

Application of DRASTIC and extension theory in the groundwater vulnerability evaluation

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Abstract

Groundwater vulnerability assessment plays a vital role in the utilization and protection of groundwater resources. DRASTIC is one of the most widely used models for groundwater vulnerability assessment. However, the DRASTIC model should be modified based on the local hydrogeological conditions in order to get a relatively accurate result. In this study, Baotou, China was chosen as a case study. The groundwater vulnerability was assessed using DRASTIC at first, but the evaluation results were not consistent with the groundwater quality. So the DRASTIC model was modified based on extension theory and analytic hierarchy process (AHP) method. The extension theory could be used to divide the groundwater vulnerability grades in the DRASTIC model. It is a new attempt to use extension theory and DRASTIC in the assessment of groundwater vulnerability, and the research results show that this method is better for assessing groundwater vulnerability.

Groundwater is the most important water resource on Earth, and it is a major source of water for domestic, industrial and agricultural uses in many countries (Alemaw *et al.* 2004; Brito *et al.* 2006; Almasri 2008; Rahman 2008). Groundwater contamination is one of the most common environmental problems. The groundwater quality is generally under a considerable potential of contamination especially in agriculture-dominated areas with intense activities that involve the use of fertilizers and pesticides (Hamza *et al.* 2007; Almasri 2008; Dimitriou *et al.* 2008). Remediation of polluted aquifers is prohibitively costly and often impractical (Thirumalaivasan *et al.* 2003). It is important to protect the groundwater resources against pollution for groundwater planning, management and land-use planning. Groundwater monitoring is time-consuming and too costly to adequately define the geographical extent of contamination at a regional scale. So the groundwater vulnerability assessment is important for a rational management of groundwater resources (Almasri 2008). In recent years, due to the shortage of groundwater resources, people pay more attention to the groundwater protection, and the groundwater vulnerability assessment has become a hot topic (Zhong 2005).

The widely accepted concept of groundwater vulnerability was put forward by the US National Research Council in 1993. Groundwater vulnerability is defined as the tendency of contaminants to reach a specified position in the groundwater system after introduction at some location above the upper-

most aquifer (Worrall & Besien 2005; Rahman 2008). DRASTIC is one of the most widely used models for groundwater vulnerability evaluation studies (Secunda *et al.* 1998; Al-Adamat *et al.* 2003; Thirumalaivasan *et al.* 2003; Babiker *et al.* 2005; Zhong 2005; Hamza *et al.* 2007; Leone *et al.* 2007). The DRASTIC model is rigid in the assignment of ratings and weights to the model parameters. However, researchers often need to modify the model based on the local hydrogeological conditions. The modifications were in the form of using additional parameters, removal of certain parameters, and usage of different ratings and weights for the parameters (Thirumalaivasan *et al.* 2003; Dixon 2005a, b; Zhong 2005; Rapti-Caputo *et al.* 2006; Nobre *et al.* 2007; Rahman 2008).

Thirumalaivasan *et al.* (2003) used analytic hierarchy process (AHP) to compute the ratings and weights of the parameters in the DRASTIC model in the groundwater vulnerability assessment in North Arcot district of Tamil Nadu, India, and some modification of the parameters were also made to adapt to the local hydrogeological settings. The DRASTIC model was modified by involving an additional parameter reflecting the anthropogenic impact, and the ranges of four parameters (D, T, C and I) were modified. The groundwater vulnerability was classified into three categories using the natural breaks method in ArcView geographic information systems (GIS).

Dixon (2005b) generated the contamination potential maps by using detailed landuse/pesticides and soil structure

information in conjunction with selected parameters from DRASTIC model. Nobre *et al.* (2007) used a modified version of the DRASTIC methodology for groundwater vulnerability mapping in a coastal urban aquifer in the city of Maceio. Rahman (2008) used DRASTIC model in a GIS environment in the groundwater vulnerability assessment in Aligarh and its surrounding areas, and a procedure similar to the DRASTIC model was utilized and enhanced, then the model sensitivity analysis was carried out.

DRASTIC model does not suggest methods to classify the groundwater vulnerability grades (Zhong 2005). The researchers need to divide the groundwater vulnerability grades into several levels based on the DRASTIC index, and the groundwater vulnerability grades proposed by different researchers are often different.

In order to put forward a more realistic method to classify the groundwater vulnerability grades, extension theory, AHP and DRASTIC model were used in the groundwater vulnerability evaluation in Baotou, Inner Mongolia, China. Groundwater vulnerability of the study area was evaluated using DRASTIC model at first, but the evaluation results were not consistent with the groundwater quality. Then the extension theory, AHP and DRASTIC were used to assess the groundwater vulnerability. AHP was used to compute the ratings and weights of the parameters in the DRASTIC model. The extension theory, GIS (Esri China Ltd., Beijing, China) and Interactive Data Language (IDL) (Esri China Ltd., Beijing, China) were used to divide the vulnerability grades, and the evaluation results are generally in line with the actual condition of groundwater quality. The major difference about this study and that of other researchers is that we used extension theory to determine the groundwater vulnerability grade.

The study area

The study area is located in Baotou City, Inner Mongolia, China. Baotou is not only the heavy industry base of North

China but also the largest industrial city in Inner Mongolia. Baotou city has developed economy and dense population. Baotou is an arid and semi-arid region. The yearly averaged value of precipitation is 306.5 mm, and the yearly averaged value of evaporation is 2273.8 mm. The natural surface water system is not developed in Baotou. The main water source for domestic, industrial and agricultural uses in Baotou is the Yellow River, which cross from west to east through the study area.

North boundary of the study area is the Piedmont fault, and the south boundary is the Yellow River. The west and east boundary are in the Dongheyan and Dengkou region. The study area contains a total area of 768 km². Figure 1 is the location of the study area.

The study area has two main aquifers, which are confined aquifer and unconfined aquifer. The unconfined aquifer is composed of upper Pleistocene to Holocene sand and gravel, and the confined aquifer is mainly composed of middle and lower Pleistocene gravel. There are widely distributed, large thickness and impermeable Pleistocene muddy clay between confined and unconfined aquifer. Based on the local groundwater quality monitoring data, the unconfined groundwater was seriously contaminated, and the exceeding rate of total hardness and dissolved solids is nearly 50%. The confined aquifer pollution is not serious, so this study focused on the unconfined aquifer. The unconfined aquifer is composed mainly by gravel and pebbles in the north and central area, and the aquifer is composed mainly by sand in the south area. The rock grain size of the unconfined aquifer and the groundwater depth become smaller from north to south in the study area. The unconfined aquifer thickness is generally 20–30 m. The aquifer recharge from lateral flow, infiltration of precipitation, irrigation and surface water. The unconfined groundwater flow from northeast to southwest, and the discharge of unconfined aquifer includes exploitation and evaporation.

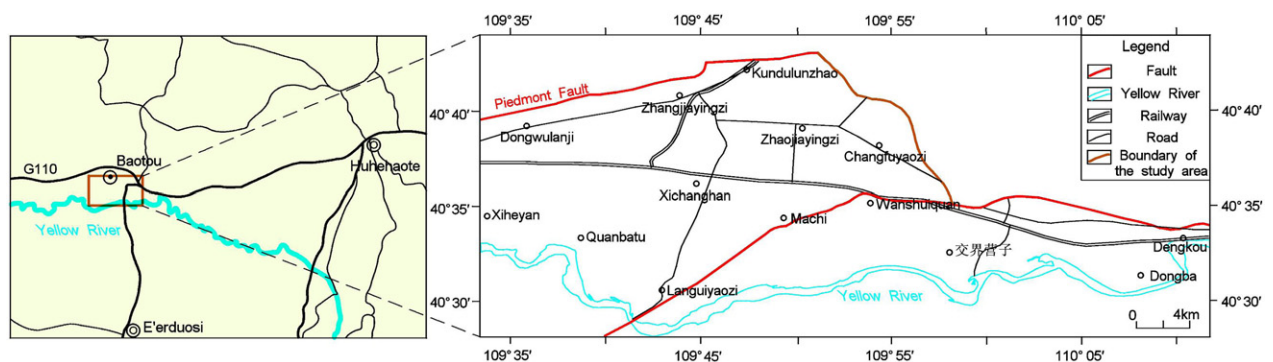


Fig. 1. Location of the study area.

Table 1 Description and weights of the DRASTIC parameters

Factors	Description	Relative weights
Depth to water	It is depth from ground to water table; the deeper the water table, the lesser will be the chances of pollutants to interact with ground water.	5
Net recharge	It is the amount of water/unit area of land that penetrates the ground surface and reaches the water table; it is the reporting agents for pollutants to the ground water.	4
Aquifer media	It is the potential area for water storage. The contaminant attenuation of aquifer depends on the amount and sorting of fine grains; the lower the grain size, the higher the attenuation capacity of aquifer media.	3
Soil media	Soil media is the uppermost and weathered part of the ground. Soil cover characteristics influence the surface and downward movement of contaminants.	2
Topography	It refers to slope or steepness; areas with low slope tend to retain water for longer. This allows a greater infiltration of recharge of water and a greater potential for contaminant migration and vulnerable to ground water contamination and vice versa.	1
Impact of vadose zone	It is the ground portion found between the aquifer and the soil cover in which pores or joints are unsaturated. Its influence on aquifer pollution potential similar to that of soil cover, depending on its permeability, and on the attenuation characteristics of the media.	5
Hydraulic conductivity	It refers to the ability of the aquifer formation to transmit water. An aquifer with high conductivity is vulnerable to substantial contamination, as a plume of contamination can move easily through the aquifer.	3

Methods

The groundwater vulnerability evaluation model was constructed through DRASTIC, AHP and the extension theory in this study. Extension theory is a knowledge system based on the concepts of matter element and extension set (Cai 1999). Extension theory regards the objective world as a world of matter element, so the contradictory problems in the real world can be transformed into those among matter elements. Extension set is a kind of mathematical method that describes the pattern recognition and classification about objective. When the standard matter element model was established, the correlation degree of a certain incident and the standard matter element could be computed, and the matter grade could be determined by the correlation degree. GIS and IDL software were used to derive the vulnerability grades. IDL is a programming language used for data analysis. IDL is vectorized, numerical and interactive, and is commonly used for interactive processing of large amounts of data.

The groundwater quantity and quality data were obtained from the environmental protection department of Baotou. The hydrogeological data, such as borehole data, stratum and lithology, geological structure and hydrogeological parameters were obtained from local department of geological exploitation.

DRASTIC-based groundwater vulnerability evaluation model

The seven variables from which the DRASTIC model name is derived are depth to water table, net recharge, aquifer media, soil media, topography, impact of vadose zone and conductivity (Aller *et al.* 1987). The parameters in the DRASTIC model are divided into ranges or zones representing

various hydrogeological settings and are assigned different ratings in a scale of 1–10. The weights value assigned to the parameters indicates their relative importance in contributing to aquifer vulnerability. Each DRASTIC factor has been assigned a relative weight ranging from 1 to 5 using a Delphi approach. Table 1 shows the description and weights of the parameters in DRASTIC model (Aller *et al.* 1987; Almasri 2008).

The DRASTIC intrinsic vulnerability index as given below (Aller *et al.* 1987):

$$\text{DRASTIC index} = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w \quad (1)$$

where the capital letters indicate the respective parameter and the subscripts 'r' and 'w' refer to their rating and weight, respectively. The value and weights of the parameters are suggested in the DRASTIC model. Once the DRASTIC Index has been computed, it is convenient to identify areas that are more likely to be susceptible to contamination relative to others. The higher the DRASTIC index, the greater the groundwater pollution potential is.

The DRASTIC model has been used in groundwater vulnerability assessment in many countries and regions, such as American (Zhong 2005), China (Chen *et al.* 2006; Sun *et al.* 2007; Zhang *et al.* 2007; Jiang & Guo 2008), Japan (Babiker *et al.* 2005), India (Thirumalaivasan *et al.* 2003), Jordan (Al-Adamat *et al.* 2003), Israel (Secunda *et al.* 1998), New Zealand (Bekesi & McConchie 1999), South Korea (Zhong 2005), Tunisia (Hamza *et al.* 2007) and South Africa (Worrall *et al.* 2002; Zhong 2005).

DRASTIC was developed to evaluate the groundwater pollution potential of any area in the United States. The model is

rigid in the assignment of ratings and weights to the parameters. However, for better addressing of local hydrogeological settings, researchers need to make several modifications of the ratings and weights for the parameters. In this study, the suggested values and weights of the parameters were used at first. But, the DRASTIC evaluation results are different from the groundwater quality. According to the local hydrogeological conditions, the parameter of aquifer media was displaced by aquifer thickness, and the parameter of hydraulic conductivity was displaced by coefficient of transmissibility. The weights for the parameters were computed by AHP, and the DRASTIC model was modified based on extension theory and AHP.

Groundwater vulnerability evaluation using DRASTIC and extension theory

DRASTIC model does not contain grades of the groundwater vulnerability (Zhong 2005). Different researchers divided the groundwater vulnerability grades into different levels based on the DRASTIC index value (DI value). Al-Adamat *et al.* (2003) divided the groundwater vulnerability into two grades based on the DRASTIC values; the range was classified as low vulnerability (92–118) and moderate vulnerability (123–139). Zheng *et al.* (2004) divided the groundwater vulnerability into five grades: very high vulnerability (> 160), high vulnerability (140–160), moderate vulnerability (120–140), low vulnerability (100–120) and very low vulnerability (< 100). Fan & Yang (2007) divided the groundwater vulnerability into five grades: very high vulnerability (> 80), high vulnerability (60–79), moderate vulnerability (40–59), low vulnerability (20–39) and very low vulnerability (< 20). Jiang & Guo (2008) divided the groundwater vulnerability into five grades: very high vulnerability (139–154), high vulnerability (122–138), moderate vulnerability (105–121), low vulnerability (88–104) and very low vulnerability (71–87).

It can be seen that too much subjective factors had been contained in the classification of groundwater vulnerability grades. The groundwater vulnerability grades should be determined by the DI value. But, the DI value may be different at different locations, so it is difficult to suggest a unified criterion of groundwater vulnerability grades because the DI value varies greatly in different locations with different hydrogeological conditions. A new method should be explored to classify the groundwater vulnerability grades. The extension theory is an effective means to solve this problem.

Basic condition of extension theory

Matter element theory and the theory of extension set are two theoretical pillars of extension theory (Cai 1999). The extension theory suggests methods to study and solve the problem of incompatibility from both qualitative and quanti-

tative point of views. The extension theory also provides new tools for computer science and artificial intelligence research. It is convenient to describe the matter and materials in the real world through the matter element and affair element.

An ordered triad $R = (N, c, v)$ is used as the basic element for describing things, which is called matter element, where N represents the matter, c is the characteristics, and v is N 's measure about the characteristics c . In extension theory, 'things' are the matters or characteristic of matters existed in the real world. Things are entity of quality and quantity.

A matter has many characteristic elements, which can be described by n -dimensional matter elements

$$R = \begin{pmatrix} N & c_1 & v_1 \\ & c_2 & v_2 \\ & \vdots & \vdots \\ & c_n & v_n \end{pmatrix} \quad (2)$$

An ordered triad $I = (d, h, u)$ is used as the basic element for describing affairs, and this triad is called affair element, where d is the verb and h is the characteristic. The

$$n\text{-dimensional affair element } I = \begin{pmatrix} d & h_1 & u_1 \\ & h_2 & u_2 \\ & \vdots & \vdots \\ & h_n & u_n \end{pmatrix} = (d, h, u) \text{ is}$$

used to describe the verb d , which is expressed by characteristics $h_1, h_2, \dots, h_n$ and respective measures $u_1, u_2, \dots, u_n$.

Various matters and affairs in the real world can be described with formalized symbols through the matter element and affair element. Various strategies and ideas can be described with the help of matter element transformations, affair element transformations and their operations. Based on the extension theory, the standard matter element model could be constructed as

$$R = \begin{pmatrix} B_j & X_1 & x_1 \\ & X_2 & x_2 \\ & \vdots & \vdots \\ & X_n & x_n \end{pmatrix} \quad (3)$$

where $X_1, X_2, \dots, X_n$ represent factors in the model. $x_1, x_2, \dots, x_n$ are the value of $X_1, X_2, \dots, X_n$, and $B_j = (j = 1, 2, \dots, n)$ represents different events.

The concept of distance in real variable functions has been generalized. The distance on real axis between point x and a given real interval $x_0 = (a, b)$ is defined as

$$\rho = (x, X_0) = |x - (a + b)/2| - (b - a)/2 \quad (4)$$

If x lies before $(a + b)/2$, then Eq. (4) simplifies to $a - x$. If x lies after $(a + b)/2$, then Eq. (4) simplifies to $x - b$.

Dependent function is used to express that the dependent degree of a given matter possesses some property. The dependent function in the extension theory is defined as

$$K(x) = \frac{\rho(x, X_0)}{D(x, X_0, X)} \quad (5)$$

where $D(x, X_0, X)$ is defined as

$$D(x, X_0, X) = \begin{cases} \rho(x, X) - \rho(x, X_0), & x \notin X_0 \\ -1 & x \in X_0 \end{cases} \quad (6)$$

Correlation degree (K_j) of the factors in a certain incident (R) and the standard matter element model should be computed at first. Which incident should happen was determined by the correlation degree of incident (R) and incident N_j in the standard matter element model. K_j is computed by the formula as follows:

$$K_j = \sum_{i=1}^n b_i K_j(v_i) \quad j = 1, 2, \dots, m; i = 1, 2, \dots, n \quad (7)$$

where b_i represents the weight of each factor. n represents factors in the model, and m represents different events.

If $K_{j0} = \max_{j \in (1, 2, \dots, m)} K_j$, then the incident B_{j0} was determined to happen in the model. For example, we can define the groundwater quality as incident (R). The groundwater quality can be classified into m grades, so $B_j (j = 1, 2, \dots, m)$ represents different grade (event). The groundwater quality grade was decided by n factors, and x_n represents factors in the model. $b_i (i = 1, 2, \dots, n)$ represents weight of each factor, and K_j is the correlation degree. For a certain groundwater quality (R), $K_j(v_i) (j = 1, 2, \dots, m; i = 1, 2, \dots, n)$ is the correlation degree of the factors in a incident (R) and the standard matter element model. If $K_{j0} = \max_{j \in (1, 2, \dots, m)} K_j$, then B_{j0} was determined to be the groundwater quality grade.

In this study, extension theory regards the groundwater vulnerability as a matter element, so the groundwater vulnerability grades were transformed into matter elements. The pattern recognition and classification about groundwater vulnerability were described by the extension set. The correlation degree of the groundwater vulnerability in a certain location and the standard matter element were computed. The groundwater vulnerability grades were determined by the correlation degree.

Groundwater vulnerability evaluation

The standard matter element model was constructed at first, then the study area was divided into squares of 1 km × 1 km. The values of seven parameters in each square were obtained by GIS software. For each unit of a certain state $R = (X_1 = x_1, X_2 = x_2, X_3 = x_3, X_4 = x_4, X_5 = x_5, X_6 = x_6, X_7 = x_7)$,

the groundwater vulnerability grades were computed through GIS and IDL method. In this research, the grades of groundwater vulnerability are 5, 4, 3, 2 and 1.

Results and discussion

Evaluation results by DRASTIC model

Data of the depth to water table, net recharge, aquifer media, soil media, topography, impact of vadose zone and conductivity were acquired by GIS software from topographical map, geological map, hydrogeological map and soil type map of the study area. There are seven layers corresponding to the seven parameters in DRASTIC model, and each parameter was evaluated by DRASTIC model. Figure 2 shows the evaluation layers of the parameters.

Based on the DI value, the groundwater vulnerability could be divided into five grades by equal interval method. DI value of 75–95 is the very low vulnerability region, DI value of 95–115 is the low vulnerability region, DI value of 115–135 is the medium vulnerability region, DI value of 135–155 is the high vulnerability region, and DI value of 155–175 is the very high vulnerability region. Overall, the groundwater vulnerability in the study area can be divided into four grades, namely the very high vulnerability region, high vulnerability region, medium vulnerability region and low vulnerability region.

Optimization of parameters selection and weights evaluation in DRASTIC model

Comparison of DRASTIC evaluation results with other evaluation results

The unconfined groundwater quality evaluation based on Nemero index was made by the Inner Mongolia geological environment monitoring station in 1995 and 2000. The main projects of the groundwater quality, including total hardness, total dissolved solids, sulphate, chloride, nitrate nitrogen, fluoride, hexavalent chromium, phenol, cyanide, arsenic and so on. According to the evaluation results, the groundwater quality was classified into four grades, namely the good water quality region, medium water quality region, bad water quality region and very bad water quality region (Fig. 3). Based on the Quality Standard for Groundwater (GB/T 14848-93), groundwater quality is divided into five grades in China. In this study, Grades I and II were integrated into one grade. So, the groundwater quality was classified into four grades.

According to the classification layer of groundwater quality in 1995 and 2000, it can be seen that the central and western region of the study area are the very bad groundwater quality region, and the southern region is the bad

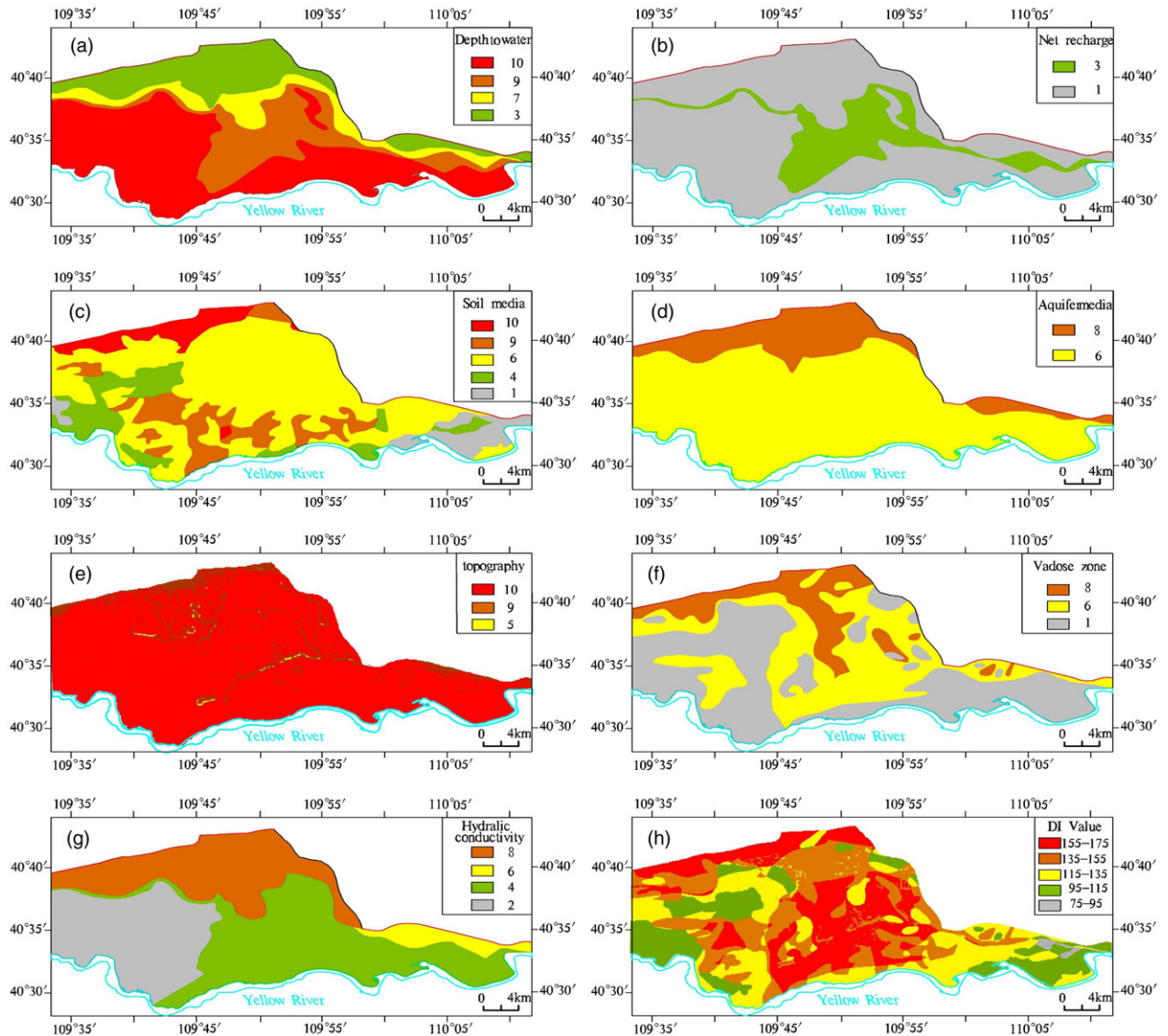


Fig. 2. Evaluation layer of the seven parameters and groundwater vulnerability. (a–g) evaluation layer of the depth to water table, net recharge, aquifer media, soil media, topography, impact of vadose zone and conductivity. The simulated year is 2000. (h) groundwater vulnerability evaluation layer of study area.

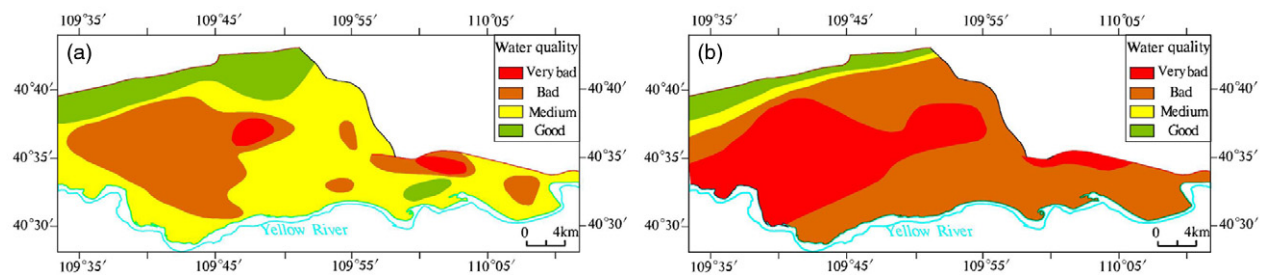


Fig. 3. Classification of groundwater quality in (a) 1995 and (b) 2000 using Nemero index.

Table 2 Parameters categories and valuation of aquifer thickness and transmissibility

Aquifer thickness		Coefficient of transmissibility	
Thickness (m)	Valuation	T/(m ² /d)	Valuation
> 45	1	> 2000	1
36–45	2	1001–2000	2
26–35	4	501–1000	4
16–25	6	101–500	6
6–15	8	0–100	8
< 6	10		

groundwater quality region. But, the DRASTIC model evaluation results show that the western and southern regions of the study area are the medium and low vulnerability regions, so the groundwater quality evaluation results are different from the DRASTIC evaluation result. As a result, the DRASTIC model needs to be modified in this study because the DRASTIC evaluation results are different from the groundwater quality.

Optimization of parameters selection and weights evaluation

Modification of the parameters selection in DRASTIC. The DRASTIC evaluation results are different from the groundwater quality, and this study suggested that this may be caused by the parameters of aquifer media and conductivity. There are many different opinions about the parameters of aquifer media and conductivity. Zhong (2005) and Liu *et al.* (2006) suggested that the parameters of aquifer media and conductivity can be deleted in the groundwater vulnerability evaluation. Zhong (2005) suggested that the parameter of aquifer thickness should be considered in the groundwater vulnerability evaluation.

In this study, the parameter of aquifer media was displaced by aquifer thickness, and the parameter of aquifer conductivity was displaced by coefficient of transmissibility. The parameters of aquifer thickness and transmissibility can reflect the aquifer dilution ability. The revised model can be called 'DRASTIT' or 'DRASTIC'. Considering the domestic and foreign research progress, this study suggested the parameters valuation of aquifer thickness and transmissibility. Table 2 shows the parameters valuation, and Fig. 4 shows the evaluation layers of aquifer thickness and transmissibility.

Computation of the parameters' weights. The DRASTIC model has some unreasonable factors on evaluation of parameters' weights, such as exaggerating the importance of net recharge, weakening the importance of soil media, and ignoring the aquifer ability to dilute the pollutants. In addition, the parameters' weights should be changed when the parameters' evaluation changes, and it is unreasonable to

copy the parameters' weights suggested in the DRASTIC model. AHP method is widely used in computing the parameters' weights by many researchers. In this study, the parameters' weights were computed using AHP method according to the groundwater monitoring data and the relative importance of different parameters. AHP was proposed by Saaty in the 1970s, in which the hierarchy of components of the decisions was used in decision-making process. AHP method was introduced to China since 1982. With its characteristic of combining qualitative and quantitative evaluation method, AHP method had been widely used in the social and economic fields in China. The process of calculating weight with AHP method is as follows:

(1) Construction of the comparison matrix

The pairwise comparison matrix should be constructed to compare all the criteria with one another. The comparison matrix in this study was constructed as:

$$P_{ij} = \begin{bmatrix} p_{11} & p_{12} & p_{13} & p_{14} & p_{15} & p_{16} & p_{17} \\ p_{21} & p_{22} & p_{23} & p_{24} & p_{25} & p_{26} & p_{27} \\ p_{31} & p_{32} & p_{33} & p_{34} & p_{35} & p_{36} & p_{37} \\ p_{41} & p_{42} & p_{43} & p_{44} & p_{45} & p_{46} & p_{47} \\ p_{51} & p_{52} & p_{53} & p_{54} & p_{55} & p_{56} & p_{57} \\ p_{61} & p_{62} & p_{63} & p_{64} & p_{65} & p_{66} & p_{67} \\ p_{71} & p_{72} & p_{73} & p_{74} & p_{75} & p_{76} & p_{77} \end{bmatrix} \quad (8)$$

The value of 1 in the matrix suggests that the criteria are equally important, and the value of 9 leads one to infer that the criterion under consideration is extremely important in relation to the other criterion with which the comparison is made. Through the matrix calculation, the maximum value of the characteristics of the corresponding eigenvector can be determined, and the feature vector is the weight of each parameter.

(2) Calculation of the product of each row element in the matrix:

$$M_i = \prod_{j=1}^7 p_{ij} \quad (i, j = 1, 2, \dots, 7) \quad (9)$$

(3) Computation of the seventh root of M_i :

$$\overline{W}_i = \sqrt[7]{M_i} \quad (10)$$

(4) Determination of the eigenvector W :

$$W = (W_1, W_2, \dots, W_7)^T$$

$$W_i = \overline{W}_i / \sum_{j=1}^7 \overline{W}_j \quad (11)$$

(5) Use CR to test the consistency of the matrix ($CR = CI/RI$; $CI = (\lambda_{\max} - m)/(m - 1)$; $\lambda_{\max}$ is the maximum eigenvalue of the judgement matrix; CI and CR are consistency index and con-

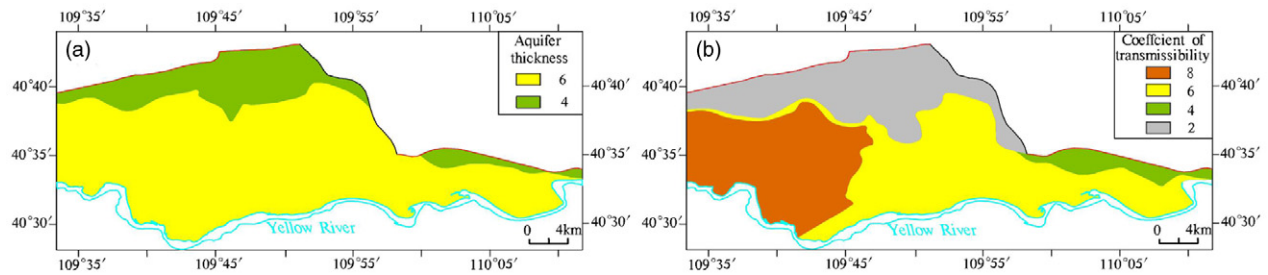


Fig. 4. Evaluation layers of (a) aquifer thickness and (b) coefficient of transmissibility.

Table 3 Paired comparison matrix in the research

	Depth to water	Net Recharge	Aquifer thickness	Soil media	Topography	Impact of vadose zone	Coefficient of transmissibility
Depth to water	1	6	2	2	8	2	2
Net Recharge	1/6	1	1/3	1/3	3	1/3	1/3
Aquifer thickness	1/2	3	1	1	5	1	1
Soil media	1/2	3	1	1	5	1	1
Topography	1/8	1/3	1/5	1/5	1	1/5	1/5
Impact of vadose zone	1/2	3	1	1	5	1	1
Coefficient of transmissibility	1/2	3	1	1	5	1	1

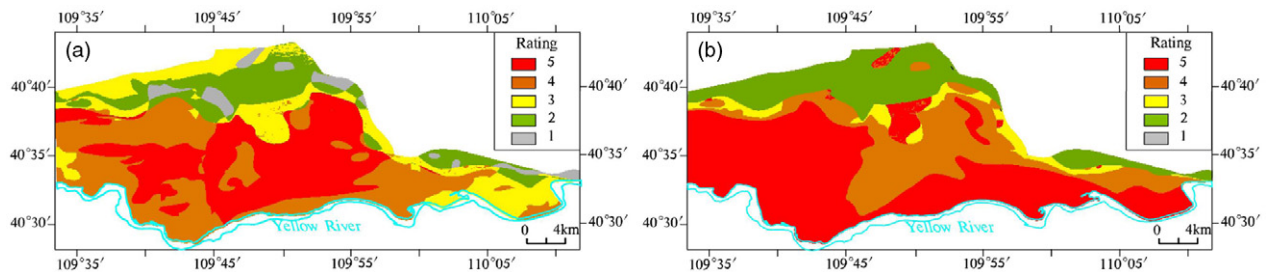


Fig. 5. Groundwater vulnerability evaluation results of the study area. (a) evaluation result through modified DRASTIC model and analytic hierarchy process (AHP) method. (b) evaluation result through modified DRASTIC model, AHP method and extension theory.

sistency ratio respectively; RI is the random consistency index). Saaty suggests the value of CR should be less than 0.1. $\lambda_{\max}$ is computed by the formula as follows:

$$\lambda_{\max} = \frac{1}{m} \sum_{i=1}^m \frac{(PW)_i}{W_i} \quad (12)$$

$$PW = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1m} \\ p_{21} & p_{22} & \cdots & p_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ p_{m1} & p_{m2} & \cdots & p_{mm} \end{bmatrix} \begin{bmatrix} W_1 \\ W_2 \\ \vdots \\ W_m \end{bmatrix}$$

Table 3 is the paired comparison matrix.

Consistency test:

$$\lambda_{\max} = 7.046, CI = 0.0077, RI = 1.32, \\ CR = 0.005838 < 0.1 (\text{acceptable})$$

Computed weights of D, R, A, S, T, I and C are 0.299, 0.056, 0.154, 0.154, 0.029, 0.154 and 0.154, respectively.

The groundwater vulnerability could be evaluated by inputting the calculated weights into the modified DRASTIC model. Figure 5 shows the groundwater vulnerability evaluation results.

Compared with the parameters' weights suggested in the DRASTIC model, the weights calculated by AHP method highlight the significance of geological medium, and reduce the weight of net recharge. From Figs 2, 3 and 5, it can be seen that the groundwater vulnerability evaluated by the modified DRASTIC model and AHP method is closer to the groundwater quality than the evaluation results by the unmodified DRASTIC model, but great difference still exists in some areas. This difference may be caused by the equal interval method used to divide the groundwater vulnerability grade;

therefore, the extension theory was used in this study to divide the grade.

Groundwater vulnerability evaluation using extension theory and DRASTIC model

Construction of the standard matter element model

The seven parameters in the modified DRASTIC model were chosen to assess the groundwater vulnerability. In this research, the standard matter element model of the groundwater vulnerability evaluation was constructed as

$$R = \begin{pmatrix} H_j & X_1 & x_1 \\ & X_2 & x_2 \\ & X_3 & x_3 \\ & X_4 & x_4 \\ & X_5 & x_5 \\ & X_6 & x_6 \\ & X_7 & x_7 \end{pmatrix} \quad (13)$$

where $X_1, X_2, X_3, X_4, X_5, X_6, X_7$ represent factors of depth to water table, net recharge, aquifer thickness, soil media, topography, impact of vadose zone and coefficient of transmissibility. $x_1, x_2, x_3, x_4, x_5, x_6, x_7$ are the value of $X_1, X_2, X_3, X_4, X_5, X_6, X_7$, and H_j ($j = 1, 2, \dots, n$) represents different vulnerability grades. The groundwater vulnerability contains five grades in this research, and the value of H_j is 1, 2, 3, 4, 5.

Based on the evaluation of each parameter and groundwater vulnerability grades in the study area, the standard matter element model is constructed as follows:

$$\begin{matrix} DI_5 \begin{pmatrix} 5 & D\langle 10 \rangle \\ & R\langle 3 \rangle \\ & A\langle 6 \rangle \\ & S\langle 10 \rangle \\ & T\langle 10 \rangle \\ & I\langle 8 \rangle \\ & C\langle 8 \rangle \end{pmatrix}, DI_4 \begin{pmatrix} 4 & D\langle 9 \rangle \\ & R\langle 3 \rangle \\ & A\langle 6 \rangle \\ & S\langle 9 \rangle \\ & T\langle 9 \rangle \\ & I\langle 8 \rangle \\ & C\langle 6 \rangle \end{pmatrix}, DI_3 \begin{pmatrix} 3 & D\langle 7 \rangle \\ & R\langle 3 \rangle \\ & A\langle 6 \rangle \\ & S\langle 6 \rangle \\ & T\langle 9 \rangle \\ & I\langle 6 \rangle \\ & C\langle 4 \rangle \end{pmatrix}, \\ DI_2 \begin{pmatrix} 2 & D\langle 3 \rangle \\ & R\langle 1 \rangle \\ & A\langle 4 \rangle \\ & S\langle 4 \rangle \\ & T\langle 5 \rangle \\ & I\langle 1 \rangle \\ & C\langle 2 \rangle \end{pmatrix}, DI_1 \begin{pmatrix} 1 & D\langle 3 \rangle \\ & R\langle 1 \rangle \\ & A\langle 4 \rangle \\ & S\langle 1 \rangle \\ & T\langle 5 \rangle \\ & I\langle 1 \rangle \\ & C\langle 2 \rangle \end{pmatrix} \end{matrix} \quad (14)$$

When classified into ranges according to the DRASTIC model, values of the seven parameters in the study area fit only several ranges, and some values do not appear.

The segment field matter elements model is

$$DI_P = \begin{pmatrix} D\langle 3, 10 \rangle \\ R\langle 1, 3 \rangle \\ A\langle 4, 6 \rangle \\ S\langle 1, 10 \rangle \\ T\langle 5, 10 \rangle \\ I\langle 1, 8 \rangle \\ C\langle 2, 8 \rangle \end{pmatrix} \quad (15)$$

Data acquisition and processing

Data of the depth to water table, net recharge, aquifer thickness, soil media, topography, impact of vadose zone and coefficient of transmissibility were acquired by GIS software from topographical map, geological map and hydrogeological map of the study area. There are seven layers corresponding to the seven parameters in the modified DRASTIC model.

Calculation of the groundwater vulnerability grades

In a unit of a certain state $R(X_1 = x_1, X_2 = x_2, X_3 = x_3, X_4 = x_4, X_5 = x_5, X_6 = x_6, X_7 = x_7)$, five events may occur in the unit. In the five events, the grades of groundwater vulnerability are 5, 4, 3, 2 and 1. Based on the extension theory, the program was designed through IDL method. The groundwater vulnerability grades classification map was got through GIS software (Fig. 5).

The groundwater vulnerability grades were divided by the dependent function value. Correlation degree (K_j) of the parameters in a certain incident (R) and the parameters in the standard matter element model should be computed at first, then the correlation degree of a certain incident and the different incident in the standard matter element model should be computed. Then, the groundwater vulnerability grades were determined by the correlation degree. Figure 5 shows the groundwater vulnerability evaluation results.

According to the groundwater vulnerability grades calculated by the modified DRASTIC model, AHP and extension theory, the groundwater vulnerability of the study area can be divided into four grades, namely the low vulnerability region (vulnerability rating of 2), medium vulnerability region (vulnerability rating of 3), high vulnerability region (vulnerability rating of 4) and very high vulnerability region (vulnerability rating of 5). The low vulnerability region mainly distributed in the north area, the medium vulnerability region mainly distributed in the area south of the low vulnerability region, the high vulnerability region mainly distributed in the area south of the

medium vulnerability region, and the highest vulnerability region mainly distributed in the southern area.

Compared with the groundwater quality in 2000, 80% of the high and very high vulnerability regions evaluated by DRASTIC have bad water quality, while 96% of the high and very high vulnerability regions by the modified DRASTIC model have bad water quality. From Figs 2, 3 and 5, it can be seen that the groundwater vulnerability evaluated by the modified DRASTIC model, AHP and extension theory is closer to the groundwater quality than the evaluation results by the modified DRASTIC model and AHP method. Therefore, the human interference problems in evaluating parameters' weights in DRASTIC model could be solved by using AHP method, and the human interference problems in dividing groundwater vulnerability grades could be solved by using the extension theory.

Conclusions

(1) DRASTIC is one of the most widely used models for groundwater vulnerability evaluation studies. The DRASTIC model often needs to be modified based on the local hydrogeological conditions. It is urgent to suggest effective methods to divide the groundwater vulnerability grades because the DRASTIC model lacks grades classification method.

(2) The groundwater quality evaluation results are different from the DRASTIC evaluation results. As a result, the DRASTIC model needs to be modified in this study. The parameters selection, weights evaluation and grades classification in the DRASTIC model were modified using AHP and extension theory, and the evaluation results are closer to the groundwater quality than the evaluation results by the unmodified DRASTIC model.

(3) Compared with the groundwater quality in the study area, 80% of the high and very high vulnerability regions evaluated by DRASTIC have bad water quality, while 96% of the high and very high vulnerability regions by the modified DRASTIC model have bad water quality. As opposed to the evaluation results by the unmodified DRASTIC model, the evaluation results through extension theory and AHP method is more suitable for groundwater vulnerability evaluation in the study area. The human interference problems in evaluating parameters' weights in DRASTIC model could be solved by the AHP method, and the human interference problems in dividing groundwater vulnerability grades could be solved by the extension theory.

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