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Fuzzy pattern recognition method for assessing groundwater vulnerability to pollution in the Zhangji area

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Abstract: Based on the widely used DRASTIC method, a fuzzy pattern recognition and optimization method was proposed and applied to the fissured-karstic aquifer of Zhangji area for assessing groundwater vulnerability to pollution. The result is compared with DRASTIC method. It is shown that by taking the fuzziness into consideration, the fuzzy pattern recognition and optimization method reflects more efficiently the fuzzy nature of the groundwater vulnerability to pollution and is more applicable in reality.

Key words: Fuzzy sets recognition and optimization method, Groundwater vulnerability to pollution, DRASTIC
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INTRODUCTION

In order to tackle the groundwater pollution and to protect the groundwater quality in a more scientific and efficient way, different methods and models have been developed for assessing the groundwater vulnerability to pollution. The DRASTIC method, since developed by the US Environmental Protection Agency (EPA) (Aller *et al*., 1987), has been widely used in the US and also been applied in various nations and regions such as Israel (Melloul and Collin, 1998), Portugal (Lobo-Ferreira and Oliveira, 1997) South Africa (Lynch *et al*., 1997), South Korea (Kim and Hamm, 1999), China (Yang and Luan, 1999), and so on. DRASTIC method is one of the most popularly used models for assessing groundwater vulnerability. Despite its popularity, DRASTIC may be unable to actually reflect the influence of hydrogeological factors by assigning ratings for related parameters falling into a certain range. According to the fuzzy nature of the groundwater vulnerability to pollution, a fuzzy pattern recognition and optimization method was developed based on the DRASTIC method (Zhou *et al*., 1999). In this paper, both of the DRASTIC method and the fuzzy method were applied to the fissured-karstic aquifer of Zhangji, a water supply place in Xuzhou City, Jiangsu Province, and the results were compared and analyzed.

DRASTIC METHOD

DRASTIC method focuses on the intrinsic features of the aquifer including hydrogeological, morphological and other aquifer characteristics. The index of DRASTIC corresponds to the weighted average values of 7 hydrogeological parameters: (1) Depth to the water table (*D*); (2) Net recharge (*R*); (3) Aquifer media (*A*); (4) Soil media (*S*); (5) Topography (*T*); (6) Impact of vadose zone (*I*); (7) Hydraulic conductivity (*C*).

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Table 1 Ranges and ratings for parameters *D*, *R*, *T* and *C*

Depth to water table (*D*)		Net recharge (*R*)		Topography (*T*)		Hydraulic conductivity (*C*)	
Range (m)	Rating	Range (mm/a)	Rating	Range (%)	Rating	Range (m/d)	Rating
0~1.5	10	0~51	1	0~2	10	0~4.1	1
1.5~4.6	9	51~02	3	2~6	9	4.1~12.2	2
4.6~9.1	7	102~178	6	6~12	5	12.2~28.5	4
9.1~15.2	5	178~254	8	12~18	3	28.5~40.7	6
15.2~22.9	3	>254	9	>18	1	40.7~81.5	8
22.9~30.5	2	−	−	−	−	>81.5	10
>30.5	1	−	−	−	−	−	−

Table 2 Ranges and ratings for parameters *A*, *S*, and *I*

Aquifer media (*A*)		Soil type (*S*)		Impact of the unsaturated zone (*I*)	
Range	Rating	Range	Rating	Range	Rating
Massive shale	2	Thin or absent	10	Confining layer	1
Metamorphic/Igneous	3	Gravel	10	Silt/Clay/Shale	3
Weathered metamorphic/Igneous	4	Sand	9	Metamorphic/Igneous	4
Glacial till	5	Peat	8	Limestone, sandstone, shale	6
Bedded sandstone, limestone and shale	6	Shrinking clay	7	Sand and gravel with silt and clay	6
Massive sandstone	6	Sandy loam	6	Sand and gravel	8
Massive limestone	6	Loam	5	Basalt	9
Sand and gravel	8	Silty loam	4	Karst limestone	10
Basalt	9	Clay loam	3	−	−
Karst limestone	10	Muck	2	−	−
−	−	Nonshrinking clay	1	−	−

A value between 1 and 10 to each parameter, except R which ranges between 1 and 9, is attributed depending on local conditions. The attributed values are generally obtained from Tables 1 and 2, which give the correspondence between local hydrogeological characteristics and the parameter values. High ratings correspond to high vulnerability. The local index of vulnerability is computed through multiplication of the value attributed to each parameter by its relative weight, and adding up all seven products. The weight of each parameter is assigned based on its relative significance contributing to the pollution potential. The most significant factors have weights of 5, the least significant a weight of 1 (Table 3). DRASTIC index is computed by:

$$DRASTIC = \sum_{j=1}^{m} (w_j R_j), \tag{1}$$

where R_j is the attributed value of the parameter, w_j is the weighting coefficient corresponding to the parameter and m is the number of the parameters.

The minimum value of the standard DRASTIC index is therefore 26 and the maximum value is 226. Such extreme values are very rare, the most common values being within the range 50 to 200. The parameters and the final evaluating results for a certain region can be graphically displayed on a map by using GIS.

Table 3 Weighting factor for standard DRASTIC

Parameter	Weighting factor
D	5
R	4
A	3
S	2
T	1
I	5
C	3

Due to its characteristics of simplicity and usefulness, DRASTIC method has been adopted and widely used for evaluating the regional groundwater vulnerability to pollution. While by assigning ratings for related parameters falling into a certain range, DRASTIC may ignore the difference of parameters within the same range and fail to reflect the influence of the variation of the parameters.

Groundwater vulnerability to pollution has the nature of fuzziness and thus can be assessed by using the fuzzy sets theory (Chen, 1994). For a certain aquifer, a number of sections are identified according to the hydrogeological conditions and taken as the fuzzy sets. The groundwater vulnerability to pollution is reflected by the membership degree (confidence) of the sections; membership degree of 1 represents that the section is mostly vulnerable to pollution, while membership degree of 0 is least. Thus a fuzzy pattern recognition and optimization method can be applied for the assessment of groundwater vulnerability to pollution.

FUZZY PATTERN RECOGNITION AND OPTIMIZATION METHOD

If the number of samples (sections) for assessment is n and the number of parameters reflecting the groundwater vulnerability to pollution is m, the parameter matrix for the samples can be written as:

$$\boldsymbol{X}=\begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix}, \qquad (2)$$

where x_{ij} equals the value of parameter j corresponding to sample i.

The parameters in DRASTIC method can be classified into two groups: A and B. In Group A, the groundwater vulnerability increases with the growing values of the parameters, while it is reverse in Group B, the groundwater vulnerability reduces when the parameter value increases. Parameters R, A, S, C and I belong to Group A, while D and T belong to Group B.

For parameter j in sample i, the relative membership degree of groundwater vulnerability can be defined as:

$$r_{ij}=\begin{cases} \dfrac{x_{ij}-x_{\min j}}{x_{\max j}-x_{\min j}}, & x_{ij}\in \text{Group } A; \\ 1-\dfrac{x_{ij}-x_{\min j}}{x_{\max j}-x_{\min j}}, & x_{ij}\in \text{Group } B, \end{cases} \qquad (3)$$

where $x_{\max j}$ and $x_{\min j}$ equal the maximum and minimum value respectively of parameter j of all the samples:

$$x_{\max j}=\max\prod_{i=1}^{n} x_{ij};\ x_{\min j}=\min\prod_{i}^{n} x_{ij},\ j=1, 2, \ldots, m.$$

By using Eq.(3), the relative membership matrix $\boldsymbol{R}$ can be derived:

$$\boldsymbol{R}=\begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix}. \qquad (4)$$

Assume the relative membership degree of sample i is u_i, the normalized weighting factor of the parameter j is w_j (Table 4), the general Euclidean distance $D(r_i)$ is used to indicate the difference between sample i and the maximum groundwater vulnerability, for which u_i=1.

$$D(r_i)=u_i\sqrt{\sum_{j=1}^{m}[w_j(r_{ij}-1)]^2}. \qquad (5)$$

Table 4 Normalized weighting factor of the parameters

Parameter	Normalized weighting factor
D	0.22
R	0.17
A	0.13
S	0.09
T	0.04
I	0.22
C	0.13

In order to acquire the optimized solution of u_i, the objective function is established (Chen, 1998):

$$\min\left\{F(u_i)=u_i^2\sum_{j=1}^{m}[w_j(r_{ij}-1)]^2+(1-u_i)^2\sum_{j=1}^{m}(w_j\times r_{ij})^2\right\}.$$

To solve $\partial F(u_i)/\partial u_i=0$, then

$$u_i=\frac{1}{1+\sum_{j=1}^{m}[w_j(r_{ij}-1)]^2\Big/\sum_{j=1}^{m}(w_j r_{ij})^2}. \qquad (6)$$

For each sample, u_i is derived and compared to see the groundwater vulnerability of the section. This is the fuzzy pattern recognition and optimization method for assessing the groundwater vulnerability to pollution.

APPLICATION TO THE ZHANGJI AREA

Hydrogeological parameters in case study area

Zhangji, covering an area of 360 km^2, is situated in the southeast of Xuzhou City, Jiangsu Province and 25 km from the city center. This area is a place for drinking water supply to Xuzhou City due to the presence of abundant groundwater resources. Two main groundwater aquifer systems occur in the area: the porous aquifer and the fissured-karstic aquifer. The porous aquifer, composed of Quaternary deposits of sand and clay, covers the whole plain area of 190 km^2 and has the characteristic of unconfined aquifer; the fissured-karstic aquifer, mainly consisting of limestone and dolomite, spreads over the whole area and has rich groundwater storage with fissures, fractures and caves present here and there.

The fissured-karstic aquifer here is chosen for the application of groundwater vulnerability assessment. In the hilly areas, the rocks outcrop and the karstic aquifer are unconfined; while in the plain area, the karstic aquifer is overlaid by the porous aquifer and it is so confined. According to the hydrogeological condition of the fissured-karstic aquifer (Qian *et al*., 2003), 12 sections (samples) are selected (Fig.1) and the values of the parameters are assigned in Table 5.

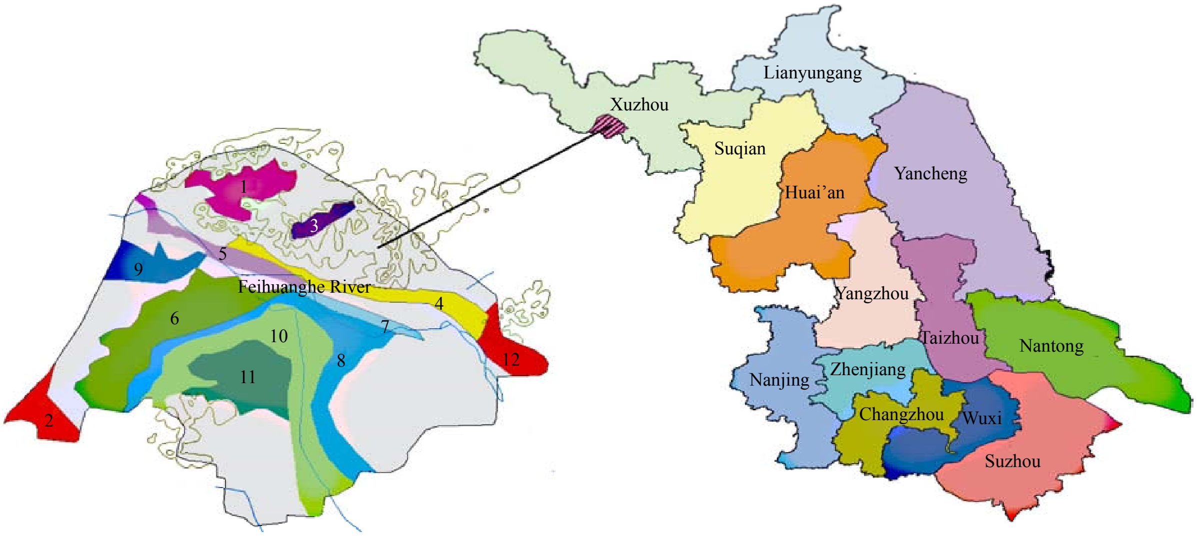

Fig.1 Zhangji case study area location in Jiangsu Province and the locations of the selected 12 samples
The contour line shows the topography of the area indicating the hilly area

Table 5 Hydrogeological parameter values in case study area

Samples	Values						
	D (m)	R (mm)	A	S	T (%)	I	C (m/d)
1	3.0	275.0	9	6	3.4	1	5.9
2	50.6	225.0	6	6	0.2	1	5.7
3	101.5	225.0	9	10	8.6	8	1.7
4	15.5	375.0	9	6	0.2	1	28.5
5	27.0	375.0	6	6	0.2	1	3.0
6	37.0	225.0	6	6	0.2	1	3.5
7	25.9	325.0	6	6	0.2	1	3.0
8	24.7	225.0	6	6	0.2	1	3.0
9	37.5	325.0	9	6	0.2	1	77.5
10	13.3	225.0	6	6	0.2	1	2.8
11	5.0	225.0	6	6	1.0	6	2.8
12	52.3	375.0	9	10	4.7	1	2.9

DRASTIC method application

According to the ranges and ratings for the parameters in Tables 1 and 2, the rating is assigned for the parameters of each sample and the results are presented in Table 6.

Table 6 Ratings of the parameters of each sample

Sample	Rating						
	D (m)	*R* (mm)	*A*	*S*	*T* (%)	*I*	*C* (m/d)
1	9	9	9	6	9	1	2
2	1	8	6	6	10	1	2
3	1	8	9	10	5	8	1
4	3	9	9	6	10	1	4
5	2	9	6	6	10	1	1
6	1	8	6	6	10	1	1
7	2	9	6	6	10	1	1
8	2	8	6	6	10	1	1
9	1	9	9	6	10	1	8
10	5	8	6	6	10	1	1
11	7	8	6	6	10	6	1
12	1	9	9	10	9	1	1

Based on the rating results and the weighting factors in Table 3, the DRASTIC index is computed by using Eq.(1). The results are shown in Table 7.

Table 7 DRASTIC index of the samples and the ranking order of groundwater vulnerability

Sample	DRASTIC index	Ranking order
1	140	9
2	88	2
3	132	8
4	117	6
5	94	4
6	85	1
7	94	4
8	90	3
9	119	7
10	105	5
11	140	9
12	105	5

Fuzzy method application

By using Eq.(3), the relative membership degree for the parameters of each sample is derived in Table 8. Finally the relative membership degree of the samples is computed by Eq.(6) in Table 9.

Table 8 Hydrogeological parameter values in case study area

Sample	Relative membership degree						
	D (m)	*R* (mm)	*A*	*S*	*T* (%)	*I*	*C* (m/d)
1	1.00	0.33	1.00	0.00	0.62	0.00	0.06
2	0.52	0.00	0.00	0.00	1.00	0.00	0.05
3	0.00	0.00	1.00	1.00	0.00	1.00	0.00
4	0.87	1.00	1.00	0.00	1.00	0.00	0.35
5	0.76	1.00	0.00	0.00	1.00	0.00	0.02
6	0.66	0.00	0.00	0.00	1.00	0.00	0.02
7	0.77	0.67	0.00	0.00	1.00	0.00	0.02
8	0.78	0.00	0.00	0.00	1.00	0.00	0.02
9	0.65	0.67	1.00	0.00	1.00	0.00	1.00
10	0.90	0.00	0.00	0.00	1.00	0.00	0.01
11	0.98	0.00	0.00	0.00	0.91	0.71	0.01
12	0.50	1.00	1.00	1.00	0.47	0.00	0.02

Table 9 Relative membership degree of vulnerability and the ranking order for samples

Samples	Membership degree	Ranking order
1	0.45	8
2	0.10	1
3	0.43	7
4	0.58	12
5	0.39	6
6	0.15	2
7	0.31	5
8	0.20	3
9	0.52	11
10	0.25	4
11	0.49	10
12	0.47	9

Comparison of two methods

Fig.2 shows the groundwater vulnerability results derived both from DRASTIC method and fuzzy method. It demonstrates that generally the vulnerability variation of the samples from the two methods is similar: the groundwater vulnerability is comparatively high for samples 1, 3, 4, 9 and 11 and low for samples 2, 5, 6, 7, 8 and 10. While some inconsistence occurs, for sample 12, the vulnerability is relatively low from DRASTIC method but high from fuzzy method. Moreover from DRASTIC method, samples 1 and 11, 5 and 7, 10 and 12 have the same index values which indicates that they have the same groundwater vulnerability. But from Fuzzy method, their relative membership degree values are different which shows that their groundwater vulnerability differs from each other.

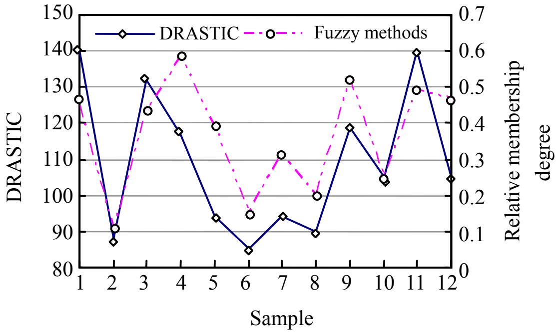

Fig.2 Comparison of groundwater vulnerability results of DRASTIC and fuzzy methods

CONCLUSION AND REMARKS

Both the DRASTIC method and the fuzzy pattern recognition method are applied to a case study area, the fissured-karstic aquifer of the Zhangji area, and the results are compared and analyzed. It is shown that by assigning ratings for related parameters falling into a certain range, DRASTIC method will in some cases ignore the difference of parameter values within the same range and is unable to reflect the influence of the variation of hydrogeological parameters on the groundwater vulnerability. By taking the fuzziness into consideration, the results from the fuzzy method reflect more efficiently the fuzzy nature of the groundwater vulnerability and the influence of the hydrogeological parameters. The fuzzy pattern recognition and optimization method has significant advantages over the DRASTIC approach. It is should be remarked that the accuracy of the data in the local area is of vital importance for the assessment, more detailed and robust data will bring better results and should be preferred.

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