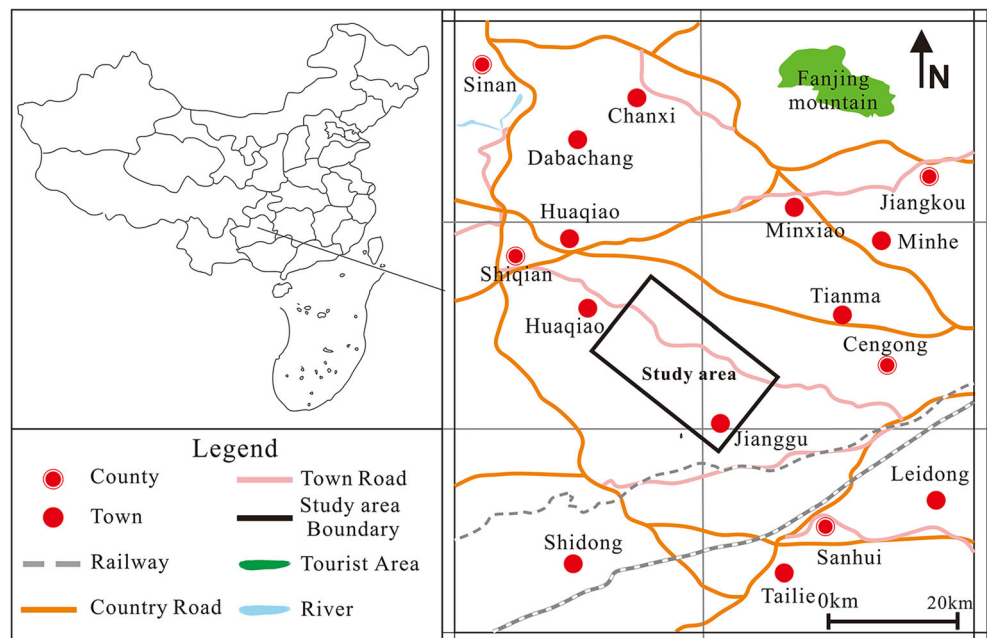
(2) Calculation of proportion $P_{ij}$ of standard value of the $j$-th evaluation index of the $i$-th evaluation unit:

$$P_{ij} = \frac{U_{ij}}{\sum\limits_{i=1}^{m} U_{ij}} \tag{4}$$

(3) Calculation of the entropy $e_j (0 \le e_j \le 1)$ of the $j$-th index:

$$e_j = -k \sum\limits_{i=1}^{m} \left( p_{ij} \cdot \ln p_{ij} \right) \tag{5}$$

(4) Calculation of the utility value $d_j$ of the $j$-th index. The greater $d_j$, the greater the value of the index and the greater its weight.

$$d_j = 1 - e_j \tag{6}$$

(5) Calculation of the entropy weight $W_j^1$ of the $j$-th index:

$$w_j^1 = \frac{d_j}{\sum\limits_{i=1}^{n} d_j} \text{ and } \sum\limits_{j=1}^{n} w_j^1 = 1 \tag{7}$$

Where $U_{ij}$ is the standard value of the $j$-th evaluation index of the $i$-th evaluation unit; $n$ is the number of evaluation indexes; $k$ is the adjustment coefficient, and $k = 1/\ln(m)$ ($m$ is the number of evaluation unit in the evaluation system).

### Calculation of combined weight

Take the evaluation standard value of the $j$-th index as the evaluation set V = {$v_1$, $v_2$…$v_s$}, s is the number of the

evaluation grades. The calculation process of combined weight is as follows:

(1). According to the exceeding standard of each evaluation index. The more it exceeds the standard value, the greater its single index weight. Calculate the single index weight $q_j$ of $j$-th index (Zhang et al. 2015; Su et al. 2016):

$$q_j = \frac{x_{ij}}{\sum\limits_{i=1}^{m} v_{ij}} \tag{8}$$

(2) Calculation of each evaluation unit of the fuzzy weight $W_j^2$ of $j$-th index:

$$W_j^2 = \frac{q_j}{\sum\limits_{i=1}^{m} q_j} \tag{9}$$

(3) Calculation of the combined weight $W_j$ of $j$-th index by liner weighting $W^1$ and $W^2$:

$$W_j = \frac{W_j^1 \cdot W_j^2}{\sum\limits_{j=1}^{n} \left( W_j^1 \cdot W_j^2 \right)} \tag{10}$$

### Calculation of fuzzy evaluation matrix

The fuzzy evaluation matrix $Y$ can be obtained by multiplying the combined weight matrix W and the membership matrix $R$ (Luo et al. 2020). The grade of the maximum value in the

**Table 1** Detection data of groundwater quality in study area (units: mg/L)

| Borehole | x | y | Ammonia nitrogen | Nitrate | Total hardness | Total dissolved solids | iron | Sulfate | Cyanide | Lead | Manganese |
|---|---|---|---|---|---|---|---|---|---|---|---|
| zk01 | 3,028,275.80 | 19,286,903.40 | 0.0500 | 0.7158 | 303.3300 | 480.4000 | 0.0030 | 12.4600 | 0.0020 | 0.0010 | 0.0010 |
| zk02 | 3,031,164.50 | 19,298,282.30 | 0.0500 | 2.4520 | 262.4800 | 388.0000 | 0.1340 | 11.4500 | 0.0020 | 0.0020 | 0.0490 |
| zk03 | 3,042,795.30 | 19,284,490.00 | 0.0500 | 2.1858 | 307.9300 | 485.3000 | 0.1690 | 19.0700 | 0.0020 | 0.0010 | 0.0010 |
| zk04 | 3,040,123.20 | 19,275,457.00 | 0.0500 | 0.6680 | 278.8200 | 432.3000 | 0.0370 | 12.6300 | 0.0020 | 0.0010 | 0.0020 |
| zk05 | 3,034,143.90 | 19,279,032.00 | 0.0500 | 1.0700 | 378.9300 | 591.0000 | 0.1250 | 15.1700 | 0.0020 | 0.0010 | 0.0540 |
| zk06 | 3,030,788.10 | 19,296,818.70 | 0.0500 | 2.4570 | 276.2700 | 423.9000 | 0.0320 | 17.5100 | 0.0020 | 0.0010 | 0.0010 |
| zk07 | 3,038,484.30 | 19,282,655.40 | 0.0500 | 8.2740 | 375.8500 | 592.0000 | 0.1970 | 33.1000 | 0.0020 | 0.0010 | 0.0030 |
| zk08 | 3,034,663.70 | 19,288,003.60 | 0.0500 | 1.7800 | 381.9700 | 604.0000 | 0.2680 | 20.3600 | 0.0020 | 0.0010 | 0.0110 |
| Zk09 | 3,023,464.90 | 19,290,837.60 | 0.0000 | 2.1900 | 300.1400 | 295.1600 | 0.0000 | 6.0000 | 0.0000 | 0.0030 | 0.0000 |
| Zk10 | 3,027,069.70 | 19,288,973.20 | 0.0000 | 1.3140 | 333.6800 | 324.6800 | 0.0000 | 10.6000 | 0.0000 | 0.0000 | 0.0000 |
| zk11 | 3,028,479.70 | 19,298,595.80 | 0.0000 | 1.3140 | 256.7000 | 263.1900 | 0.0000 | 10.0000 | 0.0000 | 0.0090 | 0.0000 |
| zk12 | 3,029,549.40 | 19,289,868.10 | 0.0000 | 1.5810 | 357.3800 | 356.4200 | 0.0100 | 20.0000 | 0.0000 | 0.0020 | 0.0000 |
| zk13 | 3,038,831.30 | 19,289,257.10 | 0.0500 | 2.5000 | 253.5400 | 426.3000 | 0.1130 | 12.9200 | 0.0020 | 0.0010 | 0.0010 |
| zk14 | 3,031,647.10 | 19,289,683.90 | 0.0500 | 1.4320 | 282.1100 | 468.3000 | 1.6100 | 10.2300 | 0.0020 | 0.0010 | 0.0170 |

fuzzy evaluation matrix is the corresponding grade of the evaluation object.

$$Y = W \times R = [y_1, y_2, \cdots y_s] \qquad (11)$$

## Application examples

### Geographical overview

The study area is located in Cengong county, Guizhou province, China. And its geographical coordinates are: 108°51′24″ ~ 108°56′49″, 27°18′25″ ~ 27°28′49″, as shown in Fig. 1. The

climate are subtropical monsoon humid climate in the study area, with distinct seasons and abundant rainfall. The geomorphology belongs to karst depression geomorphology. The recharge of groundwater is mainly the infiltration of atmospheric precipitation, and the aquifer there is the Cambrian Middle Cambrian Gaotai formation (∈2 g). The lithology there is mainly gray, deep gray white medium thick layered fine dolomite, where water is abundant there. The groundwater type is carbonate karst fissure water, and the aqueous medium is the dissolution fracture. In this area, human activities are dominated by agricultural production. Besides, there is no production activity by large chemical companies, and the water environment is in good condition.



**Fig. 2** Distribution of Iron's content
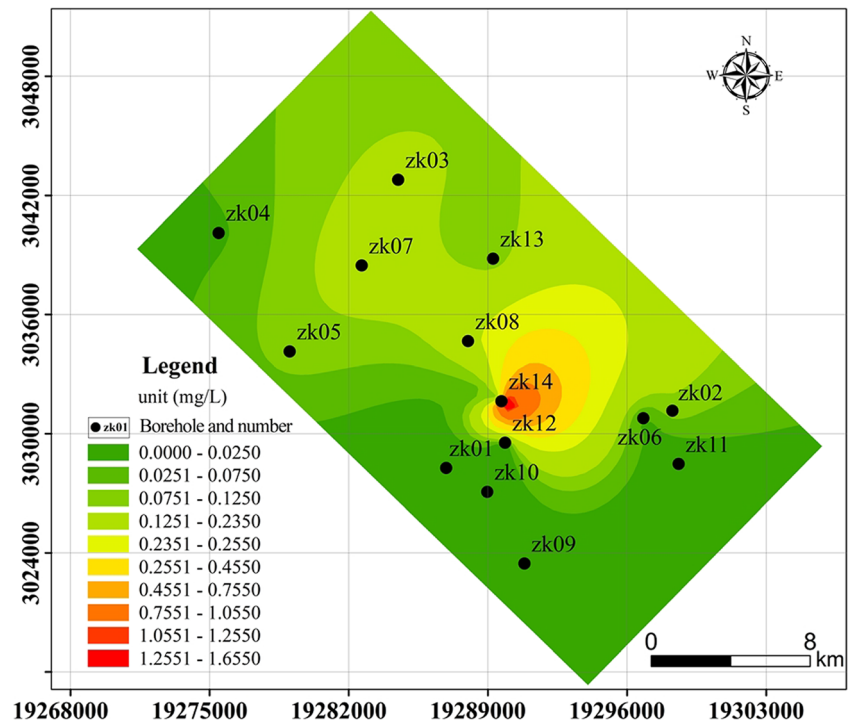
**Fig. 3** Distribution of
Manganese's content
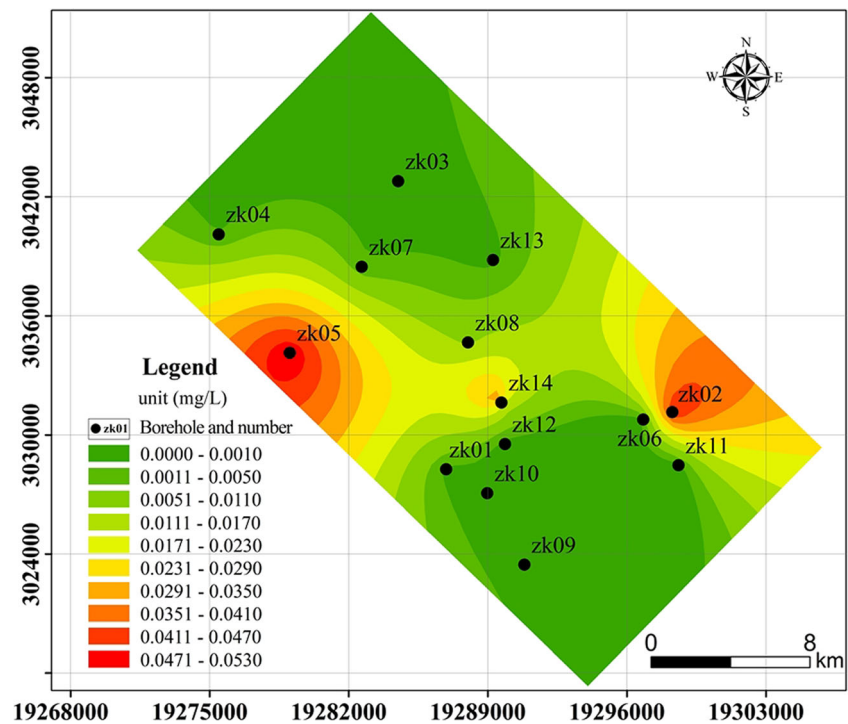


## Establishment of the thematic map groundwater quality evaluation indexes

Taking the aquifer of Gaotai formation of Cambrian Middle Series as the evaluation object, the water sample detection data of 14 hydrogeological boreholes were collected as the evaluation indexes, as shown in Table 1. The attribute database and spatial distribution map of each water chemical index were made by GIS. The distribution maps of iron content and manganese content are shown in Figs. 2 and 3, and the distribution maps of other indexes content are shown in Attachment S1-S8.

## Evaluation of groundwater quality based on IFCEM

### Standard of groundwater quality

According to the standard of the groundwater quality of the people's Republic of China (China Geological Survey 2017), the groundwater quality types are divided into five grades, and values of grade standard are shown in Table 2. Borehole zk01 was taken as an example in this study to present the evaluation process of groundwater quality based on IFCEM.

### Calculation of membership

Based on the above method, the membership between the groundwater quality samples and the standard of groundwater

**Table 2** Standard of groundwater quality (units: mg/L)

| Standard value | I | II | III | IV | V |
|---|---|---|---|---|---|
| Ammonia nitrogen | <0.02 | <0.1 | <0.5 | <1.5 | ≥1.5 |
| Nitrate | <0.01 | <0.1 | <1 | <4.8 | ≥4.8 |
| Total Hardness | <150 | <300 | <450 | <650 | ≥650 |
| Total dissolved solids | <300 | <500 | <1000 | <2000 | ≥2000 |
| iron | <0.1 | <0.2 | <0.3 | <2 | ≥2 |
| Sulfate | <50 | <150 | <250 | <350 | ≥350 |
| Cyanide | <0.001 | <0.01 | <0.05 | <0.1 | ≥0.1 |
| Lead | <0.005 | <0.005 | <0.01 | <0.1 | ≥0.1 |
| Manganese | <0.05 | <0.05 | <0.1 | <1.5 | ≥1.5 |

**Table 3** Membership matrix of the borehole zk01

| Membership | $R_{1j}$, I | $R_{1j}$, II | $R_{1j}$, III | $R_{1j}$, IV | $R_{1j}$, V |
|---|---|---|---|---|---|
| Ammonia nitrogen | 0.625 | 0.375 | 0.000 | 0.000 | 0.000 |
| Nitrate | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Total hardness | 0.000 | 0.978 | 0.022 | 0.000 | 0.000 |
| Total dissolved solids | 0.098 | 0.902 | 0.000 | 0.000 | 0.000 |
| iron | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Sulfate | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Cyanide | 0.889 | 0.111 | 0.000 | 0.000 | 0.000 |
| Lead | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Manganese | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 |

**Table 4** Entropy weight $W^1$ of evaluation indexes for groundwater quality

| Indexes | Ammonia nitrogen | Nitrate | Total hardness | Total dissolved solids | iron | Sulfate | Cyanide | Lead | Manganese |
|---|---|---|---|---|---|---|---|---|---|
| Entropy | 0.8679 | 0.8468 | 0.8650 | 0.9242 | 0.6687 | 0.9024 | 0.7401 | 0.6568 | 0.6433 |
| Utility value | 0.1321 | 0.1532 | 0.1350 | 0.0758 | 0.3313 | 0.0976 | 0.2599 | 0.3432 | 0.3567 |
| Weight | 0.0701 | 0.0813 | 0.0716 | 0.0402 | 0.1758 | 0.0518 | 0.1379 | 0.1821 | 0.1892 |

quality of the borehole zk01 can be calculated. The water quality samples at the boreholes showed that the concentration values of nitrate, iron, sulfate, lead, and manganese were lower than the standard value of Grade I water; The content of ammonia nitrogen, dissolved solids and cyanide were between the standard values of Grade I water and Grade II water, and the content of total hardness was between the standard values of Grade II water and Grade III water. The standard value of Grade II water and Grade III water were 300 mg/L and 450 mg/L respectively. According to Formula 1, the membership degree of the third index total hardness of the test point can be calculated as follows: $(r_{13}, I) = 0$, $(r_{13}, II) = 0.9778$, $(r_{13}, III) = 0.0222$. $(r_{13}, IV) = 0$, $(r_{13}, V) = 0$. On this basis, we can know the degree of membership indicates that 97.78% of the total hardness of the third index of the borehole zk01 belongs to Grade II water and 2.22% belongs to Grade III water, the degree of belonging to other types of water is 0%. Similarly, the membership degrees of other indexes of the borehole zk01 (Table 3) and the membership degrees of other boreholes (Table S1) can be calculated.

## Calculation of the combined weight of each borehole and index

Based on the detection value of each index, the standard value $U_{ij}$ of indexes of each borehole was calculated by Formula 3. And the proportion $P_{ij}$ of the influencing factors of each borehole was calculated by Formula 4.

The entropy value $e_j$ and utility value $d_j$ of each index were calculated with Formulas 5 and 6, respectively (Table 4). If one index has a smaller entropy value, it's indicated that the index has more information, which plays a greater role in the analysis of GQE and has a greater weight. Finally, the entropy weight value $W^1$ of each influencing index was calculated by Formula 7 (Table 4).

The detection value of the total hardness of borehole zk01 is 303.3 mg/L, and its values of standard of groundwater quality are 150 mg/L, 300 mg/L, 450 mg/L and 650 mg/L. The parameter weight of total hardness is 0.7828, and its fuzzy weight was calculated by Formula 9, which is 0.3190. Similarly, the fuzzy weight $W^2$ of other indexes and boreholes was calculated (Table 5).

The entropy weight and the fuzzy weight was used to calculate the combined weight W (Table 6) of indexes in the study area by Formula 10.

## Calculation of the fuzzy evaluation matrix

The membership matrix R of the borehole zk01 shown in Table 3, and the combined weights W = (0.0633, 0.0391, 0.5364, 0.1947, 0.0078, 0.0309, 0.0656, 0.0581, 0.0043). The fuzzy evaluation matrix is calculated by Formula 11, and the fuzzy evaluation matrix Y = (0.2570, 0.7311, 0.0119, 0.0000, 0.0000). The fuzzy evaluation matrix of other

**Table 5** The fuzzy weight $W^2$ of evaluation indexes for groundwater quality

| $W^2$ | Ammonia nitrogen | Nitrate | Total hardness | Total dissolved solids | iron | Sulfate | Cyanide | Lead | Manganese |
|---|---|---|---|---|---|---|---|---|---|
| zk01 | 0.0595 | 0.0317 | 0.4938 | 0.3190 | 0.0029 | 0.0393 | 0.0313 | 0.0210 | 0.0015 |
| zk02 | 0.0511 | 0.0931 | 0.3667 | 0.2211 | 0.1116 | 0.0310 | 0.0269 | 0.0361 | 0.0624 |
| zk03 | 0.0473 | 0.0769 | 0.3985 | 0.2562 | 0.1304 | 0.0478 | 0.0249 | 0.0167 | 0.0012 |
| zk04 | 0.0619 | 0.0308 | 0.4723 | 0.2987 | 0.0374 | 0.0414 | 0.0326 | 0.0219 | 0.0031 |
| zk05 | 0.0420 | 0.0334 | 0.4351 | 0.2768 | 0.0856 | 0.0337 | 0.0221 | 0.0148 | 0.0565 |
| zk06 | 0.0572 | 0.1046 | 0.4326 | 0.2707 | 0.0299 | 0.0531 | 0.0301 | 0.0202 | 0.0014 |
| zk07 | 0.0334 | 0.2054 | 0.3431 | 0.2205 | 0.1072 | 0.0585 | 0.0176 | 0.0118 | 0.0025 |
| zk08 | 0.0383 | 0.0507 | 0.4001 | 0.2581 | 0.1673 | 0.0413 | 0.0202 | 0.0135 | 0.0105 |
| Zk09 | 0.0000 | 0.1123 | 0.5658 | 0.2270 | 0.0000 | 0.0219 | 0.0000 | 0.0730 | 0.0000 |
| Zk10 | 0.0000 | 0.0684 | 0.6388 | 0.2535 | 0.0000 | 0.0393 | 0.0000 | 0.0000 | 0.0000 |
| zk11 | 0.0000 | 0.0667 | 0.4794 | 0.2005 | 0.0000 | 0.0362 | 0.0000 | 0.2171 | 0.0000 |
| zk12 | 0.0000 | 0.0698 | 0.5799 | 0.2359 | 0.0097 | 0.0629 | 0.0000 | 0.0419 | 0.0000 |
| zk13 | 0.0556 | 0.1034 | 0.3856 | 0.2645 | 0.1025 | 0.0381 | 0.0293 | 0.0196 | 0.0014 |
| zk14 | 0.0232 | 0.0247 | 0.1790 | 0.1212 | 0.6090 | 0.0126 | 0.0122 | 0.0082 | 0.0098 |

**Table 6** The combined weight W of evaluation indexes for groundwater quality

| Borehole | Ammonia nitrogen | Nitrate | Total hardness | Total dissolved solids | iron | Sulfate | Cyanide | Lead | Manganese |
|---|---|---|---|---|---|---|---|---|---|
| zk01 | 0.0633 | 0.0391 | 0.5364 | 0.1947 | 0.0078 | 0.0309 | 0.0656 | 0.0581 | 0.0043 |
| zk02 | 0.0400 | 0.0845 | 0.2930 | 0.0992 | 0.2189 | 0.0179 | 0.0414 | 0.0733 | 0.1318 |
| zk03 | 0.0412 | 0.0776 | 0.3545 | 0.1280 | 0.2847 | 0.0308 | 0.0427 | 0.0378 | 0.0028 |
| zk04 | 0.0616 | 0.0355 | 0.4800 | 0.1705 | 0.0932 | 0.0305 | 0.0638 | 0.0565 | 0.0083 |
| zk05 | 0.0362 | 0.0334 | 0.3838 | 0.1372 | 0.1853 | 0.0215 | 0.0376 | 0.0333 | 0.1318 |
| zk06 | 0.0569 | 0.1206 | 0.4394 | 0.1545 | 0.0745 | 0.0390 | 0.0590 | 0.0522 | 0.0038 |
| zk07 | 0.0295 | 0.2103 | 0.3095 | 0.1117 | 0.2374 | 0.0382 | 0.0305 | 0.0270 | 0.0060 |
| zk08 | 0.0317 | 0.0487 | 0.3386 | 0.1227 | 0.3476 | 0.0253 | 0.0329 | 0.0291 | 0.0235 |
| Zk09 | 0.0000 | 0.1246 | 0.5535 | 0.1247 | 0.0000 | 0.0155 | 0.0000 | 0.1817 | 0.0000 |
| Zk10 | 0.0000 | 0.0875 | 0.7199 | 0.1605 | 0.0000 | 0.0320 | 0.0000 | 0.0000 | 0.0000 |
| zk11 | 0.0000 | 0.0608 | 0.3848 | 0.0904 | 0.0000 | 0.0210 | 0.0000 | 0.4430 | 0.0000 |
| zk12 | 0.0000 | 0.0818 | 0.5994 | 0.1370 | 0.0245 | 0.0470 | 0.0000 | 0.1102 | 0.0000 |
| zk13 | 0.0497 | 0.1072 | 0.3522 | 0.1357 | 0.2297 | 0.0251 | 0.0515 | 0.0456 | 0.0033 |
| zk14 | 0.0121 | 0.0150 | 0.0956 | 0.0364 | 0.7985 | 0.0049 | 0.0126 | 0.0111 | 0.0139 |

boreholes can be calculated by the same principle as shown in the following Table 7.

## Results of GQE in study area

On the basis of obtaining the fuzzy evaluation matrix Y (Table 7) of each borehole, according to the principle that the maximum value of the fuzzy evaluation matrix is the evaluation object level, the groundwater quality grade of each borehole is obtained shown in Table 8. Among the 14 boreholes in the study area, zk02 and zk13 belong to Grade I water, zk14 belongs to Grade IV water, zk08 belongs to Grade III

water and the other boreholes belong to Grade II water. The results of GQE are shown in Table 8. At the same time, data analysis and processing function of GIS was used to make the comprehensive evaluation division map of groundwater quality in the study area, as shown in Fig. 4.

It can be seen from Fig. 4 that the water quality in the study area is good on the whole, and the water quality types are mainly Grade I water and Grade II water; Grade I water is distributed in the north and east of the study area, with Grade II water distributed in the north and south of the study area, occupying a dominant position; Contents of sulfate, total hardness and soluble solids in Grade II water are slightly higher than those in Grade I water. The main reason for this

**Table 7** Fuzzy evaluation matrix of each borehole

| Borehole | $y_n$, Grade I water | $y_n$, Grade II water | $y_n$, Grade III water | $y_n$, Grade IV water | $y_n$, Grade V water |
|---|---|---|---|---|---|
| zk01 | 0.2570 | 0.7311 | 0.0119 | 0.0000 | 0.0000 |
| zk02 | 0.6299 | 0.3701 | 0.0000 | 0.0000 | 0.0000 |
| zk03 | 0.3055 | 0.6757 | 0.0187 | 0.0000 | 0.0000 |
| zk04 | 0.4448 | 0.5552 | 0.0000 | 0.0000 | 0.0000 |
| zk05 | 0.2832 | 0.4793 | 0.2374 | 0.0000 | 0.0000 |
| zk06 | 0.4881 | 0.5119 | 0.0000 | 0.0000 | 0.0000 |
| zk07 | 0.1239 | 0.6532 | 0.2229 | 0.0000 | 0.0000 |
| zk08 | 0.1756 | 0.3775 | 0.4469 | 0.0000 | 0.0000 |
| Zk09 | 0.4386 | 0.5608 | 0.0005 | 0.0000 | 0.0000 |
| Zk10 | 0.2603 | 0.5781 | 0.1617 | 0.0000 | 0.0000 |
| zk11 | 0.2833 | 0.3623 | 0.3544 | 0.0000 | 0.0000 |
| zk12 | 0.3619 | 0.4088 | 0.2293 | 0.0000 | 0.0000 |
| zk13 | 0.5992 | 0.4008 | 0.0000 | 0.0000 | 0.0000 |
| zk14 | 0.0808 | 0.1208 | 0.1832 | 0.6153 | 0.0000 |

**Table 8** The results of GQE in the study area

| Borehole | zk01 | zk02 | zk03 | zk04 | zk05 | zk06 | zk07 |
|---|---|---|---|---|---|---|---|
| $y_{max}$ | 0.7311 | 0.6299 | 0.6757 | 0.5552 | 0.4793 | 0.5119 | 0.6532 |
| Grade | Grade II water | Grade I water | Grade II water | Grade II water | Grade II water | Grade II water | Grade II water |
| Borehole | zk08 | Zk9 | zk10 | zk11 | zk12 | zk13 | zk14 |
| $y_{max}$ | 0.4469 | 0.5608 | 0.5781 | 0.3623 | 0.4088 | 0.5992 | 0.6153 |
| Grade | Grade III water | Grade II water | Grade II water | Grade I water | Grade II water | Grade I water | Grade IV water |

phenomenon is that the residents living and agricultural activities in the region will produce domestic sewage, domestic garbage and agricultural sewage, which often contain pollutants such as nitrogen, phosphorus and sulfide. These pollutants are not discharged in a standardized way, which is easy to cause pollutants to infiltrate into the aquifer along karst pipelines and fissures and pollute groundwater; Grade III water is annularly distributed from zk08 to south with small distribution area. In the north, east and south of the area, there are a large number of farmland and residential areas, and the area belongs to the valley area with a south-west direction where the groundwater is collected to the middle in this area, resulting in a high concentration of pollution in the area; Grade IV water expands outward with zk14 as the center. A large number of farmland and residential areas are around the zk14, and the red clay layer of Quaternary is thicker in the area. Since red clay contains a large amount of iron ions (Yuan et al. 2016), these iron ions and other pollutants infiltrate into karst aquifers through cracks, dissolution gaps and other ways, which resulted in the surrounding groundwater content

of iron, total hardness, sulfate and dissolved total solids exceeding the standard. In addition, the area is located in the valley, and the terrain is gentle. This resulted in weak groundwater mobility, small velocity, and formed a relatively closed area, which can cause pollution accumulation in the area.

To sum up, the evaluation results of groundwater quality evaluation model based on IFCEM are consistent with the actual situation, which indicates that the model is effective and feasible in karst groundwater evaluation.

# Conclusion

GQE plays an important role in the management and protection of groundwater resources. Groundwater quality has the characteristics of randomness, fuzziness and uncertainties. In this study, Cengong county was taken as a typical research object and the groundwater quality detection data of 14 boreholes was used to establish an evaluation model of karst groundwater quality as well as a database of evaluation index



**Fig. 4** Zoning map of groundwater quality evaluation results in the study area
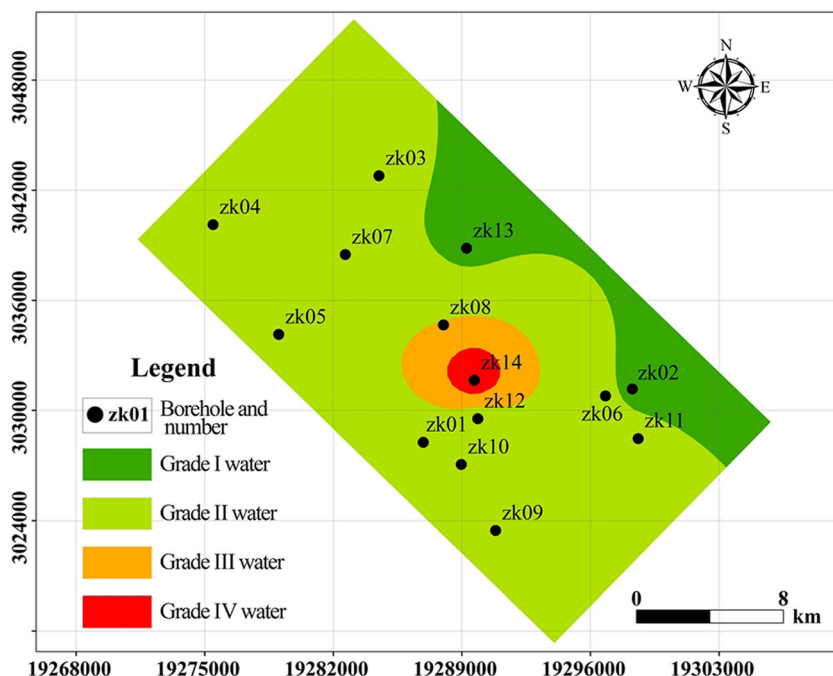
based on the IFCEM. This model was applied to the analysis of GQE of the study area, which verified the rationality and effectiveness of the model.

By adopting the groundwater quality evaluation model based on IFCEM, problems like data's limitation and weight assignment can be avoided. Through the fuzzy membership degree constructed, the influence of each evaluation index on groundwater quality can be reflected. And the combination weight of each index is calculated by using the index variability, which realizes the full utilization of the measured data. The results showed that it is reasonable and feasible to apply this method to the evaluation of karst groundwater quality. Besides, it is a new approach and can provide certain reference for karst GQE.

# References

Atikul Islam M, Rahman MM, Bodrud-Doza M, Muhib MI, Shammi M, Zahid A, Akter Y, Kurasaki M (2018) A study of groundwater irrigation water quality in south-Central Bangladesh:a geo-statistical model approach using GIS and multivariate statics. Original Article 37(2):193–214

Bouderrala A (2017) Assessment of groundwater quality and its suitability for domestic and agricultural uses in low-Isser plain. Arab J Geosci 10(15):33–346

Bouteraa O, Mebarki A, Bouaicha F, Nouaceur Z, Laignel B (2019) Groundwater quality assessment using multivariate analysis, geostatistical modeling, and water quality index (WQI): a case of study in Boumerzoug-EI Khroub valley of Northeast Algeria. Acta Geochim 38(6):796–814

Chen SZ, Wang XJ, Zhao XY (2008) An attribute recognition model based on entropy weight for evaluating the quality of groundwater sources. Science Direct (Journal of university of Mining and Technology) 45(18):72–75

China Geological Survey (2017) Standard for groundwater quality (GB/T 14848-2017). General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China&National Standardization Administration of China, 1–14

El Moujabber M, Bou Samra B, Darwish T, Atallah T (2006) Comparison of different indicators for groundwater contamination by seawater intrusion on the Lebanese coast. Water Resour Manag 20:161–180

Fei YH, Zhang ZJ, Gou CY, Tian X (2015) Quality evaluation of groundwater in North China plain. J Groundwater Sci Eng 4(3):306–315

Hou SJ (2020) The risk assessment of tunnel surrounding rock deformation based on entropy weight method and extension matter element method. Earth Environ Sci 558(4):032–043

Huang YY, Su JY, Chen WC (2016) Application of improved matter-element extension method in comprehensive assessment of shallow groundwater. J Landsc Res 8(4):16–20

Ismai AH, Shareef MA, Mahmood W (2018) Hydrochemical characterization of groundwater in Balad district, Salah Al-Din governorate, Iraq. J Groundw Sci Eng 6(4):306–322

Li B, Zeng YF, Zhang BB, Wang XQ (2018a) A risk evaluation model for karst groundwater pollution based on geographic information system and artificial neural network applications. Environ Earth Sci 77:344–358

Li B, Wang XQ, Wei T, Zeng YF, Zhang BB (2018b) Analysis of sustainable utilization of water resources in karst region based on the ecological footprint model, Liupanshui city case. J Water Supply Res Technol 67(6):566–575

Lin YD, Men BH, Jia WS (2002) Application of entropy weight coeffcient method to evaluating on alimentative type of water. Northwest Water Resources & Water Engineering 13(3):27–28

Liu RT, Fu Q, Gai ZM (2007) Entropy weight coefficient model and its application evaluation of groundwater vulnerability of the Sanjing plain. J Northeast Agric Univ 14(4):368–373

Luo QF, Li W, Su HL, Chen XR (2020) Evaluating construction risks of modified shield machine applicable to soft soils based on fuzzy comprehensive evaluation method. Math Probl Eng 2020:01–15

Mao HX, Ren XR, Zhou LH, Li Y (2014) Groundwater quality analysis and vulnerability assessment in Longdong area. Meteorol Environ Res 5(10):49–51 55

Srinivas Y, Hudson Oliver D, Stanley Raj A, Chandrasekar N (2014) Quality assessment and hydrogeochemical characteristics of groundwater in Agastheeswaram taluk, Kanyakumari district, Tamil Nadu, India. Chin J Geochem 33:221–235

Su JY, Huang YY, Li B (2016) Application of improved SPA method in the comprehensive assessment of groundwater environment quality: a case study of Jinjiang, Fujian Province. J Landsc Res 8(1):73–75

Verma P, Singh PK, Sinha RR, Tiwari AK (2019) Assessment of groundwater quality status by using water quality index (wqi) and geographic information system (gis) approaches: a case study of the Bokaro District, India. Appl Water Sci 10(3):142–158

Wang YM, Dang JF (2000) Analysis on underground water pollution in oil and gas fields. J Geol Hazards & Environ Preserv 11(3):271–273

Wu TW, Wang LH, Wang LS (2018) Evaluation of groundwater quality and pollution in Daqing oilfield. J Groundw Sci Eng 6(4):40–48

Xiao JQ, Zhou X, Pan Y, Ferruleadg X (2019) Application of a GA-BP optimized TSFNN water quality monitoring and evaluation system prediction model. J Southwest Univ (natural science edition) 41(12): 111–118 (in Chinese)

Yuan JB, He Y, Liu JH (2016) Construction of weak expansive red clay on Dongxin expressway in Hunan Province, China. J Perform Constr Facil 30(1):C4015001–C4015010

Zhang YL, Zhou Y, Cheng Z, Yao ZP, Shen J, Wang XL (2015) Comparison and Analrsis of different evaluation methods for water quality in the Danjiangkou Valley. Environ Monitoring in China 31(3):58–61 (in Chinese)

Zhao X, Kang WD, Zhao XH, Luo QB (1993) Application of fuzzy comprehensive evaluation method in evaluation of water quality in guide region. J Anhui Agric 71(4):289–294 (in Chinese)

Zheng XH, Zhang Q, Luo M (2000) The application of entropy-weight coefficient method to risk decision. Ci-Technology and Management 6(2):73–75