Research on the evaluation method of groundwater quantity and pollution vulnerability
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ABSTRACT
Current research on groundwater vulnerability is aimed mainly at groundwater pollution vulnerability (GPV), and the vulnerability of groundwater quantity is seldom considered. It is important to carry out the groundwater vulnerability evaluation for the management of groundwater resources. This paper presents evaluation models and methods for assessing groundwater quantity and pollution vulnerability. The models and methods were used to evaluate the groundwater vulnerability in the plain area of Baotou, Inner Mongolia, China. The groundwater quantity vulnerability was assessed by computing the groundwater recharge rate, and the GPV was evaluated by simulating the migration time for pollutants traveling from ground surface to the aquifer. The research results could provide scientific support for the management of regional groundwater resources, prevention and control of groundwater pollution.

Key words | groundwater pollution, groundwater quantity, groundwater vulnerability evaluation

INTRODUCTION
Groundwater is one of the most important and widely-distributed water resources on the Earth. More than 1.5 billion people around the world rely mainly on groundwater resources as their drinking water, and one-third of China’s total water resources and nearly 20% of its national water supply is groundwater (Xue & Zhang 2009).

Groundwater is the important water resource in China, however, continual overdraft of groundwater resources for many years has led to a continual decline of groundwater levels in some regions. Overdraft of groundwater has caused a series of ecological and environmental problems, such as groundwater drawdown funnels, groundwater subsidence, ground fissure, land collapse, eco-environment degradation and seawater intrusion. At present, more than 180 groundwater drawdown funnels have formed in China, and the drawdown funnel area is nearly 190,000 km². The seawater intrusion area was 2,457 km² in 2003, an increase of 937 kilometers from the area in the 1980s (Fan 2009).

Groundwater pollution is another major problem that has emerged during the process of water resources exploitation and utilization (Bai et al. 2011). The situation of groundwater pollution in some regions of China is becoming more serious day by day because few groundwater protective measures have been adopted in the process of groundwater resources exploitation and utilization. The problem of water resources shortage and imbalance between supply and demand has become increasingly serious with irrational land utilization, improper disposal of industrial waste and municipal solid waste, and excessive use of fertilizer and...
pesticides. At present, groundwater pollution is prevalent in some cities of China. The shortage of groundwater sources in China has created an increasingly serious pollution problem.

In recent years, the shortage of water resources has caused people to pay much more attention to groundwater resources protection. Research on groundwater vulnerability evaluation in different kinds of geological and hydrogeological conditions has become a hot topic. The results obtained from the evaluation of groundwater vulnerability can be used in the management of groundwater resources. The management of groundwater resources focuses on the regions that have the lowest groundwater pollution vulnerability (GPV). The groundwater sources and protection areas in districts that could be seriously disturbed by human activities should be protected for the sustainable utilization of groundwater resources.

The shortage of groundwater resources is contributing to a global worsening environment of soil and groundwater resources. It is important to carry out the groundwater vulnerability evaluation for the development and utilization of groundwater resources. At present, the research of groundwater vulnerability evaluation is focused mainly on GPV; groundwater quantity vulnerability (GQV) is seldom considered. This paper suggests that groundwater vulnerability should consider the inherent characteristics of the groundwater system and the factors of water quality and water quantity. Evaluation models and methods of GQV and pollution vulnerability are presented in this paper. Then the models and methods were used to evaluate the groundwater vulnerability in the plain area of Baotou, Inner Mongolia, China. The GQV was assessed by conducting a balance analysis of groundwater resources, and the GPV was evaluated by simulating the migration time for pollutants to travel from ground surface to the aquifer. The research results can be used in the planning and management of groundwater resources development and utilization.

MODELS AND METHODS OF GROUNDWATER QUANTITY AND POLLUTION VULNERABILITY

Evaluation of groundwater quantity vulnerability

The concept of groundwater vulnerability was first developed in the 1960s in Europe. Different researchers and institutions have given various kinds of definitions of groundwater vulnerability, but no unified definition has been formed up to now (Worrall et al. 2002; Worrall & Besien 2005; Antonakos & Lambrakis 2007; Bai & Wang 2009). At present, the GQV is seldom considered in the evaluation of groundwater vulnerability and the definition of groundwater vulnerability is usually based on the groundwater quality. Overdraft of groundwater resources may cause a series of environmental problems, therefore, this paper asserts that the GQV should be considered in the evaluation of groundwater vulnerability.

The GQV is affected mainly by the groundwater recharge rate, so the evaluation of groundwater quantity should be based on the balance analysis of groundwater resources. According to the law of quality conservation, the variation of groundwater inflow and outflow is equal to the variation of groundwater reserve capacity in any area at any time. The total groundwater resources balance equation is (Fang 1996)

$$\mu \Delta h + V + P = (X + Y_1 + Z_1 + W_1 + R_1) - (Y_2 + Z_2 + W_2 + R_2)$$

(1)

In Equation (1), $\mu$ is the specific yield of phreatic water; $\Delta h$ is the variation of the phreatic water level; $V$, $P$ are the storage variation of surface water and water in the aeration zone respectively; $L$; $X$ is the precipitation; $L$; $Y_1$, $Y_2$ are the surface water inflow and outflow respectively; $L$; $Z_1$, $Z_2$ are the condensation water and evaporation, $L$; $W_1$, $W_2$ are the inflow and outflow of underground runoff respectively, $L$; $R_1$, $R_2$ are the artificial recharge and discharge of water, $L$.

The balance equation of phreatic water is:

$$\mu \Delta h = (X_f + Y_f + W_1 + Z_1' + R_1') - (W_2 + W_s + Z_2 + R_2')$$

(2)

In Equation (2), $X_f$ is the precipitation infiltration recharge, $L$; $Z_1'$, $Z_2'$ are the condensation water and evaporation of phreatic water respectively, $L$; $W_s$ is the spring flow, $L$; $Y_f$ is phreatic water recharge from surface water, $L$; $R_1'$, $R_2'$ are the artificial recharge and discharge of water respectively, $L$.

The balance equation of confined water is:

$$\mu \ast \Delta h = (W_1 + E_1) - (W_2 + R_2)$$

(3)
In Equation (3), $\mu_*$ is the storage coefficient of the confined aquifer; $E_1$ is the leakage recharge, L; $R_2$ is the exploitation of confined water, L.

The groundwater balance includes variation of water resources and recharge and discharge of the groundwater system. The most important factors of recharge are precipitation infiltration, surface water seepage recharge and underground runoff. The most important factors of discharge are evaporation, underground runoff discharge and exploitation. Our suggestion is that the groundwater recharge rate be used to evaluate the GQV in this research.

**Evaluation of groundwater pollution vulnerability**

The methods of assessing groundwater vulnerability at present can be classified into three categories namely, the overlay and index method, the process based simulation method and the statistical method (Collins & Bolin 2007; Nobre et al. 2007; Almasri 2008).

The overlay and index method, the simplest and most widely used method to assess the groundwater vulnerability, is a qualitative or half quantitative method. The most effective factors are selected first, then the evaluation factors are chosen to form the index which reflects the degree of vulnerability. The groundwater vulnerability is evaluated based on this index (Nobre et al. 2007). The accuracy of the overlay and index method is based on the availability of data and the experience of experts. A groundwater vulnerability map can be made through this method, and the grades of different aquifers can be displayed by different colors. The typical models of overlay and index methods include DRASTIC, GOD, SINTACS, among others.

The statistical method is established based on mathematical statistics and an analysis of groundwater pollution data. The relevance between groundwater vulnerability and different factors can be determined through the evaluation model. The groundwater vulnerability grades can be evaluated based on the model (Collins & Bolin 2007; Almasri 2008).

The process based simulation method simulates contaminant migration and transportation processes in the vadose zone and aquifers through physical, chemical and biological models. A vulnerability index can be obtained by this method. The process based simulation method can simulate and forecast the contaminant migration process at different times and at various points in space, which is different to other methods. The complex mathematical models are considered to be the most reliable method in groundwater vulnerability evaluation.

As noted earlier, the overlay and index method is the most widely used method, in addition, DRASTIC is the most widely used model in groundwater vulnerability evaluation (Al-Adamat et al. 2003; Thirumalaivasan et al. 2003; Insaf et al. 2005; Hamza et al. 2007; Nobre et al. 2007; Pusatli et al. 2009). The parameters of DRASTIC often need to be modified based on the hydrogeological conditions in different regions (Worrall & Besien 2005; Mende et al. 2007; Nobre et al. 2007). The process based simulation method is considered as the most efficient method in the regions with detailed hydrogeological data. In this paper, we propose that the numerical model be used to evaluate groundwater vulnerability. The travel time for the contaminants entering the aquifer can be computed by the unsaturated soil water and solute transport models, then the different grades of GPV can be evaluated with the aid of the model. The one-dimensional soil water and solute transport models were used in this research.

**Soil water flow model**

The equation of soil water flow is derived form the mass conservation continuous equation and Darcy's law. One-dimensional uniform water movement in a partially saturated rigid porous medium is described with the assumptions that the air phase plays an insignificant role in the liquid flow process and that water flow due to thermal gradients can be neglected (Šimůnek et al. 2009):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[ K \left( \frac{\partial h}{\partial z} + \cos \alpha \right) \right] - S$$  (4)

In Equation (4), $\theta$ is the volumetric water content, L$^3$L$^{-3}$; $h$ is the water pressure head, L; $t$ is time, T; $z$ is the spatial coordinate (positive upward), L; $\alpha$ is the angle between the flow direction and the vertical axis; $S$ is the sink term, L$^3$L$^{-3}$T$^{-1}$; and $K$ is the unsaturated hydraulic conductivity function [LT$^{-1}$].
The initial distribution of the pressure head is:

\[ h(z, t) = h_0(t) \quad z = 0 \quad \text{or} \quad z = H \]

In Equation (5), \( h_0 \) is a prescribed function of \( z \), \( L \); \( t_0 \) is the time when the simulation begins, \( T \).

One of the following boundary conditions can be specified with system-independent boundary conditions:

\[ h(z, t) = h_0(t) \quad z = 0 \quad \text{or} \quad z = H \]

\[ -K \left( \frac{\partial h}{\partial z} + \cos \alpha \right) = q_0(t) \quad z = 0 \quad \text{or} \quad z = H \]

\[ \frac{\partial h}{\partial z} = 0 \quad z = 0 \]

In Equation (6), \( h_0 \) is the prescribed value of the pressure head, \( L \); \( q_0 \) is the soil water flux at the boundary, \( LT^{-1} \).

### Solute transport model

The one-dimensional solute transport equation is:

\[ \frac{\partial (\theta c)}{\partial t} + \frac{\partial (\theta s)}{\partial t} = \frac{\partial}{\partial z} \left( \theta D \frac{\partial c}{\partial z} \right) - \frac{\partial (qc)}{\partial z} + \sum \phi_i(c, s) \]

In Equation (7), \( \theta \) is the volumetric water content, \( L^3 L^{-3} \); \( c \) is the solute concentration, \( ML^{-3} \); \( t \) is time, \( T \); \( \rho \) is the soil dry bulk density, \( ML^{-3} \); \( s \) is the solute content in the soil solid components, \( MM^{-1} \); \( D \) is the hydrodynamic dispersion coefficient, \( L^2 T^{-1} \); \( q \) is the water flux, \( LT^{-1} \); \( \phi_i \) is the source and sink function, \( L^3 L^{-3} T^{-1} \).

The initial distribution of the solute concentration is:

\[ c(z, 0) = c_i(z) \]

where, \( c_i \) is the prescribed function of \( z \), \( ML^{-3} \).

The boundary conditions are:

\[ c(z, t) = c_0(z, t) \quad z = 0 \quad \text{or} \quad z = H \]

\[ \theta D \frac{\partial c}{\partial z} = 0 \quad z = 0 \quad \text{or} \quad z = H \]

\[ -\theta D \frac{\partial c}{\partial z} + qc = q_0 c_0 \quad z = 0 \quad \text{or} \quad z = H \]

In Equation (9), \( q_0 \) represents the upward fluid flux and \( c_0 \) is the concentration of the incoming fluid, \( ML^{-3} \).

### CASE STUDY

#### The study area

The study area is located in the plain area of Baotou city, Inner Mongolia, China. In the northern part of the study area is the piedmont plain which has an average slope of 8‰, and in the southern part is the alluvial plain with an average slope of 1.5‰. The total area is about 768 km². The average annual precipitation is 306.5 mm, and the average annual evaporation is 2,273.8 mm. The quaternary strata are widely distributed in the study area, and the stratum thickness is about 2,000–2,300 m. The unconfined aquifers are composed mainly of sand and gravel of the Upper Pleistocene and Holocene Series. The depth of the unconfined aquifer in the piedmont plain is about 20–30 m in the northern and middle areas and 5–10 m in the southern area. The depth of the unconfined aquifer in the alluvial plain is about 5–10 m.

#### Groundwater quantity vulnerability evaluation

The aquifers in the piedmont plain are composed of five alluvial and diluvial fans; namely, the Ha fan, Kun fan, Dongben fan, Liu fan and Babai fan. The alluvial plain in the south of the study area is divided into the western and eastern alluvial plain by a fault. A balance analysis of the groundwater resources was carried out based on these divisions. Equation (1) was used in the research of the study area, and the calculation equations of the balance analysis are:

\[ Q_{re} = Q_s + Q_i + Q_f + Q_{fr} \]

\[ Q_s = \beta Q_{sq} \]

\[ Q_i = \gamma Q_{iq} \]

\[ Q_f = 365 \cdot H \cdot L \cdot K \cdot I \]

In Equation (10), \( Q_{re} \) refers to the total recharge of groundwater in the calculation period, \( m^3 \); \( Q_s \) refers to the precipitation infiltration recharge, \( m^3 \); \( Q_i \) refers to the surface water recharge, \( m^3 \); \( Q_{fr} \) refers to the farmland irrigation recharge, \( m^3 \); \( Q_f \) refers to the lateral inflow recharge, \( m^3 \); \( Q_f \) refers to the seepage recharge, \( m^3 \); and \( \alpha \) is the precipitation infiltration coefficient; \( F \) is the area of the calculation region, \( m^2 \); \( X \) is the precipitation, \( m \); \( \beta \) is the surface water infiltration coefficient; and \( \gamma \) is the groundwater discharge coefficient. The groundwater recharge \( Q_{re} \) is the total sum of all these sources and is the main component of the groundwater recharge.
parameter; \( Q_{sq} \) is the surface water quantity, \( m^3 \); \( \gamma \) is the infiltration coefficient; \( Q_{iq} \) is the irrigation water quantity, \( m^3 \); \( H \) is the aquifer thickness, \( m \); \( L \) is the length of the calculated section, \( m \); \( K \) is the aquifer permeability coefficient, \( m/d \); \( I \) is the hydraulic gradient of groundwater.

The precipitation infiltration coefficient, permeability coefficient and the hydraulic gradient of groundwater were obtained from the geological data. The water quantity data were collected from the local water resources bureau. Table 1 gives the values of the main parameters, and Table 2 shows the calculated results of the groundwater recharge in the different regions. The total average recharge of groundwater resources is \( 9658.90 \times 10^4 \) m\(^3\).

The groundwater recharge per unit area should be considered in groundwater vulnerability evaluation. The GQV values were assigned by the groundwater recharge per unit area, and the GQV grades were classified as 1, 2, 3 and 4. The Babai fan has the largest recharge per unit area, and the GQV value is 1. The GQV value of Ha fan and Liu fan is 2, and the GQV value of Kun fan and Dongben fan is 3. The western and eastern alluvial plain have the minimum recharge per unit area, and the GQV value is 4. Figure 1 shows the GQV evaluation results.

### Table 1 | Values of parameters used in the groundwater resources balance analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha )</td>
<td>0.004 (groundwater depth is between 1 and 3 m)</td>
</tr>
<tr>
<td>( \beta )</td>
<td>0.11 (groundwater depth is between 3 and 5 m)</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>0.051 (groundwater depth is between 5 and 10 m)</td>
</tr>
<tr>
<td>( \delta )</td>
<td>0 (groundwater depth is greater than 10 m)</td>
</tr>
</tbody>
</table>

### Groundwater pollution vulnerability evaluation

The stratum in the study area is composed of different kinds of unconsolidated sediments from different geological periods. The migration time for pollutants to travel from the surface to the aquifer was computed by the Hydrus model in this research (Šimůnek et al. 2005), and the GPV was evaluated by the simulated migration time.

In the numerical model, land surface was considered as the upper boundary and defined as the third-type boundary. The bottom of the unconfined aquifer was considered as the lower boundary and defined as the first-type boundary. The initial moisture content and solute concentration in the soil are known in the numerical simulation. For the first-type boundary, the water content and solute concentration are known. For the third-type boundary, the ground surface is in the infiltration state. In this research, the conservative material (\( Cl^- \)) was selected as the pollutant.

The space discrete interval is 10 cm, and the time discrete interval is 1 day. The soil water flow and solute transport equations were solved through iterative method. The Galerkin finite element method was used to solve the solute and heat transport equations subject to appropriate initial and boundary conditions. The Galerkin method is used only for approximating the spatial derivatives while the time derivatives are discretized by means of finite differences. The parameters of particle size and bulk density were obtained by the measured data from soil samples collected from the study area. The parameters of soil residual moisture, saturation moisture, coefficient of permeability, adsorption characteristic and dispersion coefficient were obtained from soil sampling tests, leaching experiments and adsorption experiments. The soil water characteristic

### Table 2 | The calculated results of groundwater recharge in different regions

<table>
<thead>
<tr>
<th>Region</th>
<th>( F ) (km(^2))</th>
<th>( Q_p ) (10(^4) m(^3))</th>
<th>( Q_s ) (10(^4) m(^3))</th>
<th>( Q_i ) (10(^4) m(^3))</th>
<th>( Q_l ) (10(^4) m(^3))</th>
<th>( Q_r ) (10(^4) m(^3))</th>
<th>( Q_w ) (10(^4) m(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piedmont plain</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ha fan</td>
<td>102.66</td>
<td>47.65</td>
<td>94.95</td>
<td>202.34</td>
<td>1,777.84</td>
<td>0</td>
<td>2,122.78</td>
</tr>
<tr>
<td>Kun fan</td>
<td>251.21</td>
<td>370.48</td>
<td>584.25</td>
<td>892.23</td>
<td>2,373.48</td>
<td>0</td>
<td>4,220.44</td>
</tr>
<tr>
<td>Dongben fan</td>
<td>33.98</td>
<td>67.14</td>
<td>32.47</td>
<td>111.05</td>
<td>317.53</td>
<td>0</td>
<td>528.19</td>
</tr>
<tr>
<td>Liu fan</td>
<td>23.69</td>
<td>20.02</td>
<td>69.84</td>
<td>206.66</td>
<td>554.34</td>
<td>0</td>
<td>850.86</td>
</tr>
<tr>
<td>Babai fan</td>
<td>12.33</td>
<td>10.09</td>
<td>53.47</td>
<td>71.64</td>
<td>605.33</td>
<td>543.06</td>
<td>1,283.59</td>
</tr>
<tr>
<td>Alluvial plain</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Western region</td>
<td>136.83</td>
<td>16.42</td>
<td>0</td>
<td>135.65</td>
<td>0</td>
<td>0</td>
<td>152.07</td>
</tr>
<tr>
<td>Eastern region</td>
<td>208.14</td>
<td>226.74</td>
<td>0</td>
<td>274.23</td>
<td>0</td>
<td>0</td>
<td>500.97</td>
</tr>
<tr>
<td>Total</td>
<td>768.84</td>
<td>758.54</td>
<td>834.98</td>
<td>1,893.80</td>
<td>5,628.52</td>
<td>543.06</td>
<td>9,658.90</td>
</tr>
</tbody>
</table>
curve was obtained by the Hydrus software, which was used to simulate soil hydraulic characteristic parameters. Table 3 give the values of the primary parameters in the numerical model.

According to the simulation results of the numerical models, the migration time for contaminants entering the aquifer increased linearly with increasing thickness of the unsaturated zone, while the quantity of contaminants entering the aquifer diminished. The migration time for pollutants traveling from surface to the aquifer was computed by the model, and the GPV value was assigned as 1–4. Figure 2 shows the evaluation results of GPV.

According to the GPV value evaluated by the model, the GPV of the study area can be divided into four grades. The low pollution vulnerability area (vulnerability value of 1) is mainly distributed in the northern part of the study area.

Table 3 | Values of the primary parameters in the numerical model

<table>
<thead>
<tr>
<th>Partitions</th>
<th>Bulk density $\rho$ (g/cm$^3$)</th>
<th>Residual soil water content $\theta_r$ (%)</th>
<th>Soil porosity $n$ (%)</th>
<th>Saturation $S_r$</th>
<th>Freundlich $K_f$</th>
<th>$1/n$</th>
<th>$R^2$</th>
<th>$K_s$ (cm/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.79</td>
<td>16.42</td>
<td>40.54</td>
<td>0.62</td>
<td>4.52</td>
<td>0.62</td>
<td>0.91</td>
<td>38.44</td>
</tr>
<tr>
<td>2</td>
<td>1.61</td>
<td>10.22</td>
<td>44.10</td>
<td>0.34</td>
<td>0.12</td>
<td>0.20</td>
<td>1.16</td>
<td>408.27</td>
</tr>
<tr>
<td>3</td>
<td>1.51</td>
<td>3.65</td>
<td>40.01</td>
<td>0.13</td>
<td>0.33</td>
<td>0.33</td>
<td>1.05</td>
<td>266.08</td>
</tr>
<tr>
<td>4</td>
<td>1.91</td>
<td>13.20</td>
<td>37.78</td>
<td>0.59</td>
<td>1.66</td>
<td>0.45</td>
<td>0.90</td>
<td>24.84</td>
</tr>
</tbody>
</table>

Figure 1 | Evaluation results of groundwater quantity vulnerability.

Figure 2 | Evaluation results of groundwater pollution vulnerability.
the medium pollution vulnerability area (vulnerability value of 2) is mainly distributed in the area south of the low pollution vulnerability area, the high pollution vulnerability area (vulnerability value of 3) is mainly distributed in the area south of the medium vulnerability area, and the highest pollution vulnerability area (vulnerability value of 4) is mainly distributed in the southern area. The evaluation results are satisfied as compared with the groundwater vulnerability evaluation results obtained by DRASTIC, AHP and extension theory (Bai et al. 2012).

The purpose of GQV assessment is to distinguish the groundwater vulnerability grade in a certain region, and the purpose of GPV assessment is to classify the GPV grade in the region. Therefore, it is feasible to divide the GQV and GPV grades by different levels. The assessment method of GQV and GPV suggested in this paper could be used in different regions. Based on the GQV and GPV evaluation results, the groundwater management departments could take effective measures to protect groundwater resources. The exploitation of groundwater resources should be reduced in the high GQV grade area. The mass exploitation region of groundwater resources and the large surface pollution sources should be placed in the low GQV and QPV grade area.

CONCLUSIONS

1. This research is based on the premise that groundwater vulnerability analysis should be based on the inherent characteristics of the groundwater system, and the factors of water quality and water quantity should be considered. The GQV could be assessed by the balance analysis of groundwater resources, and the GPV could be evaluated by the simulated migration time for pollutants traveling from the ground surface to the aquifer.

2. The groundwater recharge per unit area was considered in the groundwater vulnerability evaluation in this research, and the GPV was evaluated by the Hydrus model.

3. Based on the GPV value evaluated by the model, the GPV of the study area can be divided into four grades. Basically, the GPV grades increase gradually from the north to the south of the study area.

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