Application of GIS and Modified DRASTIC Model Based on Entropy Weight and Fuzzy Theory to Ground Water Vulnerability Evaluation

Shaofei Li, Guanyou Li

Application of GIS and modified DRASTIC model based on entropy weight and fuzzy theory to ground water vulnerability evaluation

Shaofei LI[1(✉)], Guanyou LI[1]

[1]College of Hydraulic Engineering, Tianjin Agricultural University,Tianjin, 300384, China

lishaofei79@126.com

Abstract. Groundwater vulnerability assessment coupling with geographic information systems (GIS) should be considered as an important means for groundwater management, especially in agricultural areas. Nowadays, for groundwater vulnerability evaluating, DRASTIC model has been very popular and widely used in the world. However, DRASTIC model has some disadvantage. To overcome the problem, this paper proposed a modified DRASTIC model based on entropy theory and fuzzy theory. Moreover，three additional parameters, were added to the modified DRASTIC model, which were wastewater discharge of unit area, fertilizer usage of unit area, and density of river network. Using ArcGIS10.2 and the modified model, groundwater vulnerability grade(GVG) in Tianjin plain was analyzed and calculated. Groundwater vulnerability map of the plain area in Tianjin was constructed. According to the results, the study area was divided into five level zones: low vulnerability zone, lower vulnerability zone, medium vulnerability zone, higher vulnerability zone and high vulnerability zone, with coverage area of 17.1%, 26.7%, 25.2%, 22% and 9%, respectively. The results are consistent with the actual situation of studied area.

Keywords: Groundwater vulnerability, GIS, modified DRASTIC model, entropy weight, fuzzy theory

1 Introduction

In North China, groundwater plays an important role in water supply especially in agricultural areas, as a result of the shortage of surface water resources and the huge demand of irrigation water. However, today in those areas the using of groundwater as an available water supply source has been restricted by increasingly serious pollution mainly caused by human activities, such as intensive fertilizer application in agriculture, rapid urbanization, industrialization and population. Human activities on the earth's surface could be regarded as the main possible contamination source for groundwater, which may make water quality worse, even cause deterioration of groundwater environment. It is not easy for groundwater resource to be contaminated, however, if this occurred , it would be very difficult and expensive to restore. So, groundwater protection and management are very important. Groundwater vulnerability evaluation is the basis of groundwater management. Groundwater vulnerability maps based on GIS can reveal the possibility and the possible extent of groundwater contamination. GIS has become a commonly used tool in the process of land use planning, which considers a lot about groundwater protection from contamination. According to groundwater vulnerability mapping, human activities which may be harmful to groundwater should be appropriately located in low vulnerability zones. Moreover, the monitor well should be installed in high vulnerability z evaluation ones.

Aiming to forecast groundwater vulnerability to contamination, for decades of years, various methods have been proposed, which include over lay and index methods, process-based simulation methods, and statistic methods (Dixon 2004, Dixon 2005). Over lay methods and index methods focus on the synthesization of a number of different index maps at the studied area. Either method is easy to be combined with geographic information systems (GIS), especially at region scale. So， over lay and index methods are regarded as the most popular ones applied to analyze groundwater vulnerability. These techniques include GOD model, AVI model, and DRASTIC model (Foster, 1987; Van Stemproot et al. 1993; Aller etal. 1987). Among these methods, DRASTIC indexing is the most popular, and it has been widely used in the US (Plymale and Angle 2002;), and other regions worldwide (Naqa et al. 2006; Yin et al. 2012), since it is improved by USEPA in the late 1980s.

GIS worked well in studies in regard with groundwater contamination risk problem(Chenini, 2010; Carrera-Herna, 2006). Combining with GIS groundwater vulnerability evaluation models can help recognize high contamination risk areas and low contamination risk areas more effectively and economically. Halliday (1991) used GIS and the DRASTIC method to calculate groundwater vulnerability to contamination. Dixon (2004) combined a neuro-fuzzy technique and GIS to forecast groundwater vulnerability to pollution in watershed. These study revealed that combining GIS with regional groundwater computation models have some advantages. These advantages mainly exist in the following aspects: (i) Interfaces for inputting and outputting is improved (ii) spatial data obtained from different source can be integrated and displayed on the same layer; (iii) different data at various spatial scales can be compared. (Jha etal.,2007).

Generally, the DRASTIC model is composed of seven hydro-geological factors as seven parameters. Each parameter is assigned specific weight and rating. This method uses the weighed sum of these parameters as the vulnerability index. Although DRASTIC method is very popular, it has some advantages in practical application, listed as follows: (i) the effect of human activities to groundwater pollution is disregarded; (ii) the weight of each parameters is fixed and uniform ignoring the effects of regional characteristics. (iii) the objective fact that change of parameter value is continuous is ignored.

In this study, the objective is to establish a modified DRASTIC model based on entropy weight and fuzzy pattern recognition. Combining with GIS, the modified DRASTIC model was applied to calculate and analyze groundwater vulnerability to pollution in Tianjin plain area.

2 Material and methods

2. 1 Study Area

Tianjin plain area situates in the eastern part of North China Plain, which covers an area of 11919km^2. It is located in 116°42′05″~118°03′31″E and 38°33′57″~40°00′07″N. Tianjin plain is adjacent to the Bohai Bay in the east and leans against Yanshan Mountain in the north, shown in Fig.1. The terrain is higher comparatively in North West, and it becomes lower gradually to South East. It is dominated by semi-arid climate. The mean annual temperature is 12℃. The average annual precipitation is 580 mm.

Fig.1 Location of the study area

The study area is commonly filled with unconsolidated Quaternary sediments, with smaller and smaller stratigraphic particles from North West to South East. Baodi fracture divides the broad plain area from the north-western foothills to the eastern coast into two parts. At the north part, the geological structure is mainly alluvial deposits, the bedrock depth is no more than 300m, filled with a large volume of the fourth series of pore water. While at the south part, the geological structure has the thick Cenozoic aquifer, with pore water. Recharges of shallow groundwater is mainly from precipitation, irrigation return influent and river water leakage, and evaporation and exploitation are the dominant form of discharge.

2.2 DRASTIC model

The acronym DRASTIC represents the most seven important hydrologic and geological properties in a hydrologic setting, which effect the possibility of groundwater pollution, listed as depth of water table(D), net recharge(R), aquifer media (A), soil type (S), topography (T), impact of vadose zone media (I), and aquifer hydraulic conductivity(C). Specific weight and rating is appointed to each indexes. (Aller et al. 1987).

DRASTIC index could be deduced using equation (1).

DRASTIC Index (DI)

$$= D_W \times D_R + R_W \times R_R + A_W \times A_R + S_W \times S_R + T_W \times T_R + I_W \times I_R + C_W \times C_R \qquad (1)$$

Where, *D,R,A,S,T,I,* and *C* are the seven indexes and the subscripts *W* and *R* are the corresponding weights and ratings, respectively.

The higher score of DRASTIC index represent the greater groundwater vulnerability.

2.3 Modified DRASTIC model based on entropy weight and fuzzy theory

Mainly for the disadvantage of DRASTIC model, we make the following modifications on it.

2.3.1 Adding parameters reflecting effect of human activities

Human activities, such as agricultural activities and industrial production, and the pollution of surface water have had great impacts on the groundwater environment. However, DRASTIC model doesn't include parameters reflecting this. To overcome this problem, we add additional parameters, wastewater discharge of unit area(W), fertilizer usage of unit area(F), density of river network(N) to improve DRASTIC model. So the modified model can be written as DRASTICWFN model.

2.3.2 Determining parameter weight combining entropy method and AHP

Entropy theory use effective information provided by measured index data to delete human interference in weight calculating. It is an objective weight determining method, which make the evaluation result more reasonable and precious.

Analytic hierarchy process (AHP) is a very popular subjective method to calculate weight (Kahraman et al. 2003). In order to get more confident decision, we combine entropy theory and AHP to determine each parameter weights.The detailed steps are as follows:

A. Calculating entropy weight

a) Developing the Judgment Matrix of m *Parameters and* n *Things*

$$X = (X_{ij})_{m\times n}, \quad (i = 1,2,\cdots,m; j = 1,2,\cdots,n)$$

b) Normalizing the Judgment Matrix

For the parameter which is the larger, the bigger the result,

$$b_{ij} = \frac{X_{ij} - X_{i\min}}{X_{i\max} - X_{i\min}} \tag{2}$$

For the parameter which is the larger, the smaller the result ,

$$b_{ij} = \frac{X_{i\max} - X_{ij}}{X_{i\max} - X_{i\min}} \tag{3}$$

Where, X_{imax} and X_{imin} is the greatest value or the smallest one among the different things under the same parameter, respectively; X_{ij} is the original value of the i^{th} parameter and the j^{th} thing.

c)Determining the Entropy of each parameter

For m things and n parameters, the entropy of evaluation indexes could be determined:

$$H_i = -\frac{1}{\ln n}[\sum_{j=1}^{n} f_{ij} \ln f_{ij}] \tag{4}$$

$$f_{ij} = b_{ij} \Big/ \sum_{i=1}^{n} b_{ij} \; (i = 1, 2, \cdots, m; j = 1, 2, \cdots, n) \tag{5}$$

In order to make $\ln f_{ij}$ meaningful, when, $f_{ij} = 0$, $f_{ij} \bullet \ln f_{ij} = 0$. But when $f_{ij} = 1$, f_{ij} is defined as:

$$f_{ij} = \frac{1 + b_{ij}}{\sum_{j=1}^{n} (1 + b_{ij})} \tag{6}$$

d) Determining the Entropy weight of each parameter

The weight of the the i^{th} parameter could be:

$$\omega_i = \frac{1-H_i}{n-\sum_{i=1}^{n} H_i}, \quad (0 \le \omega_i \le 1, \sum_{i=1}^{m} \omega_i = 1) \tag{7}$$

B Calculating comprehensive weight

Using AHP (Kahraman et al. 2003), AHP weight of each parameter were derived. Then calculate the average value of Entropy weight and AHP weight for each parameter. So we can get the final comprehensive weight of each parameter, written as weight vector *W*.

2.3.3 Fuzzy comprehensive evaluating

A Calculating fuzzy membership matrix R

To calculate the fuzzy membership, the standards for groundwater vulnerability evaluating must be developed. In this study groundwater vulnerability level is divided into ten grades. Grade Ⅰ~Ⅹ represent ten groundwater vulnerability level from low to high correspondingly. Combining with past relative research achievements, and the actual situation of Tianjin, the evaluating standards for each parameter is shown in Tab.1.

Tab.1 the evaluating standards for groundwater vulnerability

Vulnerability level	Ⅰ	Ⅱ	Ⅲ	Ⅳ	Ⅴ	Ⅵ	Ⅶ	Ⅷ	Ⅸ	Ⅹ
D(m)	30.6	26.8	22.8	15.3	12.2	9.2	6.9	4.7	1.6	0
R(mm)	0	51.1	71.5	91.7	117.3	147.7	179	217	236	254
A	1	2	3	4	5	6	7	8	9	10
S	1	2	3	4	5	6	7	8	9	10
T(‰)	18	17	15	13	11	9	7	4	2	0
I	1	2	3	4	5	6	7	8	9	10
C(m/d)	0	4.1	12.2	20.3	28.5	34.6	40.7	61.1	71.5	81.5
W(10^4t/km^2)	0	1	3	4	5	6	8	10	15	20
F(t/km^2)	0	5	10	20	30	35	40	45	50	60
N(km/km^2)	0	0.1	0.25	0.4	0.5	0.6	0.75	0.9	1.25	2.0

Several fuzzy distribution curves have been developed. In this study, "trapezoid distribution method" is used to calculate membership functions of each parameter for each grade.

The membership functions of grade Ⅰ,

$$r_{ij} = \begin{cases} 1 \quad (x_i \le a_{i,1}) \\ (a_{i,2} - x_i)/(a_{i,2} - a_{i,1}) \quad (a_{i,1} < x_i \le a_{i,2}) \\ 0 \quad (x_i > a_{i,2}) \end{cases} \tag{8}$$

The membership functions of grade Ⅱ~Ⅸ:

$$r_{ij}=\begin{cases}0 \quad (x_i \le a_{i,j-1}, or, x_i > a_{i,j}) \\ (x_i - a_{i,j-1})/(a_{i,j} - a_{i,j-1}) \quad (a_{i,j-1} \le x_i < a_{i,j}) \\ (x_i - a_{i,j})/(a_{i,j+1} - a_{i,j}) \quad (a_{i,j} \le x_i < a_{i,j+1})\end{cases} \tag{9}$$

The membership functions of grade Ⅹ,

$$r_{ij}=\begin{cases}1 \quad (x_i \ge a_{i,10}) \\ (x_i - a_{i,9})/(a_{i,10} - a_{i,9}) \quad (a_{i,9} \le x_i < a_{i,10}) \\ 0 \quad (x_i < a_{i,9})\end{cases} \tag{10}$$

where, $a_{i,j-1}$, a_{ij} and $a_{i,j+1}$ are the standard values of the $(j\text{-}1)^{th}$, j^{th} *and* $(j+1)^{th}$ grade for the i^{th} parameter, respectively. x_i stands for the measured value of the i^{th} parameter. r_{ij} shows the possibility that the i^{th} parameter can be considered as the groundwater vulnerability standards of the j^{th} grade, that is, the membership degree *i* parameter to *j* grade.

So, for a given calculating unit, the fuzzy relation matrix *R* consist of these membership degree is derived.

$$R=(r_{ij})_{m\times n}, \quad (i=1,2,\cdots,m; j=1,2,\cdots,n) \tag{11}$$

where, *m* is the count of parameters, *m=10*; *n* is the count of groundwater vulnerability grades, *n=10*.

B. Calculating groundwater vulnerability grade

A comprehensive assessment grade vector is obtained by multiplying the weight vector *W* by the fuzzy relationship matrix *R*. In this study, we use the weighed average model operator $M(\wedge,\oplus)$ to decide final grade of groundwater vulnerability. So the final *comprehensive* groundwater vulnerability grade (GVG) for a given calculating unit, is derived by Eq.(12).

$$GVG = W \bullet R \bullet C^T \tag{12}$$

where, *W* is weight vector, *R* is fuzzy relationship matrix, *C* is groundwater vulnerability grade vector, $C=(1,2,\cdots,10)^T$.

3 Results and discussion

3.1 Maps of each DRASTICWFN parameters

In ArcGIS10.2, the studied area were divided into 11652 square grids of 1km ×1km using the tool of fishnet. Taking each grid as one calculating unit, we obtained the original data for the ten DRASTICWFN parameters. According to the evaluating standards in Tab.1, thematic layer maps of each parameter except topography (T) were constructed using mapping function in ArcGIS10.2, shown as Fig.2.

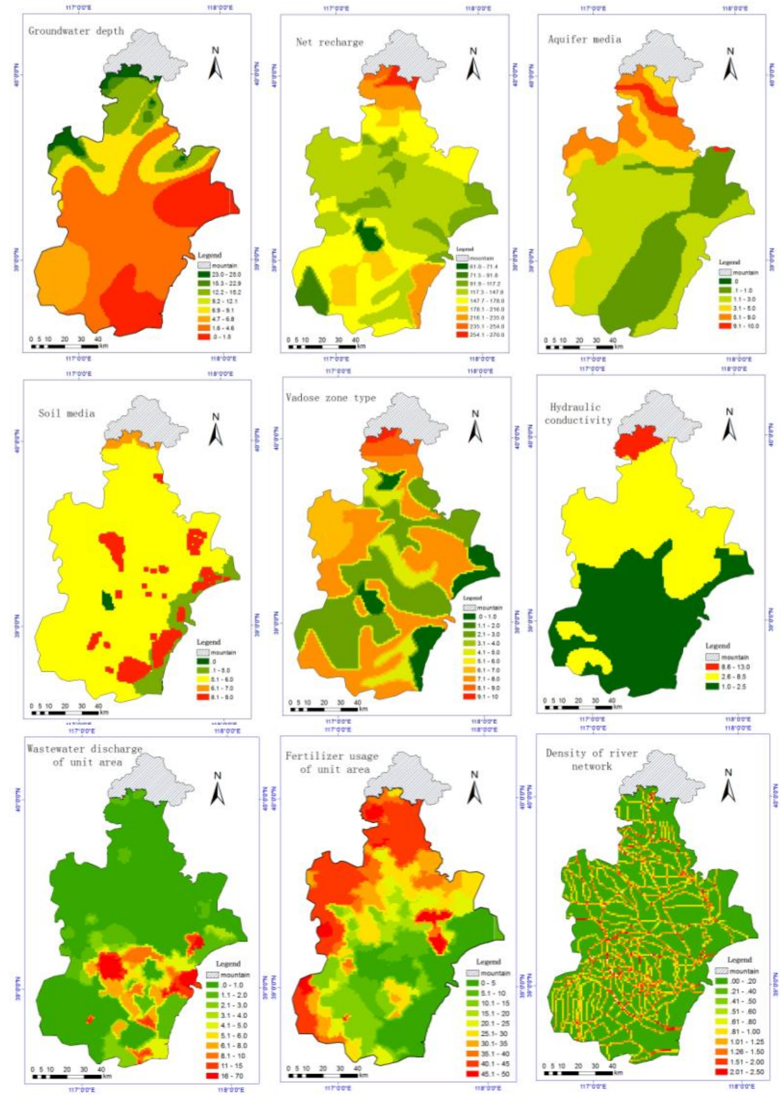

Fig. 2. Parameter maps in DRASTICWFN model

The data includes water well, precipitation, irrigation, aquifer systems, soil, lithology, aquifer transmissivity, river system distribution, land use type and discharge data. These data was obtained from various sources such as Tianjin

Municipal Water Affairs Bureau, Tianjin Municipal Geological Survey, Tianjin Municipal Water Resources Bulletin, and Statistics Yearbook of Tianjin City.

Depth to water is the distance through which contaminants transport from the earth's surface to the groundwater body. The smaller the depth is, the shorter time contaminants take to enter groundwater body, the less chance for contaminants to react with the surrounding media in redox condition, so the greater possibility of groundwater contamination. In study area, depth to groundwater varies from 0.3 m to 25m (Fig. 2a). Net recharge is the average annual water added into groundwater. In this area, the recharge mainly results from precipitation infiltration and irrigation return influent. The net recharge varies from 62 mm a^{-1} to 271 mm a^{-1} (Fig. 2b). In north, sand and fine sand are the dominant aquifer media, while silt, muddy-silt and fine silt dominate the aquifer media in south. According to the quantization in DRASTIC model (Aller et al. 1987), parameter A ranges from 1 to 10 (Fig. 2c). Sediment is respectively fluvial, lake-alluvial deposits and marine deposit in the north ,central and eastern coastal areas. Correspondingly, soil media are respectively cinnamon soil, fluvio-aquatic soil and saline-alkali soil in the north ,central and eastern coastal areas. According to quantization in DRASTIC model, parameter S ranges from 1 to 9 (Fig. 2d). Tianjin plain, is a low and flat plain. The slop ranges from 0.1% to 1%. In most area, vadose media is commonly sandy loam and silt clay, and parameter I varies from 3 to 6 (Fig. 2e). Hydraulic conductivity describes the velocity of groundwater flowing in the aquifer media, which varies from 0.1 m d^{-1} to 20 m d^{-1} in study area by pumping test and calculating (Fig. 2f). Wastewater discharge is a main pollution source of human industrial production and living activities to groundwater. In the studied area, wastewater discharge of unit area ranges from 0 to 70 t/km^2, which is mainly centered in Downtown and suburban areas around downtown (Fig. 2g). Fertilizer usage is the primary non-point pollution source in agricultural areas, and it is a threat to groundwater environment. Fertilizer usage of unit area ranges from 0 to 50 t/km^2, which is mainly in the rural areas in the north and west, a few parts of Ninghe District in the east (Fig. 2h). Surface water is also an important pollution source to groundwater due to flow recharging. In studied area, 96.2 percentage of river quality is polluted more or less. (Tianjin Municipal Water Resources Bulletin, 2013). Density of river network means length of river in unit area. Parameter N ranges from 0 to 4.2 km/km^2. (Fig. 2i).

3.2 **Groundwater vulnerability map**

Taking each grid, as a calculating unit, for each parameters, based on the original data, using the method of determining weight mentioned above, the entropy weight, AHP weight and comprehensive weight were computed. For all the 11652 calculating units in the whole studied area, the topography only have two values, 0.1% and 1%, that is all the studied area almost have the same values for parameter T. The results show that entropy method is not applicable for calculating entropy weight of parameter T. So we remove it. Weights of the parameters in DRASTICWFN model except parameter T are shown in Tab.2.

Tab.2 Entropy weight, AHP weight and comprehensive weight for each parameters

parameter	entropy weight	AHP weight	comprehensive weight
D	0.013	0.2053	0.10915
R	0.0057	0.2053	0.1055
A	0.0448	0.0678	0.0563
S	0.0027	0.0173	0.01
I	0.0246	0.2053	0.11495
C	0.033	0.0678	0.0504
W	0.1889	0.0771	0.133
F	0.4556	0.0771	0.26635
N	0.2318	0.0771	0.15445

Based on the data, evaluating standards i, and weights, using the calculating method mentioned above, fuzzy membership matrix was obtained for each calculating unit. Then groundwater vulnerability grade (GVG) for each calculating unit was derived. In study area, GVG ranges from 1.6 to 8.9. It is deduced from Tab.1. that, GVG under 2 usually stands for low vulnerability level, GVG varying from 2 to 4 usually stands for lower vulnerability level, GVG varying from 4 to 6 usually stands for medium vulnerability level, GVG varying from 6 to 8 usually stands for higher vulnerability level, and GVG over 8 often stands for high vulnerability level. Using mapping function of ArcGIS10.2, groundwater vulnerability map was constructed, shown as Fig.3.

3.3 Discussion

In Fig.3, distribution of high groundwater vulnerability zone covers 9% of the total area, mainly distributing along with large river and a few areas in Xiqing, Hangu and Tanggu District, owing to the developed industrial production and a large amount of wastewater discharge. Higher groundwater vulnerability zone accounts for 26.7% of the total area, covering almost the whole area of Downtown and Jixian District, a few areas of Baodi and Wuqing Districts. Jixian District and a few areas of Baodi and Wuqing District, are the mainly agricultural areas in Tianjin, with a large amount of fertilizer usage. At the same time, at these areas groundwater recharge is large. Medium groundwater vulnerability zone, covering 25.2% of total area, is mainly distributed in Baodi, Wuqing and Jinghai District and scattered in the other districts except Jixian District. Low groundwater vulnerability zone, accounting for 17.1% of the study area. Lower groundwater vulnerability zone, covers 22% of the total area, mainly locates in the center and east plain areas, due to less agricultural land and weak permeability of aeration zone.

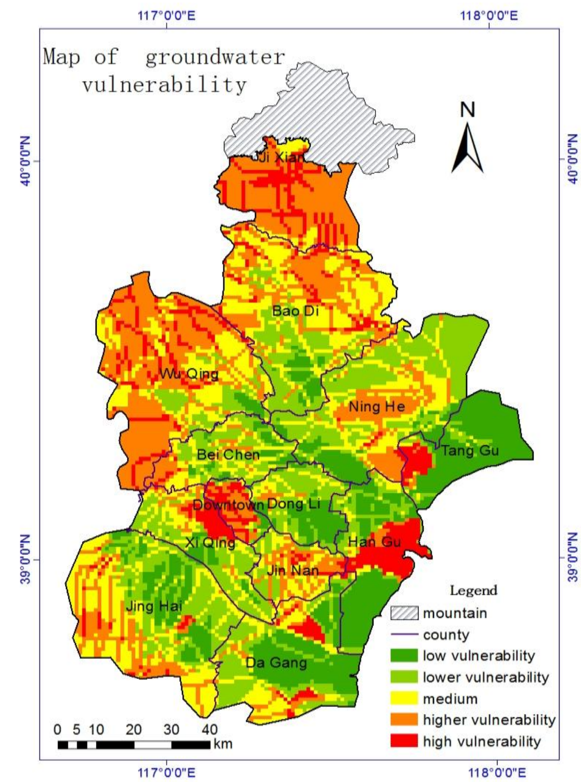

Fig. 3 Map of Groundwater vulnerability zones in Tianjin Plain

4. Conclussion

Groundwater vulnerability assessment should be accepted as a powerful tool for groundwater management, especially in agricultural areas. Nowadays, although DRASTIC model is very popular and widely used in the world in groundwater vulnerability evaluating field, it has some disadvantage. Aiming to overcome the problem, this paper proposed a modified DRASTICWFN model, which added three additional parameters, wastewater discharge of unit area, fertilizer usage of unit area, density of river network. A new computing method based on entropy theory and fuzzy mathematics also was proposed to get more confident computing results. Using ArcGIS10.2 and the modified model, groundwater vulnerability grade(GVG) in Tianjin plain was analyzed and calculated. Using the mapping function of ArcGIS10.2, groundwater vulnerability map in Tianjin plain was constructed. According to the results, the study area was classified into five levels of groundwater vulnerability zones: low vulnerability zone, lower vulnerability zone, medium vulnerability zone, higher vulnerability zone and high vulnerability zone, with coverage area of 17.1%, 26.7%, 25.2%, 22% and 9%, respectively. The result is in accordance with the practical groundwater situation in studied area.

Acknowledgment

This research was funded by the Key project of Tianjin Municipal Natural Science Foundation (Grant No.15JCZDJC41400), National Water Pollution Control and Treatment Key Specialized Project (Grant No.2017ZX07106003)

References

1. Dixon B. Prediction of groundwater vulnerability using an integrated GIS-based neuro-fuzzy techniques. J Hydrology 2004, 4(309):17–38.
2. Dixon B (2005) Groundwater vulnerability mapping: a GIS and fuzzy rule based integrated tool. Appl Geogr ,2005, 25(4): 327–347.
3. Foster SS. Fundamental concepts in aquifer vulnerability, pollution risk and protection strategy. In: Duijvenbooden W Van, Waegeningh HG Van (eds) TNO Committee on Hydrological Research, The Hague Vulnerability of soil and groundwater to pollutants. Proceedings and Information.1987, 38: 69–86.
4. Daly D, Drew D. Irish methodologies for karst aquifer protection. In: Beek B (ed) Hydrogeology and engineering geology of sinkholes and karst. [J] Balkema, Rotterdam.1999, 267–327.
5. Van Stemproot D, Evert L, Wassenaar L. Aquifer vulnerability index: a GIS compatible method for groundwater vulnerability mapping. [J] Can Water Resour J,1993, 18:25–37.

6. Aller L, Bennet T, Lehr JH, Petty RJ, et al. DRASTIC: a standardized system for evaluating groundwater pollution potential using hydrogeological settings. US Environmental Protection Agency, Ada.1987, EPA/600/2–87/035.
7. Fritch TG, McKnight CL, Yelderman JC, et al. An aquifer vulnerability assessment of the Paluxy aquifer, Central Texas, USA, using GIS and a modified DRASTIC approach. [J]Environ Manage. 2000, 25:337–345.
8. Plymale CL, Angle MP .Groundwater pollution potential of Fulton County, Ohio. Ohio Department of natural resources division of water, water resources section. Groundwater Pollution Potential, Report No 45, 2002.
9. Shukla S, Mostaghimi S, Shanholt VO, et al. A county-level assessment of ground water contamination by pesticides. [J]Ground Water Monit R .2000, 20(1):104–119.
10. Naqa A, Hammouri N, Kuisi M. GIS-based evaluation of groundwater vulnerability in the Russeifa area, Jordan. [J]Revista Mexicana de Ciencias Geologicas.2006,23(3):277–287.
11. Yin L, Zhang E, Wang X, Wenninger J, et al. A GIS-based DRASTIC model for assessing groundwater vulnerability in the Ordos Plateau, China. [J] Environ Earth Sci. 2012, 69(1):171–185.
12. Chenini, I., Mammou, A.B. Groundwater recharge study in arid region: an approach using GIS techniques and numerical modeling. [J]Computers & Geosciences. 2010, 36 (6), 801–817.
13. Carrera-Herna´ ndez, J.J.,Gaskin,S.J..The groundwater modeling tool for GRASS(GMTG): open source ground water flow modeling. [J] Computers& Geosciences. 2006, 32(3),339–351.
14. Jha, M.K., Chowdhury, A., Chowdary, V.M.,et al. Groundwater manage- ment and development by integrated remote sensing and geographic information systems: prospects and constraints. [J]Water Resource Management.2007, 21:427–467.
15. Halliday, S.L., Wolfe, M.L. Assessing groundwater pollution potential from nitrogen fertilizer using a GIS. [J]Water Resources Bulletin, AWRA , 1991, 27 (2), 237–245.
16. Ho W. Integrated analytic hierarchy process and its applications—a literature review. [J]Eur J Oper Res, 2008, 186: 211–228.
17. Kahraman C, Cebeci U, Ulukan Z. Multi-criteria supplier selection using fuzzy AHP. [J]Logis Inf Manag, 2003, 16(6): 382–394.
18. Erhan Sener ¸Sehnaz Sener. Evaluation of groundwater vulnerability to pollution using fuzzy analytic hierarchy process method, [J].Environ Earth Sci. 2015,73:

8405–8424.