

A new model (DRARCH) for assessing groundwater vulnerability to arsenic contamination at basin scale: a case study in Taiyuan basin, northern China

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Received: 27 July 2006 / Accepted: 19 September 2006 / Published online: 12 October 2006
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Abstract A modified DRASTIC model for groundwater vulnerability assessment (abbreviated as DRARCH model by combining the first letters of its six assessment indices) was proposed. It is essentially the specific application of DRASTIC model rather than a new model. Both natural hydrogeological conditions that prevent groundwater from contamination and important intrinsic hydrogeochemical properties of sediments in vadose zone that are related to the retardation of contaminants were considered as vulnerability indices. The DRARCH model consists of six indices: (1) Depth to the water table, (2) net Recharge, (3) Aquifer thickness, (4) Ratio of cumulative thickness of clay layers to total thickness of vadose zone, (5) Contaminant adsorption coefficient of sediment in vadose zone, and (6) Hydraulic conductivity of aquifer. The rating values and the weights of these vulnerability indices were obtained by contaminant transport simulation and factor analysis method respectively. Furthermore, the DRARCH model was applied to evaluate the groundwater vulnerability to arsenic contamination in Taiyuan basin, northern China, where groundwaters with high arsenic concentration occur in some localities. GIS-based mapping of groundwater vulnerability using this model indicates that the distribution of very high and high-vulnerability areas corresponds well to that of high-arsenic groundwaters. The DRARCH model is therefore reliable and useful for guiding groundwater environment management.

Keywords DRARCH model · Groundwater · Vulnerability · Arsenic · GIS · China

Introduction

In the past 50 years, groundwater contamination has become one of the most serious environmental problems in the world. Once polluted, remediation of aquifers would be very difficult and even impossible (Kavanaugh 1996; McMahon et al. 1999; Aronovsky 2000). Preventing groundwater system from contamination therefore has significant importance for groundwater resource management. Groundwater vulnerability assessment is one of the major measures of groundwater protection (Mádl-Szönyi and Füle 1998). The purpose of groundwater vulnerability assessment is to divide a geographical area into sub-areas in terms of its susceptibility to groundwater contamination, and then in areas prone to contamination, effective groundwater protection measures should be carried out. In recent years, groundwater vulnerability assessment has become a very useful tool for the planning and decision-making of groundwater protection (Gogu and Dassargues 2000; Vias et al. 2005).

In the past decade, GIS (Lasserre et al. 1999; Lake et al. 2003; Thapinta and Hudak 2003; Witkowski et al. 2003; Dixon 2005) and RS (Thunnissen et al. 1992; Al-Adamat et al. 2003) have been successfully introduced in groundwater vulnerability mapping. Although groundwater vulnerability assessment usually aims at contamination induced by the application of pesticides or fertilizers (Meinardi et al. 1995; Soutter and Musy 1998; Burkart et al. 1999; Al-Senafy and Abraham 2004; Worrall and Besien 2005), the vulnerability to

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other contaminants have been studied as well (Smith et al. 1995; Guo and Wang 2004). In this study, the groundwater arsenic contamination in Taiyuan basin of northern China was investigated, and a new model (abbreviated as DRARCH model by combining the first letters of its six assessment indices) for assessing groundwater vulnerability to arsenic contamination at basin scale was proposed by modifying the DRASTIC model and applied in the basin.

Taiyuan basin is a Cenozoic rift basin in Shanxi Province, northern China. Groundwater has been the most important source of water supply. However, the results of regional hydrogeochemical survey in this study indicates that groundwaters with arsenic concentration exceeding the maximum permissible concentration of 50 µg/L for drinking water (National Drinking Water Standard, China) occur in some localities of the basin. It was also reported by Jin et al. (2003) that there are seven localities within the basin where groundwaters with abnormal arsenic concentration occur. The high-arsenic concentration in groundwater may have close relationship with the application of fertilizers and pesticides and the discharge of wastewaters of chemical and metallurgical industry widely distributed in the basin. Therefore, groundwater vulnerability assessment is urgently needed to delineate the areas where groundwaters are vulnerable to arsenic contamination, so that effective measures can be implemented in these areas to prevent groundwater from further pollution.

Although different models have applied in groundwater vulnerability assessment, those integrating both natural conditions and contaminant properties as vulnerability assessment indices are still being developed. The objectives of the present study are: (1) to select appropriate vulnerability indices that constitute the index system of the new model; (2) to determine the rating values and the weight of each index of the model; (3) to map the groundwater vulnerability to arsenic contamination in the study area; and (4) to validate the model using the arsenic concentrations of water samples collected in this study and to find out the factors resulting in the high-groundwater vulnerability to arsenic contamination.

Regional hydrogeology and geochemical sampling

Taiyuan basin is located in the middle of Shanxi Province, with an area of 6,159 km². The annual mean air temperature of the basin has varied from 8.8 to 10.6°C in the past 50 years. The average annual rainfall from 1951 to 2000 was 446.6 mm, the largest 655.0 mm

(1964), and the smallest 259.8 mm (1972). The annual mean potential water surface evaporation is 1,774.9 mm. Surface waters in the study area are mainly Fen River that divides the basin into two parts (Fig. 1). Bedrock around the Taiyuan basin includes Cambrian-Ordovician carbonate rocks, carboniferous-Permian coal-bearing strata and Triassic sandstone and shale (Fig. 1). Cenozoic sediments with a thickness between 50 and 3,800 m occur all over the study area, and the types of sediments within the vadose zone mainly include clay, silty clay, loam sand, silty sand, and fine sand. The shallow groundwater in the upper unconfined aquifer, the most important water supply source at Taiyuan, was selected as the target aquifer for assessing vulnerability to arsenic contamination.

Twenty-eight groundwater samples were collected between July and August 2003, and the locations of samples are shown in the map of location of

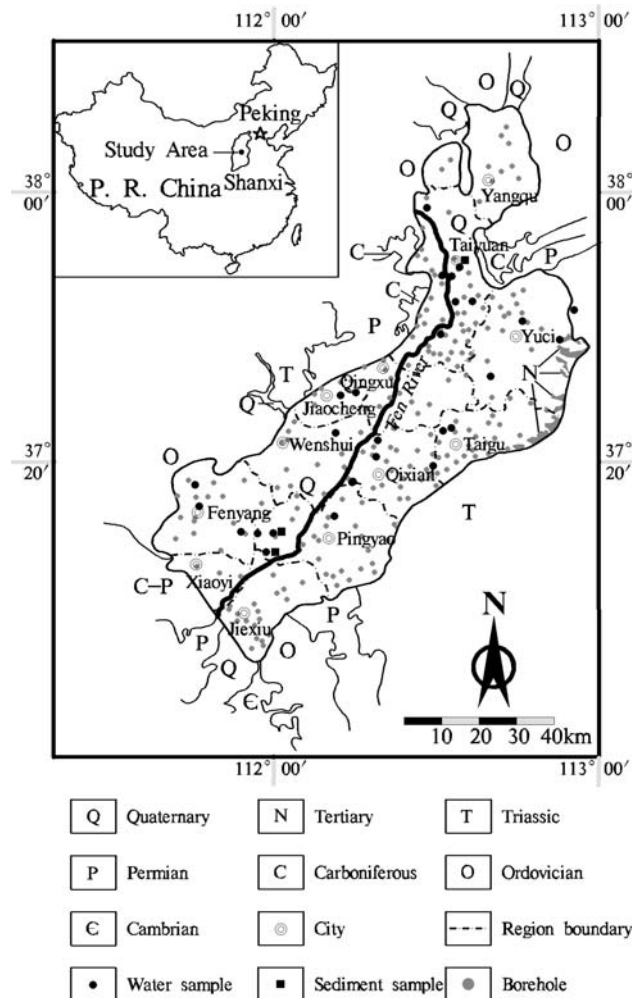


Fig. 1 Simplified geological map and location of groundwater samples, sediment samples, and boreholes

groundwater samples, sediment samples and boreholes (Fig. 1). Water samples were filtered through 0.45 μm membranes on site and collected in a new 350 ml polyethylene bottles. The bottle had been rinsed with deionized water three times before sampling, and reagent-quality HNO₃ was added into it until pH of samples reached one after sampling. The arsenic concentrations of all samples were measured using Hydride generation quartz-tube atomic absorption spectrometry (HG-QTAAS) within 1 week after sampling, and the statistical results of the sample analysis are listed in Table 1.

Five sediment samples were collected in three different places within the basin for determining adsorption coefficients. The sampling locations are shown in the map of location of groundwater samples, sediment samples, and boreholes (Fig. 1).

Mathematical methods

Solute transport simulation

In this study, the solute transport simulations based on one-dimension solute transport software Hydrus1D 2.0 were used to determine the rating values of each index of the vulnerability assessment model. The mass balance equation adopted by Hydrus1D 2.0 was represented as:

$$\frac{\partial \theta c}{\partial t} + \frac{\partial \rho s}{\partial t} = \frac{\partial}{\partial z} \left(\theta D^w \frac{\partial c}{\partial z} \right) - \frac{\partial qc}{\partial z} \tag{1}$$

where *c* and *s* are solute concentrations in the liquid and solid phases respectively, *z* and *t* are depth below the ground surface and time respectively, *D^w* the dispersion coefficient for the liquid phase, *θ* the volumetric moisture content, *ρ* the soil bulk density, and *q* is the volumetric flux density. In the simulations with Hydrus1D, the adsorption-desorption of solutes between the liquid phase and the solid phase should be

taken into account. The relation between them can be described by the isotherm adsorption equation written as:

$$s = \frac{k \times c^\beta}{1 + \eta \times c^\beta} \tag{2}$$

where *c* and *s* are the same to Eq. 1, and *k*, *β*, and *η* are empirical coefficients. When both *β* and *η* equal to zero, Eq. 2 leads to a linear isotherm adsorption, which means the concentration of the solute in the liquid phase and that in the solid phase are related by the linear expression of the form:

$$s = k \times c \tag{3}$$

Thus, combined with Eq. 3, Eq. 1 can be transformed into the following expression:

$$\frac{\partial \theta c}{\partial t} + k \frac{\partial \rho c}{\partial t} = \frac{\partial}{\partial z} \left(\theta D^w \frac{\partial c}{\partial z} \right) - \frac{\partial qc}{\partial z} \tag{4}$$

In this study, Eq. 4 was used as the basic equation for all the simulations.

The procedure for determining the rating values of the model indices is as follows. (1) A series of contaminant transport models were built in Taiyuan basin using Hydrus1D, and each model index, namely each index of the vulnerability assessment model, was used as the parameter of the contaminant transport simulations. (2) The value of each model index accepted as the simulation parameter was increased from a designated value to another, and the corresponding contaminant migration distance was calculated by the simulations. And (3) the rating values of each index were determined on the basis of the regression analysis between model index values and corresponding simulative migration distances of the contaminant.

Statistical analysis

Factor analysis as a statistical method has been widely used to reduce the number of variables and to detect structure in the relationships between variables. In other words, it has been used to classify variables. Suppose a system can be characterized by a group of variables. When factor analysis method is applied, several principal factors can be extracted from all original variables, and the variance contribution ratio of each principal factor that represents its contribution to the total characteristics of the system described by all variables can be calculated.

Factor analysis was applied in this study to calculate the weights of all indices of the vulnerability

Table 1 Statistical result of arsenic concentrations of all groundwater samples

Statistical index	Result
The maximal value of arsenic concentrations (μg/L)	115.50
The minimal value of arsenic concentrations (μg/L)	0.74
The average value of arsenic concentrations (μg/L)	19.18
The number of water samples with arsenic concentration more than 50 μg/L	5
The number of water samples with arsenic concentration less than 50 μg/L	23

assessment model, which reflect their relative importance for the vulnerability assessment result. Greater weight of an index means that it has significant effect on groundwater vulnerability. In this study, the index weights were obtained using the factor analysis method, which is different from conventional overlay and index methods for groundwater vulnerability assessment. For example, the index weights of DRASTIC model were determined based on experience.

In addition, Kriging method was used in the present study as well. As one of the most widely used geostatistical methods, Kriging is a powerful interpolating approach in unbiased estimation of the field variables at a given point. In recent years, various Kriging models had been developed, such as ordinary Kriging, factorial Kriging, and neural Kriging (Rizzo and Dougherty 1994; Goovaerts 1997). The concept of regionalized variable is the basis of Kriging. Many parameters in hydrogeology studies can be regarded as regionalized variables, such as permeability, dissolved component concentration, saturation index, etc., because these parameters not only show random spatial distribution patterns affected by many uncertain local factors, but statistically reflect regional intrinsic processes controlling the evolution of groundwater system (Wang et al. 2001).

In this study, when the groundwater vulnerability assessment to As in Taiyuan basin was performed, the vulnerability scores at 213 boreholes were first calculated. Taking into account that the vulnerability score are influenced by regional hydrological and hydrogeological conditions and can be regarded as regionalized variable, ordinary Kriging was then applied for an unbiased estimate of the spatial variation of the vulnerability score within the whole basin.

Index system of the DRARCH model

Selection of the vulnerability indices

The DRASTIC model (Aller et al. 1987) is the most widely used groundwater vulnerability assessment

model. However, when this model was used for the case study in Taiyuan basin, it was found that some modifications are needed. Some indices of the DRASTIC model are not necessary in this study, and at the same time, no index was included in this model to reflect the intrinsic geochemical properties of sediments in vadose zone related to contaminant transport. A new model, namely the DRARCH model, was therefore proposed by modifying the DRASTIC model.

Three indices of the DRASTIC model, including Depth to the water table, net Recharge, and Hydraulic conductivity of aquifer were kept as the vulnerability index of the DRARCH model. The ground surface elevations over Taiyuan basin have little variation, and consequently the contribution of topography to the groundwater vulnerability is negligible in the study area. The hydraulic conductivity of aquifer has close relation to the type of aquifer sediments, so it is not necessary to have both Hydraulic conductivity of aquifer and Aquifer material in the index system. Therefore, “Topography” and “Aquifer material” were not included in the index system of the DRARCH model.

The index systems of the DRARCH model and the DRASTIC model were compared in Table 2. It can be seen that the DRARCH model is still essentially an intrinsic vulnerability assessment model. In addition to the three original indices, a new index, Ratio of cumulative thickness of clay layers to total thickness of vadose zone, was added into the DRARCH model. The reason for considering this index is that clay has higher specific surface area and adsorption capacity with respect to other sediments, and has significant effect on the leaching potential of contaminants. Another new index, Contaminant adsorption coefficient of sediment in vadose zone, was also introduced to reflect the effect of adsorption behaviors of sediments. It is worth noting that adsorption is one of the most important intrinsic properties of sediments in vadose zone controlling contaminant transport. Besides, the new index, Aquifer thickness, was adopted in the DRARCH model to reflect the capacity of aquifer to dilute contaminants. Generally speaking, thicker aquifer has higher water volume, higher capacity to dilute contaminants in

Table 2 Comparison between the indices of the DRARCH model and those of the DRASTIC model

DRARCH model	DRASTIC model
Index 1: Depth to the water table	Index 1: Depth to the water table
Index 2: Net recharge	Index 2: Net recharge
Index 3: Aquifer thickness	Index 3: Aquifer material
Index 4: Ratio of cumulative thickness of clay layers to total thickness of vadose zone	Index 4: Soil type
Index 5: Contaminant adsorption coefficient of sediment in vadose zone	Index 5: Topography
Index 6: Hydraulic conductivity of aquifer	Index 6: Impact of the vadose zone
	Index 7: Hydraulic Conductivity of aquifer

groundwater, and therefore lower contamination potential. Thus, the index system of the DRARCH model is composed of six vulnerability indices, namely (1) Depth to the water table, (2) net Recharge, (3) Aquifer thickness, (4) Ratio of cumulative thickness of clay layers to total thickness of vadose zone, (5) Contaminant adsorption coefficient of sediment in vadose zone, and (6) Hydraulic conductivity of aquifer.

Source data for the vulnerability indices

Well logging data of 213 boreholes over the basin were collected for groundwater vulnerability assessment. The locations of all boreholes can be seen in the map of location of groundwater samples, sediment samples and boreholes (Fig. 1). The values of the indices Depth to the water table, Aquifer thickness, Ratio of cumulative thickness of clay layers to total thickness of vadose zone, and Hydraulic conductivity of aquifer at each borehole can be obtained from the borehole data.

The values of the index net Recharge in the 12 administrative regions of the basin were calculated using the data of rainfall, rainfall infiltration coefficient and irrigation infiltration coefficient in each region.

Batch experiments were carried out for sediments in the vadose zone (including clay, silty clay, loam sand, silty sand, and fine sand) to get their isothermal adsorption coefficients to as (Table 3). The results indicate that the adsorption behaviors are linear, with the regression coefficients above 0.95 (Fig. 2). The values of the index Contaminant adsorption coefficient of sediment in vadose zone at each borehole were considered as the weighted average adsorption coefficients of sediments, with the weight being the ratio of thickness of one type of sediment to total thickness of sediments in the vadose zone.

Rating values of vulnerability indices

The range between one and ten was imposed on the rating values of each vulnerability index of the

Table 3 Isothermal adsorption coefficients of sediments to As (L/kg)

Type of sediment	Adsorption coefficient
Clay	48.97
Silty clay	29.63
Loam sand	18.02
Silty sand	15.66
Fine sand	14.48

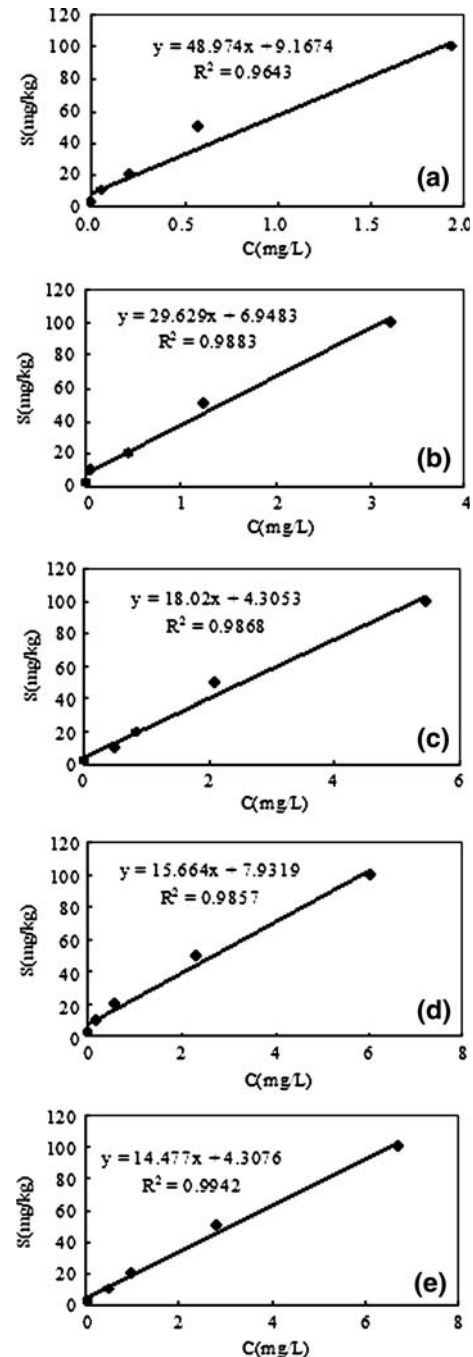


Fig. 2 Arsenic isothermal adsorption lines of sediments: **a** clay, **b** silty clay, **c** loam sand, **d** silty sand, and **e** fine sand

DRARCH model, which is the same to the DRASTIC model. Higher rating value denotes greater vulnerability to arsenic contamination of the groundwater under consideration.

How the rating values of the six vulnerability indices were determined can be seen from the procedure of getting the rating value for the index contaminant adsorption coefficient of sediment in vadose zone. As

described above, a contaminant transport model was built to simulate the effect of adsorption coefficient on contaminant transport. In the simulation process, the adsorption coefficient would increase from 1 to 100 L/kg (note that the adsorption coefficients of all kinds of sediments in Taiyuan basin are within this range according to the batch experiment results in this study), and the corresponding contaminant migration distances can be obtained through the simulation.

In the simulation, the infiltrated water with contaminant was supposed flow from the ground surface to the groundwater level. According to the maximal depth to the groundwater table in Taiyuan basin, the simulated depth of the contaminant transport model was set as 20 m. The simulated time is 3,650 days. The water flux in the upper water flow boundary was considered as the average net recharge within the basin, and the lower water flow boundary condition was set as constant pressure head (the water pressure head equals to 0). The contaminant concentration flux in the upper boundary was supposed to be 1 mg/L, and the lower contaminant transport boundary was supposed as zero gradient. The initial water flow conditions in the form of water content were given as follows. (1) The water content of the soil layer adjacent to the ground surface was supposed to be the residual soil water content, whereas that adjacent to the groundwater level the saturated soil water content. And (2) the water contents of soil layers between the ground surface and the groundwater level were obtained from the linear interpolation between the residual soil water content and the saturated soil water content. The initial contaminant concentrations over the whole simulated area was set as 0 mg/L.

The simulated results were shown in the plot of contaminant migration distance versus isothermal

adsorption coefficient (Fig. 3). It can be seen that the migration distance of contaminant decreases with the increase of the adsorption partition coefficient. When the adsorption coefficient equals to 100 L/kg, the migration distance of contaminant is close to 0. The relation between them can be expressed by the formula $Y = 20.06X^{-0.6419}$ with the regression coefficient of 0.9883 (where X and Y are adsorption coefficient and contaminant migration distance respectively). Thus, the rating value of the adsorption coefficient can be set as 1 as it equals to 100 L/kg, and 10 as 1 L/kg. The rating values in other cases can be obtained by the interpolation between one and ten and were listed in Table 4.

The determination of the rating values of other vulnerability indices is similar to that of the adsorption

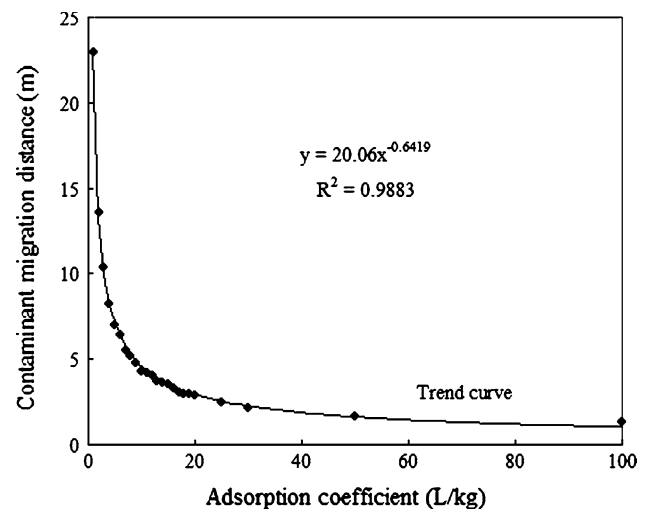


Fig. 3 Plot of contaminant migration distance versus isothermal adsorption coefficient and the trend curve

Table 4 Rating values of the six vulnerability indices of the DRARCH model

Depth to the water table							
Range (m)	0–2	2–5	5–7	7–10	10–12	12–15	>15
Rating	10	9	7	5	3	2	1
Net recharge							
Range (mm)	0–50	50–70	70–80	80–100	100–150	150–200	>200
Rating	1	2	3	4	6	9	10
Aquifer thickness							
Range (m)	0–5	5–15	15–25	25–30	30–50	>50	
Rating	10	9	8	4	2	1	
Ratio of cumulative thickness of clay layers to total thickness of vadose zone							
Range (%)	0–5	5–10	10–20	20–30	30–60	60–100	
Rating	10	8	5	3	2	1	
Contaminant adsorption coefficient of sediment in vadose zone							
Range (L/kg)	0–1	1–2	2–5	5–15	15–30	30–50	>50
Rating	10	9	7	5	3	2	1
Hydraulic conductivity of aquifer							
Range (m/d)	0–5	5–10	10–15	15–20	20–25	>25	
Rating	1	2	4	7	8	10	

coefficient, and the results were listed in Table 4. As mentioned above, the rating values of all assessment indices were acquired by one-dimension solute transport simulation based on the hydrogeological conditions in Taiyuan basin, so the rating values listed in Table 4 are more suitable for assessing the groundwater vulnerability in the basin than any other ratings. However, if the DRARCH model were to be applied in other areas, the different rating values of assessment indices obtained by the solute transport simulations in these assessment areas should be adopted.

Weights of vulnerability indices

The weights of the vulnerability indices mean their relative importance that can be estimated by analyzing the relations among all index values. As mentioned above, factor analysis method was employed in this study. Six vulnerability indices and their values at 213 boreholes within the basin were regarded as variables and cases respectively. The data were standardized and then used for factor analysis.

Four principal factors were extracted, and their variance contribution ratios along with the cumulative variance contribution ratio were listed in Table 5. The cumulative variance contribution ratio of four principal factors is up to 98.56%, implying that the information included in four principal factors is enough to reflect the groundwater vulnerability of the basin. Thus, as the groundwater vulnerability can be depicted by four principal factors, the variance contribution ratio of each principal factor denotes its contribution to the groundwater vulnerability.

Multiple regression analyses were performed between each principal factor as dependant variable and

Table 5 Variance contribution ratios of four principal factors

Principal factor	1	2	3	4
Variance contribution ratio (%)	40.12	20.06	24.09	14.29
Cumulative variance contribution ratio (%)	98.56			

Table 6 Multiple regression coefficients between each principal factor and the six indices of the DRARCH model

Multiple regression coefficients	Index 1	Index 2	Index 3	Index 4	Index 5	Index 6
Principal factor 1	0.0000	0.0000	-3.5793	-2.3808	-0.4030	-0.5934
Principal factor 2	0.0000	-0.7251	-0.1339	0.0000	-5.3977	1.1236
Principal factor 3	-4.6299	0.0000	0.0000	-5.4635	-2.8131	3.0439
Principal factor 4	0.0000	-1.4901	0.0000	9.3828	-0.7294	-5.5071

Indices 1, 2, 3, 4, 5 and 6 are, respectively, Depth to the water table, net Recharge, Aquifer thickness, Ratio of cumulative thickness of clay layers to total thickness of vadose zone, Contaminant adsorption coefficient of sediment in vadose zone, and Hydraulic conductivity of aquifer

all vulnerability indices as independent variables. For four principal factors, four regression models were generated, and the regression coefficients in four models were listed in Table 6. Then, all regression coefficients were regularized. The regularized regression coefficient between certain index and certain principal factor is considered as a parameter to represent the contribution of the former to the latter. The weighted average value of four regression coefficients between certain index and four principal factors can be calculated with four variance contribution ratios as four weight coefficients, and the result is regarded as the contribution of the index to the object characterized by four principal factors, namely the groundwater vulnerability. In other words, the calculated result can represent the weight of the index in the DRARCH model.

Thus, for the six vulnerability indices, six weighted average values were calculated using 24 regression coefficients. Then the series of six weighted average values was transformed into an integral number series, which are used as the weight series of the six indices. The weights of the six indices, following the order in Table 2, are 2, 1, 7, 9, 7, and 5, respectively.

Ranking of vulnerability score

Based on the rating standards and the weights of the model indices, total vulnerability score can be calculated using the following expression:

$$V = \sum_{j=1}^6 W_j \times R_j \tag{5}$$

where V is total vulnerability score, and W_j and R_j are the weight and the rating value of the vulnerability index j respectively ($j = 1, 2, 3, 4, 5,$ and 6 ; the name of the individual index is listed in Table 2). According to the above formula, the calculated vulnerability scores must be within the range between 31 and 310.

Thus, the ranking system of total groundwater vulnerability score can be obtained using arithmetic

average method. The five classes are as follows: very low vulnerability (the vulnerability score is between 31 and 86), low vulnerability (the vulnerability score is between 87 and 142), moderate vulnerability (the vulnerability score is between 143 and 198), high vulnerability (the vulnerability score is between 199 and 254) and very high vulnerability (the vulnerability score is between 255 and 310). The ranking results were summarized in Table 7 as well.

Mapping for groundwater vulnerability to arsenic contamination

After the index system of the DRARCH model along with the rating values and the weights of model indices had been obtained, GIS-based groundwater vulnerability mapping were performed in Taiyuan basin. The total vulnerability score at each borehole were calculated using the formula (5). It should be noticed that the rating values of six vulnerability indices at each borehole could be obtained based on their actual values and their rating standards listed in Table 4.

When the total vulnerability scores at 213 boreholes were obtained, the distribution of groundwater vulnerability scores over the whole basin was interpolated with ordinary Kriging method. Based on the total vulnerability scores and its ranking method, the groundwater vulnerability in Taiyuan basin was divided into five classes. Finally, the map of the groundwater vulnerability to As in the basin was prepared (Fig. 4).

In the map of groundwater vulnerability to As (Fig. 4), it can be noticed that the groundwater vulnerability are generally in high or moderate ranking on the banks of Fen River. In the alluvial plain areas along Fen River, the sediments in vadose zone are mainly composed of alluvial sand, fine sand and silty sand, and the adsorption capacity of these sediments to As is relatively lower, which should be one of the important factors resulting in the high or moderate groundwater vulnerability. In addition, the agricultural irrigations on the banks of Fen River are very intensive, which

Table 7 Ranking system of total groundwater vulnerability score

Vulnerability ranking	Scope of total vulnerability score
Very low	31–86
Low	87–142
Moderate	143–198
High	199–254
Very high	255–310

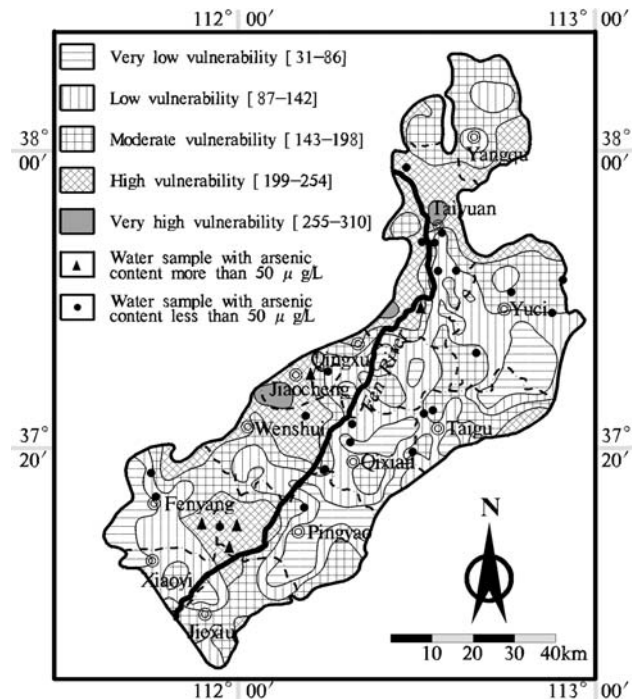


Fig. 4 Map of groundwater vulnerability to As at Taiyuan basin. The figures in the brackets are the vulnerability scores

remarkably increased the net recharge of groundwater and heightened the groundwater level, and in turn has significant contribution to the relative high-groundwater vulnerability to arsenic contamination along Fen River.

It can be also seen from the map of groundwater vulnerability to As (Fig. 4) that the very high and high-vulnerability areas are mainly distributed in Yangqu, Taiyuan, Jiaocheng, Wenshui, Fenyang, and Pingyao, which is generally in accordance with the investigation results of the distribution of high-arsenic concentration groundwater in Taiyuan basin by Jin et al. (2003). Besides, the vulnerability assessment result is also supported by the arsenic concentration measurement for water samples collected in this study. Among 28 water samples collected within the basin, all samples with arsenic concentration more than 50 µg/L are located at the high vulnerability areas, and most samples with arsenic concentration less than 50 µg/L at the moderate, low, and very low-vulnerability areas (Fig. 4). In other words, the vulnerability assessment result has no contradiction with the actual distribution of high-arsenic groundwaters in the basin, and the vulnerability assessment method built in this study is reasonable and reliable. The results of the assessment provide important information for groundwater protection in Taiyuan basin.

Moreover, it should be noted that although the DRARCH model was applied in this study with As as an example, with some minor modifications in the rating values of relative assessment indices, it is applicable for other possible contaminants whose migration in vadose zone is significantly affected by the adsorption of sediments, such as F^- . However, the vulnerability assessment results to As in this study are not representative for the contaminants on which the effect of the adsorption of sediments is negligible, such as Cl^- and NO_3^- , for the DRARCH model was specially designed for the contaminants liable to be adsorbed by sediments. It can be found that in the model, the weights of index 4 and 5 (namely Ratio of cumulative thickness of clay layers to total thickness of vadose zone and Contaminant adsorption coefficient of sediment in vadose zone) that reflect the adsorption capacity of sediments in vadose zone to contaminants are the largest (respectively, 9 and 7).

Conclusions

The arsenic contamination in groundwater was found in some localities of Taiyuan basin, and the DRARCH model for groundwater vulnerability assessment was proposed and applied to map the vulnerability of groundwater to arsenic in the basin. In this model, in addition to natural hydrological and hydrogeological conditions that prevent groundwater from contamination, intrinsic geochemical properties of sediments in vadose zone related to contaminant transport were also taken into account. Thus, the DRARCH model consists of six indices, Depth to the water table, net Recharge, Aquifer thickness, Ratio of cumulative thickness of clay layers to total thickness of vadose zone, Contaminant adsorption coefficient of sediment in vadose zone, and Hydraulic conductivity of aquifer. The rating values and the weights of the six vulnerability indices were determined using contaminant transport simulation and factor analysis method respectively.

Applying the DRARCH model, the groundwater vulnerability to As in Taiyuan basin was mapped and divided into five vulnerability rankings. The very high and high-vulnerability areas are mainly distributed in Yangqu, Taiyuan, Jiaocheng, Wenshui, Fenyang, and Pingyao, which, matches well with the distribution of high-arsenic groundwaters in the basin.

As the capital of Shanxi province, northern China, Taiyuan City is densely populated and highly industrialized. However, the city is located in a high groundwater vulnerability area according to the vulnerability

assessment results. Therefore, groundwater environment managements should be strengthened in the city to prevent from further arsenic contamination. For the same reason, the groundwater protection should be carried out in other regions with high-groundwater vulnerability to As, such as Wenshui, Jiaocheng, and Pingyao.

Acknowledgments The research work was financially supported by National Natural Science Foundation of China (Grant for outstanding young scholars, No. 40425001), China Geological Survey (No. CGS-200310400009) and the Research Foundation for Outstanding Young Teachers, China University of Geosciences (Wuhan) (No. CUGQNL0619). The manuscript greatly benefited from the helpful comments from two anonymous reviewers.

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