Assessment of shallow groundwater vulnerability in Dahei River Plain based on AHP and DRASTIC

ZHU Yu-chen, ZHANG Yi-long, HAO Qi-chen*

Institute of Hydrogeology and Environmental Geology Chinese Academy of Geosciences, Shijiazhuang 050061, China.

Abstract: Based on the special hydrogeological conditions of the Dahei River Plain in the Inner Mongolia area, assessment of shallow groundwater vulnerability is conducted based on DRASTIC model. Each evaluation indicator weight is determined by using analytic hierarchy process (AHP). The most important indicators are lithology in soil media and vadose zone. Assessment model of shallow groundwater vulnerability of the Dahei River plain is constructed. Distribution map of vulnerability index in this area is made with the spatial analysis function of ARCGIS. The results show that the particularly sensitive area is the piedmont of the Daqing Mountain, where the upstream place of the groundwater and the south-central place of the plain has the lowest vulnerability. The assessment results are more in accordance with the actual vulnerability conditions of this area by using analytic hierarchy process, and is helpful for groundwater protection.

Keywords: Groundwater vulnerability; DRASTIC model; AHP; Dahei River Plain; ARCGIS

Introduction

Groundwater is a precious freshwater resource. It plays an important role in domestic water use, geological environment, social development and ecological balance (CHENG Li-rong *et al.* 2009). As the economy grows, excessive human activities pose serious threat to groundwater. Prevention of groundwater pollution has become an important strategic task. The groundwater vulnerability shows how vulnerable of the groundwater to surface pollutants. Assessment of groundwater vulnerability, as the groundwork for scientific development and protection of groundwater, has become a hot research issue in international hydrogeology (SUN Cai-zhi *et al.* 2015). This paper focuses on the plain area in Hohhot, inner Mongolia. Results show that shallow groundwater is the main source of water for industry and agriculture in this area. The study on the vulnerability of shallow groundwater plays an important role in groundwater resources protection in this area.

Groundwater vulnerability is a comprehensive reflection of the sensitivity, variability and elasticity of the structure and functional of groundwater system (SUN Cai-zhi and PAN Jun, 2000; HUAN Huan *et al.* 2011; ZHONG Zuo-shen, 2005). Vulnerability is divided into inherent vulnerability and special vulnerability. DRASTIC model is simple and can be widely used, especially for the evaluation of vulnerability of large-scale shallow groundwater (MENG Su-hua *et al.* 2010). This paper, based on the hydrogeological conditions of Dahei River Plain, used DRASTIC model, analytic hierarchy process (AHP), ARCGIS platform as data preprocessing platform and GIS spatial analysis technology to evaluate the natural vulnerability of shallow groundwater in this area (Thirumalaivasan D *et al.* 2003; Chitsazan M and Akhtari Y, 2009).

1 Overview of the study area

The study area is located in Hohhot, with its north and its east adjacent to mountains: The Daqing Mountain to the north, the Manhan

*Corresponding author. E-mail: haoqichen1986@163.com

Mountain in the east and the Yellow River to the south. The geographical coordinates are 110°45′-12′ N, 40°00′-41°00′ E. It covers an area of about 5 040 km^2. The total terrain is tilted from the northeast to southwest, with an altitude from 950 m to 1 300 m. The study area is shown in Fig. 1.

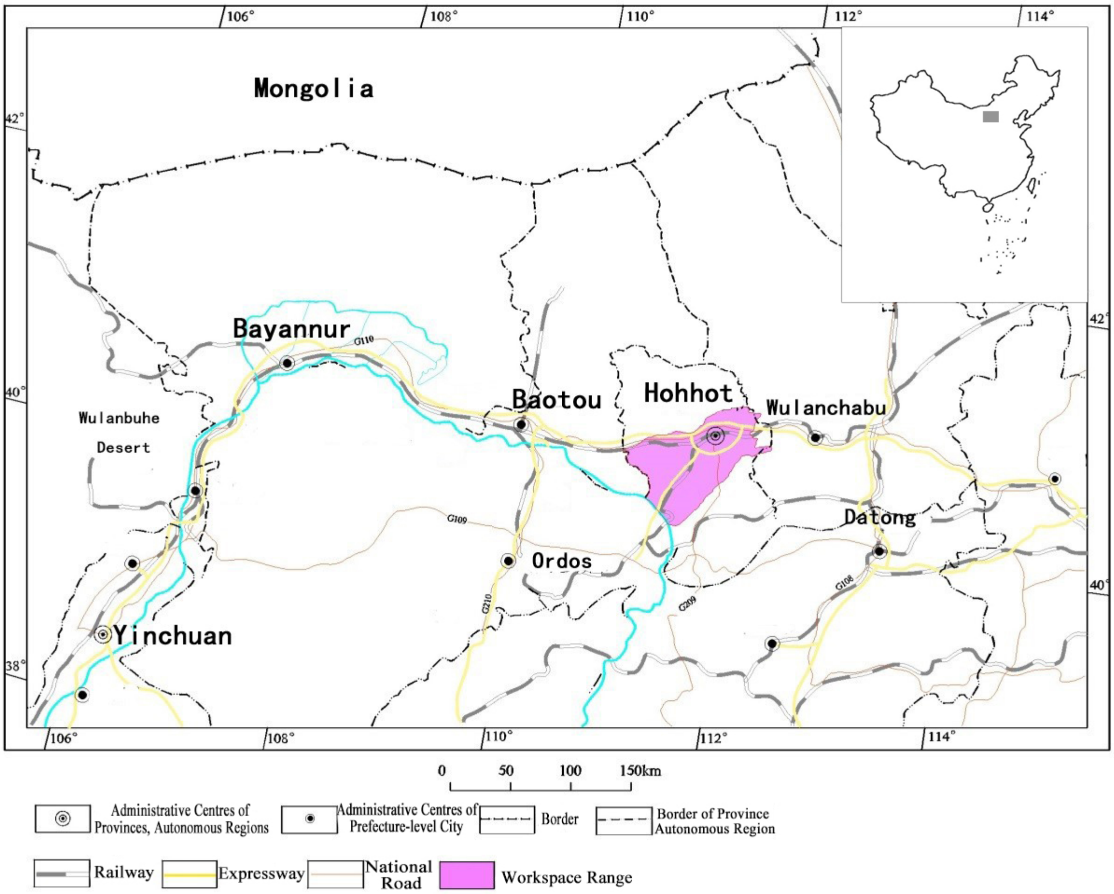

Fig. 1 Location of the Dahei River Plain

This area enjoys arid and semi-arid continental monsoon climate. The climate is dry with obvious seasonal change. The annual precipitation in the large area is 387 mm. Average annual evaporation capacity (φ 20) is about 2 643 mm. The average temperature is about 7 ℃. The water system in the study area is an internal one, belonging to the tributary of the yellow river. The main rivers are the Yellow River, the Dahei River, the Xiaohei River and the Salawusu River.

The Dahei River Plain is composed of alluvial flood plain in front of the Daqing Mountain in the north, alluvial and lacustrine plain of the Dahei River in the middle, alluvial and lacustrine plain of the Yellow River in the southwest and lacustrine terrace in the south. Fig. 2 shows the typical north-south strata profile in the Plain. The borehole data and existing research results show that the quaternary pore water aquifer system is controlled by the new tectonic movement and climate evolution, especially the lacustrine deposit formed at the end of middle Pleistocene and stable silt layer formed in the middle of the basin. The silt layer divides the quaternary pore water aquifer into shallow aquifer and confined aquifer. The piedmont zone around the Plain is dominated by the alluvial deposits of coarse grain size, forming a connected single-structure phreatic aquifer. Therefore, the pore water aquifer system can be divided into three aquifers: a single-structure phreatic aquifer, shallow aquifer and confined aquifer. The basalt aquifer system mainly includes four rock sections of water, but the hydraulic linkage between these rock sections is highly close with unified recharge, runoff and draining conditions. Thus, it is regarded as a single aquifer. Fig. 3 shows the horizontal distribution of aquifers.

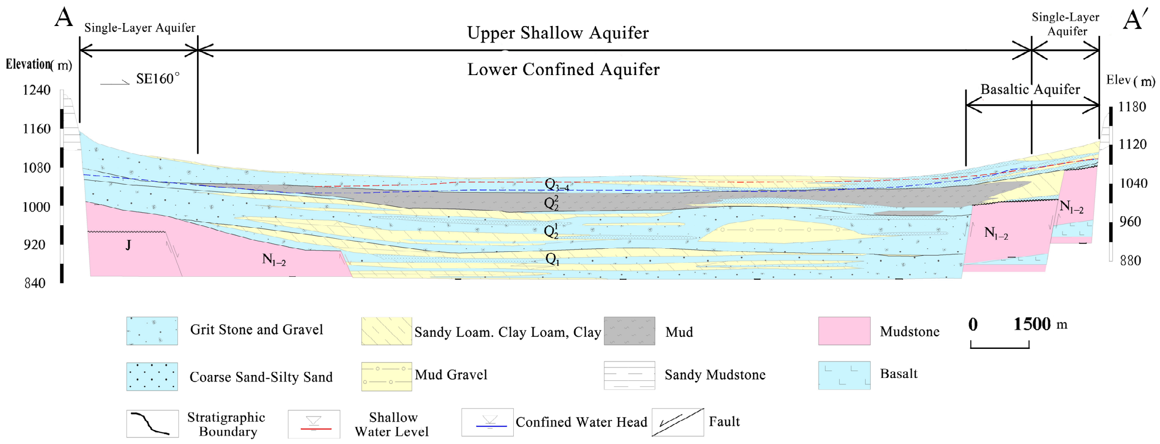

Fig. 2 Hydrogeological section in eastern Dahei River Plain

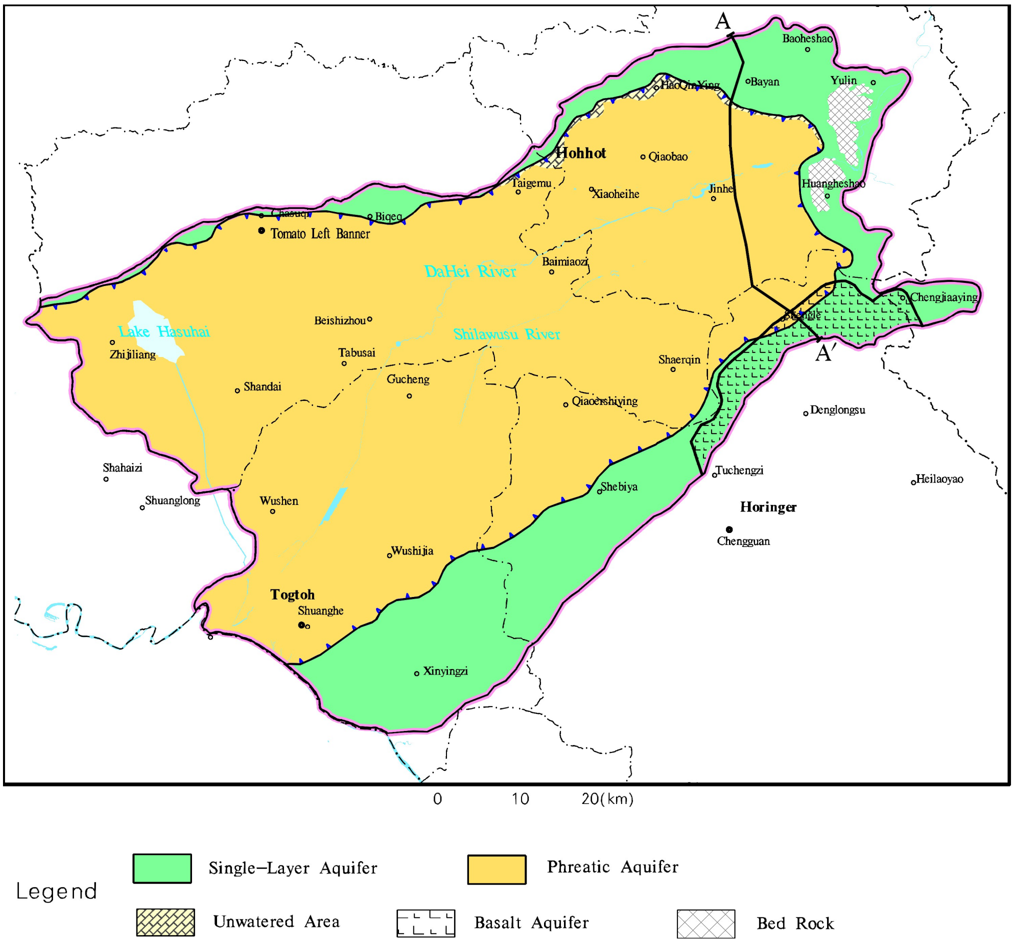

Fig. 3 Horizontal distribution of aquifer in Dahei River Plain

From the piedmont alluvial plain in the north to the alluvial lacustrine plain in the south, hydrogeological conditions have obvious east-west differences. In the north, water is abundant with the unit amount of water more than 500 m^3/d. The water inflow is reduced to less than 50 m^3/d in the south. The single-structure shallow groundwater mainly comes from the lateral runoff from the fissure water, the ravine of the bedrock and the recharge of the spring water. The water flows from north to south, and runs laterally to the alluvial plain in the south and near the Yellow River. The double-layer-structure shallow groundwater comes from the single-structure runoff from the northern piedmont in front of the mountains. Other supply sources include infiltration of atmospheric precipitation, canal infiltration, irrigation infiltration, confined water recharge and runoff replenishment of the alluvial plain in the south of the Yellow River. In the south of lacustrine plain, the shallow groundwater of water is also supplied by the lateral seepage from the Yellow River.

In the development of groundwater resources, the main source of groundwater in the plain is lateral recharge in front of the mountain. However, as the economy grows, there are more water conservancy projects such as reservoir in piedmont area and stream structure water projects. This leads to the decline of lateral recharge. With the development of urbanization, the utilization rate of groundwater resources in Hohhot is more than 100%, which is overexploitation. Decades of over-exploitation of groundwater result in the decline of shallow groundwater. In the urban area with centralized water supply, groundwater depression cone appears both for shallow and confined groundwater. Such cone has been expanding year by year. There are even shallow aquifers in the north of Hohhot. Although the Yellow River Diversion Project in recent years helps slow the growth of groundwater exploitation, overexploitation still exists.

2 Evaluation of groundwater vulnerability

2.1 Selection and optimization of indicators for evaluation

DRASTIC evaluation method is one of the most widely used evaluation methods on vulnerability to pollution. It gives a fixed weight to each parameter based on their impact on groundwater vulnerability in order to from a weight system, it also divides parameters into several brackets based on their ranges or their intrinsic nature and each bracket is given a certain score to form a scoring system. The weighted sum of each parameter score is Di, the groundwater vulnerability indicator. Based on the factors affecting groundwater vulnerability and local hydrogeological conditions, this part focuses on the causes, characteristics and effects of various indicators. There are 7 indicators selected for evaluation: Groundwater depth (D), net recharge (R), aquifer media (A), soil media (S), topography (T) and vadose zone (I) and hydraulic conductivity (C).

$$Di = \sum_{i=1}^{7} \omega_i T_i \quad (1)$$

In the formula: Ti refers to the value of the ith evaluation factor; ωi refers to the weight of the ith evaluation factor.

(1) Aquifer depth (D): Aquifer depth refers to the depth of shallow groundwater (Aller L*et al*. 1987; MA Tian-hai *et al*. 2014). In the study area, the piedmont is a single-structure region, aquifer depth in this area is the distance from the earth's surface to the free surface of single-structure shallow water. In the middle part of the plain, the aquifer depth is the depth of shallow groundwater above the silt layer. Due to years of over-exploitation of shallow groundwater, the shallow aquifer unwatering occurs in the north of Hohhot (Fig. 3). Thus, the aquifer depth in the above area refers to the distance from the plain roof to earth's surface. To ensure the results are representative and effective, the study is based on groundwater depth data in 2015 (normal year), covering 400 evenly distributed wells in two seasons (rainfall season and dry season).

(2) Net recharge (R): Net recharge in the DRASTIC method refers to the total amount of water infiltrated into the aquifer through the earth's surface per unit. This area works as a grain base with a high level of annual irrigation. Great proportion of pollutants comes from pumping irrigation and Yellow River irrigation. Thus, net recharge in this area includes not only rainfall infiltration, but also irrigation recharge which includes recharge from rainfall infiltration, surface water irrigation and groundwater irrigation. Net recharges are calculated based on the local rainfall infiltration coefficient and irrigation infiltration coefficient, with the millimeter as the unit. The surface water irrigation in this area includes the runoff of piedmont valley, reservoir drainage, interception ditch project and the irrigation of the north bank of the Yellow River. The seasonal runoff of piedmont valley is almost entirely used for irrigation. Thus, such runoff is regarded as the surface water irrigation.

(3) Aquifer medium (A): Based on stratigraphic structure in the study area, single-structure phreatic rock is selected as the aquifer medium in the single-structure piedmont area of the plain, and shallow ground aquifer rick above the silt layer roof selected as the aquifer medium in double-structure

area of the plain. In general, the greater the medium particles in the aquifer, the better permeability, the lower the attenuation capacity of pollutants, and the greater the vulnerability would be.

(4) Soil media (S): For soil media, surface lithology in the upper 1.5 m of the vadose zone in the study area is selected. The size of the lithologic particles directly affects the amount of recharge rom infiltration and the pollutants' ability to enter the vadose zone. The smaller the particle, the less vulnerable it will be.

(5) Topography (T): Topography determines whether the pollutant is rushed away or left in a certain surface area and eventually into the ground. For example, if topography is less than 2‰, there will be less surface runoff. Thus, pollutants are more likely to infiltrate and the groundwater more likely to be polluted; On the contrary, of the topography is over 18‰, there will be a lot of surface runoff. Then infiltration will be small, and the groundwater is less likely to be polluted.

(6) Vadose zone (I): The lithology in vadose zone is mainly dependent on the size of its particles. The smaller the particle, the slower the migration and the greater the adsorption capacity. The pollutants will be fully reacted. Thus, its antifouling performance will be good and vice versa. The project team carried out a lot of zone drilling work in the area. The results are used for the drawing of lithologic distribution map.

(7) Hydraulic conductivity (C): The hydraulic conductivity distribution map is based on data collected through a large number of hydrological geological experiments in the area. The hydraulic conductivity controls the velocity if groundwater in a certain hydraulic gradient. It also controls the speed of pollutants leaving the source site. Therefore, the greater the hydraulic conductivity, the worse the antifouling performance.

Table 1 Rate of evaluation factors

Rates	10	9	8	7	6	5	4	3	2	1
D (m)	≤1.5	1.5-4.6	4.6-6.8	6.8-9.1	9.1-12.1	12.1-15.2	15.2-22.9	22.9-26.7	26.7-30.5	>30.5
R (mm)	>254	235-254	216-235	178-216	147.6-178	117.2-147.6	91.8-117.2	71.4-91.8	51-71.4	≤51
A	Gravel-cobble	Sand gravel	Coarse sand	Medium sand	Find sand	Silty fine sand	Silt	Sandy loam	Loam	Clay
S	Gravel-cobble	Sand gravel	Coarse sand	Medium sand	Silt, find sand	Silty fine sand	Loam	Trash	Clay	Mud, bed rock
T(‰)	≤2	2-4	4-7	7-9	9-11	11-13	13-15	15-17	17-18	>18
I	Gravel-cobble	Sand gravel	Coarse sand	Medium sand	Fine sand	Silty fine sand	Silt	Loam	Loam	Clayed mud
C (m/d)	>81.5	71.5-81.5	61.1-71.5	40.7-61.1	34.6-40.7	28.5-34.6	20.3-28.5	12.2-20.3	4.1-12.2	≤4.1

2.2 Rate of evaluation factors

Based on the unique geological features in the study area, factors witness big change in the piedmont change but small change in the plain area. In order to distinguish the effect of different characteristics on the evaluation results, the rate of evaluation factor was modified and the interval number group was encrypted (Table 1). Class interval is determined by the maximum and minimum value in each factor. The rate ranges from 1 to 10, the higher the rate, the poorer the antifouling performance, and the easier the pollutants will affect groundwater. In particular, as net recharge include both precipitation and irrigation, recharge amount differs greatly in different areas. But this factor is very important in the evaluation of groundwater vulnerability. Thus, in order to fully reflect the impact of this factor, the DRASTIC rating interval is changed from 1-9 to 1-10.

2.3 Determination weight based on AHP evaluation

In traditional DRASTIC model, the weights of evaluation factors are fixed. However, hydrogeological conditions differ by regions, calculation based on fixed weight can not reflect the actual situation of different areas (MA Jin-zhu and GAO Qian-zhao, 2003; GUO Xiao-jing *et al*. 2010; YANG Gui-fang *et al*. 2012; SUN Cai-zhi *et al*. 2007; Prasad R K *et al*. 2011; XIA Xue-jun *et al*. 2011; WANG Xiu-jie *et al*. 2015; FAN Qi *et al*. 2007; BAI Li-ping and WANG Ye-yao, 2009; LI Yue-xing *et al*. 2013). In order to achieve more accurate evaluation, this paper uses the flexible weight based on actual situation of the study area through both qualitative and quantitative analysis.

Analytic Hierarchy Process is a practical multi-scheme or multi-objective decision-making method (Saaty R W, 1987) raised by Professor Saaty, an American operational research expert, in the 1980s. The key feature of this process is that it integrates qualitative and quantitative decision-making in a reasonable way and turns the decision-making process into a hierarchy and quantitative process according to the law of thinking and mentality.

According to the years of work experience in the Dahei River plain, the lithology above the aquifer greatly affects the infiltration. When soil layer or vadose zone contain weak permeable medium like clay or loam, surface water pollutants can hardly pollute groundwater. Much of this is farmland. That is why the groundwater used for agricultural production is of large amount and the water level fluctuates obviously with the development cycle. In order to reduce the wave error of groundwater depth, aquifer depth is calculated based on multi-year average data.

The matrix of DASTIC model is established (Table 2) based on the hydrogeological conditions in the study area as well as expert experience, the eigenvector of the matrix is [0.689, 1.379, 1.034, 1.379, 0.344, 2.068, 1.034]. After uniformization, the eigen value is [0.087, 0.174, 0.130, 0.174, 0.043, 0.261, 0.130] with λ_{max}=7.000.

Table 2 Matrix of DRASTIC model

Indicators	Groundwater depth	Net recharge	Aquifer media	Soil media	Topography	Vadose zone	Hydraulic conductivity
Groundwater depth	1	1/2	2/3	1/2	2	1/3	2/3
Net recharge	2	1	4/3	1	4	2/3	4/3
Aquifer media	3/2	3/4	1	3/4	3	1/2	1
Soil media	2	1	4/3	1	4	2/3	4/3
Topography	1/2	1/4	1/3	1/4	1	1/6	1/3
Vadose zone	3	3/2	2	3/2	6	1	2
Hydraulic conductivity	3/2	3/4	1	3/4	3	1/2	1

These indicators' weights are based on experts' experience. In order to ensure these indicators are weighted scientifically, a consistency test of the judgment matrix is conducted (PAN Hong-yu and FENG Ying-jun, 2015; JIANG Hai-hao *et al*. 2015; ZHANG Jia-lin and WEI Xiao-jun, 2006). The inspection formula is as follows:

$$CR = \frac{CI}{RI}, CI = \frac{1}{m-1}(\lambda_{max} - m)$$

Among them, m is the judgment matrix dimension, the value is 7, RI is a random consistency index, and the 7 order matrix is 1.32. Thus, $\mathrm{CR} = 1.83^{-10} \ll 0.1$. It shows that each indicator weight is reasonable. To make the calculation simple, weight value is integerized. Table 3 is the weight table.

Table 3 Indicators' weight in DRASTIC model

Indicator	D	R	A	S	T	I	C
Wight	2	4	3	4	1	6	3

In the DRASTIC model, the rate of each indicator multiplied by the corresponding weight is the comprehensive index of vulnerability DI:

$$D_i = \sum_{i=1}^{7} w_i r_i \quad (2)$$

r_i refers to the rate of indicator i and w_i refers to the weight of indicator *i*.

3 Assessment results and comparative analysis

3.1 Assessment results and comparative analysis

Since all the original data of the model indicators are two-dimensional tables based on the sampling point values and the sampling point coordinates, when they are shown in maps, there are only discrete sampling points. Therefore, on the ArcGIS platform, the assessment area needs to be divided into a total of 20 450, 500 m ×500 m units of the regular grid and spatial interpolation is used to calculate the value of each factor in each grid. The scale expression of spatial interpolation results is shown in seven single-factor maps (Fig. 4-Fig. 10), including map of hydraulic conductivity, map of depth to water, map of topography, map of aquifer media, map of net recharge, map of Vadose Zone Media, and map of soil media zone, and corresponding index is assigned to each attribute data of each unit according to Table 1. DI values for each unit are calculated with the above-mentioned calculation formula for pollution vulnerability assessment index DI. Based on the assessment results, groundwater vulnerability assessment map is conducted according to the classification levels shown in Table 3. Comprehensive assessment is conducted and the comprehensive vulnerability index is between 60-200. The index range is divided into five scales based on the research needs, which is shown in Table 4. The different scale results are shown in Fig. 11.

Table 4 Groundwater vulnerability index scale

Vulnerability scale	Very low	Low	Medium	High	Very high
Index range of comprehensive vulnerability assessment	60-80	80-110	110-140	140-170	170-200

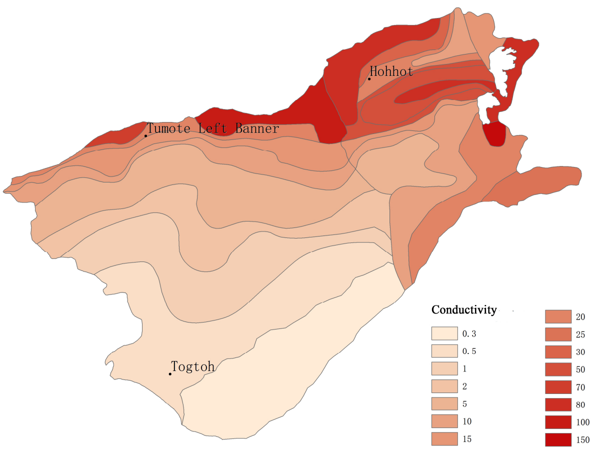

Fig. 4 Map of hydraulic conductivity

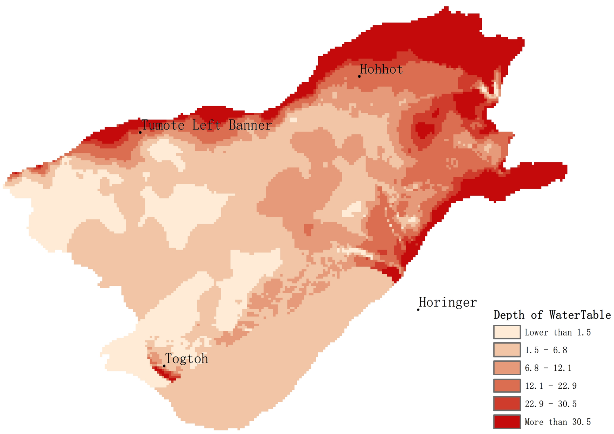

Fig. 5 Map of depth to water

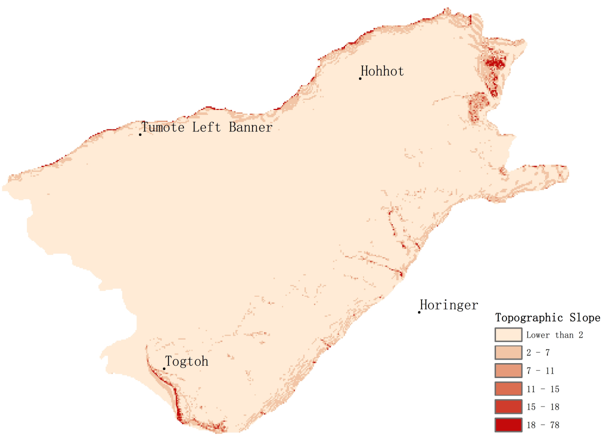

Fig. 6 Map of topography

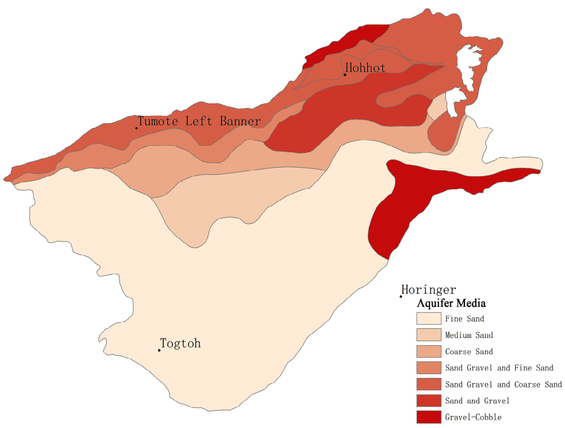

Fig. 7 Map of aquifer media

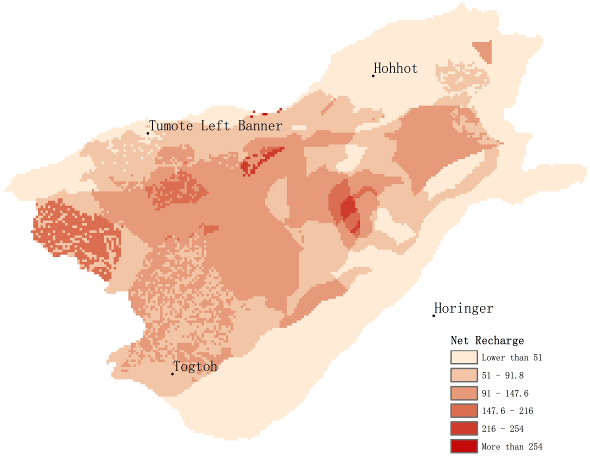

Fig. 8 Map of net recharge

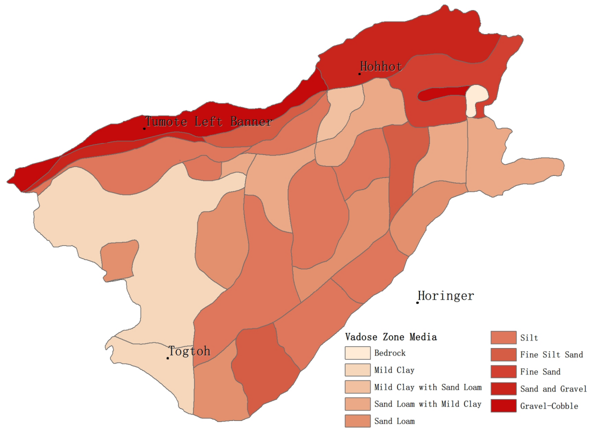

Fig. 9 Map of vadose zone media

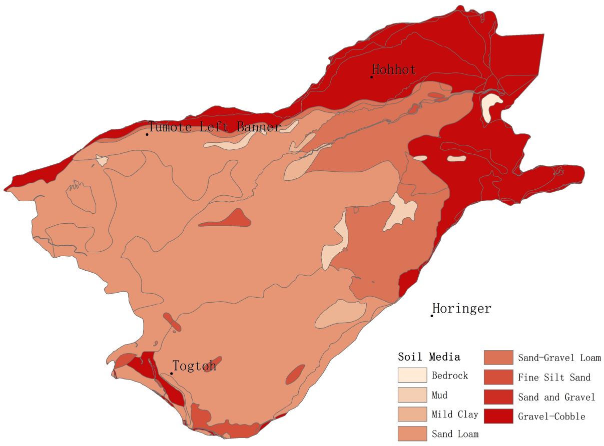

Fig. 10 Map of surface soil media zone

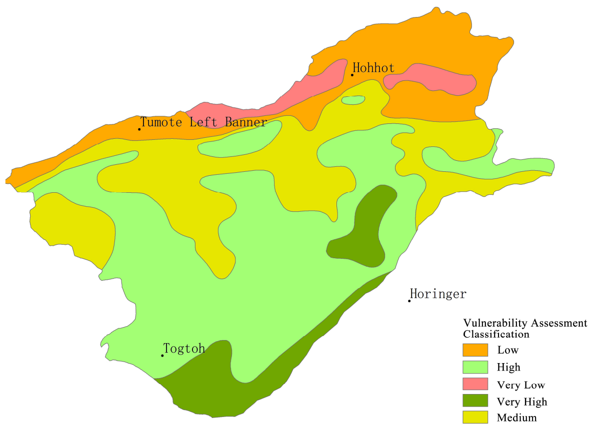

Fig. 11 Distribution map of groundwater vulnerability assessment

(1) Areas with very low vulnerability

With a total area of 456 km^2, two areas have very low vulnerability, which accounts for 8.9% of the total work area. One area is located in Sha'erqin Township and some areas to its south with an area of 132 km^2 and an index ranging of 60-80. In this area, the surface soil layer is mainly clay loam. The clay loam-dominant vadose zone is 5-15 m thick. Therefore, it is difficult for surface pollutants to penetrate into aquifers through surface water. The low vulnerability is more attributed to the low hydraulic conductivity (0.3 m/d-2 m/d), which makes it difficult for pollutants to diffuse. All of the above-mentioned factors have contributed to the very low vulnerability in this area. Tuoketuo mesa also has very low vulnerability. Its surface is covered with loess, which makes it difficult for ground water to infiltrate. In addition, the Quaternary aquifer in this area is very thin; some areas have exposed bedrock, and the slope of this area is larger than the plain. On one hand, very low vulnerability in the assessment in this area shows that this area is not sensitive to pollution based on the assessment model, but on the other hand, it shows that the Quaternary aquifer in this area yields small volumes of underground water.

(2) Areas with low vulnerability

Areas with low vulnerability, with an area of 2 248 km^2, accounting for 44% of the total work area, are concentrated in the southern and central part of the plain area, vast pieces of areas close to the southern border and western border of the work area, and discharge areas of groundwater. Southern and central parts of the plain is mostly sediment plain with mostly low permeability medium such as clay and clay loam in the surface soil layer and vadose zone. In addition, the aquifers in this area also have low hydraulic conductivity at 0.5 m/d-5 m/d in most parts. Therefore, they are assessed with low vulnerability with an index ranging of

80-110. Several small pieces of areas in the mud layer of the piedmont also have low vulnerability because these areas are mostly fan-shaped low-lying lands, parts of the soil layer and the vadose area have clay loam and mud, the net recharge is not prominent and the area has a certain slope. Thanks to these factors, some small pieces of areas in the piedmont have a low vulnerability of 95-110.

(3) Areas with medium vulnerability

Areas with medium vulnerability are located in the northern part of the piedmont, the transition zone from the trailing edge of the alluvial fan areas to the middle of the plain, with an area about 1 390 km^2, accounting for 27% of the whole work area. As a whole, the area is divided into three parts from the west to the east: in the southwest part of Hasuhai Lake, Zhijiliang Township in the division of Tumed Left Banner, the lithology of the surface soil is dominated by sandy loam; the vadose zone contains a large amount of clay; the hydraulic conductivity is low at 1 m/d-2 m/d; the shallow groundwater is shallow and the terrain has a very small slope. Therefore, this area has medium vulnerability with an index ranging from 115-125. The second area with medium vulnerability goes along the river course of the Daheihe River from the west to the east including Tabusai Township, most part of Tiemao Township-Baimiaozi Township, Sha'erying Township-most part of Xiaoheihe Township. This area covers a large span from the west to the east. The lithology of the surface soil is dominated by sandy loam with clay loam in some parts. The surrounding areas of the east part of the Daheihe River's river course is mainly covered with sandy loam with gravel. The vadose zone is dominated by sandy loam and clay loam in the western part, sandy loam with gravel and fine sand in the eastern part and some parts of the vadose zone have clay loam. Overall, the soil layer and the vadose zone have medium hydraulic conductivity, which changes greatly from the west to the east. In the western part, including Tabusai Township and Tiemao Township, the hydraulic conductivity is 1 m/d; then the conductivity increases gradually in the east and reaches about 50 m/d in areas around Xiaoheihe Township. From the west to the east, the surface net recharge decreases and the vulnerability does not change greatly. On average, the vulnerability index changes from 128 to 118 from the west to the east, which stands for medium vulnerability. The third area with medium vulnerability is located in south Jinhe Township, Gecilaocun Village–Niangetucun Village–Gonglamacun Village in the leading edge of the alluvial fan areas of Shala Wusu River. In this area, the vadose zone is dominated by sandy loam and fine sand with a hydraulic conductivity of 20 m/d. The lithology of the aquifers is mainly sand gravel with medium and coarse sand. Some areas close to the piedmont have big slope with a DI between 100-140, which stands for medium vulnerability.

(4) Areas with high vulnerability

Areas with high vulnerability are located in the leading edge of the alluvial fan areas of piedmont fault in the north around the northern border of the silt layer. They are distributed in the shape of a strip from the east to the west with an area about 812 km^2, accounting for 15.9% of the total work area. The soil layer and vadose zone are mostly gritstone and gravel with clay loam in the soil layer in some parts. The surface contaminants can easily contaminate the aquifers through loose media. From the west to the east, the vadose zone is 30 m-80 m thick with the hydraulic conductivity ranging from 5 m/d to 30 m/d. DI in this strip ranges from 140-170, which stands for high vulnerability.

(5) The area with very high vulnerability

The area spans along the trailing edge of the alluvial fan areas of Shuimogou Ditch in the piedmont in the north to the trailing edge of the alluvial fan areas of Halaqin Ditch and the alluvial fan areas of the mountain exit of Daheihe River with an area around 205 km^2, accounting for 4% of the total work area. The lithology of the soil layer and the vadose zone in this area is loose sand gravel. Although the vadose zone is 20 m-50 m thick, the hydraulic conductivity of the vadose zone is big (80 m/d-100 m/d), which makes the pollutants very easy to penetrate and pollute the aquifers. The DI for this area is 170-200, the highest in the whole research area and therefore, this area is the most vulnerable to pollution in the research area.

Table 5 Evaluation indicator weight of traditional methods

Index	D	R	A	S	T	I	C
Weight	5	4	3	2	1	5	3

3.2 Comparison with traditional DRASTIC methods

To highlight the feature of deciding parameters based on AHP, the traditional DRASTIC method is used in this area (Table 5) and vulnerability-to-pollution DI distribution map is designed, with DI value ranging from 66 to 176 in 5 ranks (Table 6). Please see the distribution in Fig. 12.

Table 6 Classification of DRASTIC index

Ranks	Excellent	Good	Medium	Bad	Serious
Scoring	66-88	88-110	110-132	132-154	154-176

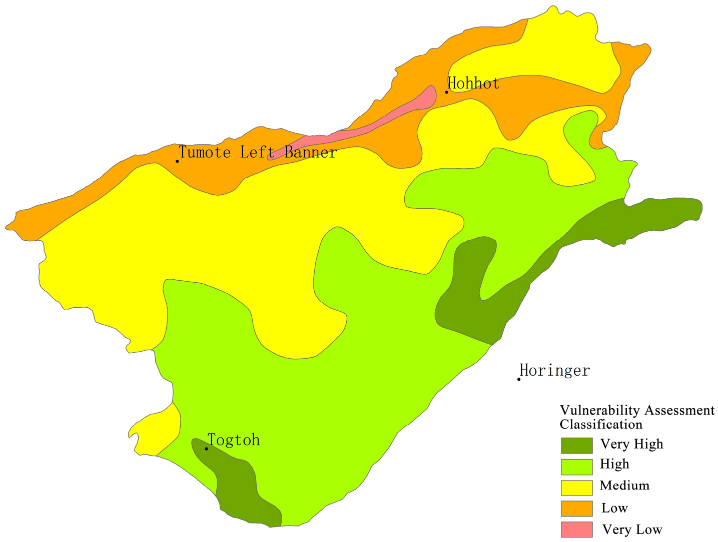

Fig. 12 Distribution map of traditional vulnerability index

By comparing the distribution map of the traditional method and the new method, the vulnerability index range of traditional methods is bigger than the one of the new method: Index range of the traditional method is 60-200 while the index range of the new method is 66-176, which is shown as follows.

Table 7 Results of the two methods

	Area km^2 and percentage of the traditional method		Area km^2 and percentage of the new method	
Excellent	293.97	5.75%	555.58	10.87%
Good	2 093.72	40.97%	2 048.11	40.07%
Medium	1 994.24	39.02%	1 389.90	27.20%
Bad	682.35	13.35%	812.06	15.89%
Serious	46.57	0.91%	305.19	5.97%

By comparison, there are two major differences between the results of the traditional method and the results of the new method:

(1) Due to reasonable adjustment of weights, the adjusted evaluation result shows a more obvious property of intermontane depressions in front of the Daqing Mountain in the north: The intermontane depressions are much less vulnerable to pollution than pluvial alluvial regions.

(2) Due to unreasonable allocation of weights, the bracket of extreme scenarios including excellent and serious is too large or too small, not being able to highlight areas in need of protection and treatment; the evaluation method with adjusted weights are more scientific and more in line with local conditions compared than the traditional DRASTIC method with fixed weights.

4 Conclusions

DRASTIC method is a typical representative of the iterative index methods. It has many advantages such as low cost, easy access to data and straight-forward results. However, this method is very subjective and needs to be combined with other methods that can quantify the assessment index such as fuzzy mathematics comprehensive evaluation method and other methods to obtain more scientific and objective assessment results. Therefore, according to the actual hydrogeological conditions of the Daheihe plain in Hohhot, this paper optimizes some factors of the DRASTIC model, compares and analyzes the results with those from traditional methods to make the assessment results more in line with the actual local conditions. Each assessment factor weight is determined by using analytic hierarchy process (AHP) to avoid the limitation of traditional DRASTIC method giving the same weight to factors in different regions and make the distribution of the weights more reasonable.

The vulnerability distribution map can straight-forwardly show the distribution of the areas where groundwater is susceptible to contamination in the research area. In the entire research area, vulnerability decreases from high to low from the piedmont in the north to the central areas of the north shore of the Yellow River in the south. Piedmont, as the "upstream" of groundwater recharge, is the most vulnerable area to pollution. Therefore, special attention needs to be given to prevent pollution in this area when it comes to local land use and planning.

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