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ORIGINAL ARTICLE

DRAV model and its application in assessing groundwater vulnerability in arid area: a case study of pore phreatic water in Tarim Basin, Xinjiang, Northwest China

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Abstract According to the characteristics of groundwater in arid area, this paper proposes DRAV model for groundwater vulnerability assessment, where *D* is groundwater depth, *R* is the net recharge of aquifer, *A* is the aquifer characteristics, and *V* is the lithology of vadose zone. As a case study, the paper assesses the vulnerability of pore phreatic water in Tarim Basin of Xinjiang, China by using the DRAV model. The results indicate that the areas of phreatic water with vulnerability index ranges of 2–4, 4–6, 6–8 and >8 accounting for 10.1, 80.4, 9.2 and 0.2% of the total plain area of the Tarim Basin respectively, and the areas with the latter two vulnerability ranges (6–8 and >8) are mainly located in the irrigation districts with thin soil layer (20–30 cm thick surface soil of vadose zone, mainly with underlying sandy gravel) and with silty and fine sand layer. Such vadose zone generally lacks sandy loam and clayey soil and has larger recharge by infiltration of irrigation water.

Keywords Groundwater · Vulnerability · DRAV model · Tarim Basin

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Introduction

Study of groundwater vulnerability is of great significance in protecting groundwater environment and ensuring sustainable groundwater utilization. In accordance with the objects to be assessed, assessment of groundwater vulnerability can be divided into assessment of intrinsic vulnerability of aquifers (i.e. assessment of intrinsic vulnerability) and assessment of specific vulnerability of aquifers for certain pollutant(s) (i.e. assessment of specific vulnerability). Assessment of intrinsic vulnerability specifies the pollution resistance capacity to natural conditions, including geological, hydrological and hydro-geological conditions, to pollution caused by human activities without the consideration of the hydrogeochemical features of the pollutant(s), while assessment of specific vulnerability aims at assessing the sensitivity of aquifers to a certain pollutant or a group of pollutants with consideration of the certain pollutant or the group of the pollutants and its/their interaction with various factors of the intrinsic vulnerability.

There is rapid development of groundwater vulnerability assessment in past 10 years, as well as the introduction of various new techniques and methods applied to the assessment. GIS techniques have been becoming the most commonly used platform for assessment of groundwater vulnerability (Meinardi et al.1995; Secunda et al.1998; Lasserrea et al.1999; Al-Adamat et al. 2003; Lake et al. 2003; Thapinta and Hudak 2003) along with the use of remote sensing techniques (Zhong et al. 2008), random theory (Soutter and Musy 1998), statistical method (Burkart et al. 1999; Worrall et al. 2002), environmental isotope and water chemistry method (Sadek and El-Samie 2001), and fuzzy mathematical method (Zhou et al. 2004). In China, since Yang and Luan (1999) assessed groundwater vulnerability in the coastal area of Dalian City, Liaoning province using DRASTIC model, most of the studies have put emphasis particularly on intrinsic assessment (Yang and Luan 1999; Ma 2001; Ma et al. 2000; Jiang and Zhu 2001; Lei and Zhang 2003; Jiang 2002). Wang et al. (2004) assessed vulnerability of shallow groundwater system in Datong Basin of Shanxi province, China to arsenic and cadmium by using improved migration capacity index model, and Guo et al. (2007) assessed specific vulnerability of groundwater in Taiyuan Basin, Shanxi province, China to arsenical pollution using DRARCH model.

Located in the arid area of northwestern China, Tarim Basin of Xinjiang is an important oil, natural gas, and cotton production base, and pore phreatic water resources in the basin are the most important water source for home, industrial and agricultural purposes. However, along with exploitation of oil and natural gas resources, development of transportation, construction of cities and towns and expansion of agricultural production, pore phreatic water in the basin has been polluted in some areas. In order to strengthen groundwater resources management, it is necessary to conduct assessment of groundwater vulnerability in the basin by using suitable assessment model and taking into account the characteristics of groundwater in the arid area.

General description of the study area

Tarim Basin is the biggest arid inland basin in China, covering an area of 103.74×10^4 km^2. It is surrounded by high mountains. With Kunlun Mountains in the south and Tianshan Mountains in the north, it is a large basin characterized by developed inland centripetal water systems, including rivers that originate from the Kunlun and Tianshan mountains and flow to the basin, though most of which dissipate at the front edge of the oases located in the peripheral areas. The basin consists of piedmont gravel plain, fine soil plain and Takla Makan Desert.

In Tarim Basin, there exist pore phreatic water and pore confined water in Quaternary unconsolidated sediments. In the piedmont plain area at the northern foot of Kunlun Mountains, there is mainly phreatic water; apart from phreatic water existing in the Kashgar plain, confined water is also found in some local areas of the plain. In the piedmont plain area at the southern foot of Tianshan Mountains, there is mainly phreatic water (Dong et al. 2005).

Features of storage and distribution of pore phreatic water in Tarim Basin

At the southern foot of Tianshan Mountains and at the northern foot of Kunlun Mountains, changes of storage and distribution of groundwater from the piedmont gobi-gravel zone to the fine soil plain at the downstream of the overflow zone follow similar laws, and the features of groundwater storage and distribution are typical and representative in arid area.

Piedmont gobi-gravel zone has merely phreatic water. Its aquifers are made mainly of sand-gravels and characterized by big thickness, good replenishment conditions, and bigger unit yield, with unit well yield ranging from 3,000 to 5,000 m^3/day. Because of steep slope and good groundwater runoff conditions, the mineral concentration of groundwater in such zone is mostly less than 1 g/L. But in some small watersheds of the eastern and southern parts of the basin, the mineral concentration of groundwater ranges from 1 to 3 g/L due to poor water quality of the rivers flowing out off the mountain passes.

In the overflow zone and its downstream alluvial and diluvial plain, the aquifers are multilayers, with the upper part consisting of a layer of phreatic aquifer and lower part consisting of one layer or several layers of confined aquifers. Such phreatic aquifer is mainly made of silty sands and fine sands, with uneven storativity in various locations and unit well yield of 100–1,000 m^3/day. TDS of phreatic water in the overflow zone is averagely 1–3 g/L. In the downstream fine soil plain, due to strong evaporation and poor groundwater runoff conditions, groundwater level becomes higher and TDS of phreatic water rises to 3–50 g/L and even higher in some places, resulting in serious ground surface salt accumulation and thus large area of salinized soil.

Pore water in the alluvial plain of Tarim River

Aksu River, Yerqiang River, and Hotan River converge at Xiaoxiake and form Tarim River. The alluvial plain of Tarim River is a low-lying, gently sloping strip-shaped plain stretching from the east to the west in between Takla Makan Desert and the alluvial and diluvial plain at the northern foot of Tianshan Mountains, mainly with phreatic water distribution.

According to the previously conducted surveys and investigations, groundwater in the plain is mainly recharged by Tarim River, and a fresh water zone of certain scale is formed at the bottom of the riverbed and along the riverbanks, with TDS between 0.5 and 1.5 g/L. The fresh water zone is normally 50–100 m deep from the ground surface and, due to differences of geological and hydro-geological conditions in places along the riverbanks, its width varies from one place to another. But fresh phreatic water zone can always be found at the bottom of the river bed and at its periphery exists phreatic water or confined water in some places, both having higher TDS of 5–10 g/L.

Table 1 Weights of indexes in DRAV model

Assessment indexes	Groundwater depth (*D*)	Net recharge to the aquifers (*R*)	Aquifer characteristics (*A*)	Lithology of vadose zone (*V*)
Aller et al. (1987)	0.227	0.182	0.273	0.318
Ibe and Nwankwor (2001)	0.227	0.137	0.318	0.318
Dixon (2005)	0.217	0.174	0.217	0.391
Bukowski et al. (2006)	0.136	0.182	0.296	0.386
Panagopoulos et al. (2006)	0.261	0.087	0.435	0.217
Nobre et al. (2007)	0.313	0.188	0.313	0.188
Guo et al. (2007)	0.065	0.032	0.387	0.516
Kourosh et al. (2008)	0.144	0.225	0.260	0.371
Present study	0.20	0.15	0.31	0.34

Methods used in the study

GOD method and DRASTIC model are the two vulnerability assessment methods presented at an earlier time but still widely used now.

GOD method for groundwater vulnerability assessment was first put forward by Foster (1987). It is an experiential system, simple in assessment process but practical in use. It mainly considers three indexes, including groundwater status (*G*), overburden feature (*O*) and groundwater depth (*D*), of which 'groundwater status' refers to various types of groundwater such as unconfined water, semi-confined water or confined water, etc., 'overburden feature' refers to concretion status and lithologic character of the overburden. GOD index is the arithmetic product of scores of the three indexes. Each of the scores is below 1.

Based on indexes' system, DRASTIC model is the earliest groundwater vulnerability assessment model developed by Aller et al. (1987) for Environmental Protection Agency (EPA) of United States, and was used in groundwater vulnerability assessment in 40 counties or districts in Colombia and Wyoming State of the US. It is also adopted by Canada, South Africa and other countries. DRASTIC method involves seven indexes of groundwater depth, net recharge to the aquifers, aquifer medium, soil medium, topography, vadose zone, and hydraulic conductivity.

Considering that under conditions of natural rainfall and artificial irrigation, generally there will not be horizontal runoffs in arid area, Index *T* (topographical) in the DRASTIC model can be abnegated, and Index *A* (aquifer) that reflects factors of aquifer type, lithology and conductivity can be used to comprehensively represent status of groundwater (*G*) and overburden (*O*) in GOD model and aquifer medium (*A*) and hydraulic conductivity (*C*) in the DRASTIC model. Meanwhile, since soil is on the top of the vadose zone, Index *V* (lithology of vadose zone) can fully reflect impact of soil medium (Index *S* in the DRASTIC model) on groundwater vulnerability. Therefore, based on GOD method and DRASTIC model for groundwater vulnerability assessment and in line with the Guidelines on Groundwater Resources Mapping (Chen et al. 2001), DRAV model based on four indexes of *D* (groundwater depth), *R* (net recharge of aquifer), *A* (aquifer characteristics) and *V* (lithology of vadose zone) can be used to assess the vulnerability of groundwater in arid area. To each of the four indexes, corresponding weight will be assigned in accordance with the significance of its impact on groundwater vulnerability. At present, there is neither unified method for assessment of groundwater vulnerability, nor unified standards for the assessment (Huang et al. 2005). To comply with the principles of universality, intelligibility, and readability, comprehensive assessment method is used in this study to assessment groundwater vulnerability in arid area, and the vulnerability comprehensive assessment index VI_i is the weighted sum of the above-mentioned four indexes, as calculated using the following formula:

$$\mathrm{VI}_i = \sum_{j=1}^{4} (W_{ij} R_{ij}) \tag{1}$$

where VI_i is the comprehensive assessment index of *i*th sub-system of the groundwater vulnerability system; W_{ij} is the weight of the *j*th comprehensive assessment Index of the *i*th sub-system, and

$$\sum_{j=1}^{4} W_{ij} = 1\,; \tag{2}$$

R_{ij} is the value of the *j*th assessment Index of the *i*th sub-system; m is the quantity of indexes, and $m = 4$

The smaller the VI_i is, the lower the vulnerability of the groundwater system and the better the stability and self-recovery capability of groundwater system will be. Contrarily, the bigger the VI_i is the higher the vulnerability of the groundwater system and the poorer the stability and self-

Table 2 Vulnerability scores of groundwater depth

	Groundwater depth (m)						
	≤1	1–3	3–6	6–10	10–30	>30	Total
Scores	10	7	5	3	2	1	
Weighted scores	2	1.4	1	0.6	0.4	0.2	
Area (km^2)	759	50,227	65,616	100,755	31,925	43,611	292,894
Area (%)	0.3	17.1	22.4	34.4	10.9	14.9	100.0

Table 3 Vulnerability scores of net recharge

	Recharge modules ($\times 10^4$m^3/km^2/area)						
	<5	5–10	10–20	20–30	30–50	>50	Total
Scores	1	2	4	6	8	10	
Weighted scores	0.15	0.3	0.6	0.9	1.2	1.5	
Area (km^2)	232,747	16,945	9,856	6,775	14,316	12,254	292,894
Area (%)	79.5	5.8	3.4	2.3	4.9	4.2	100.0

recovery capability of groundwater system. Groundwater vulnerability zoning can be conducted with the comprehensive assessment index VI$_i$, and bigger VI$_i$ indicates higher vulnerability of the groundwater system. According to the commonly used numerical grading method in assessment, groundwater vulnerability assessment uses equally spaced grades, i.e. five grades including extremely low vulnerability, low vulnerability, medium vulnerability, high vulnerability, and extremely high vulnerability.

Definition of weights of indexes

In assessing groundwater vulnerability, generally five to seven indexes are used by various researchers. In the DRAV model, those five to seven indexes are integrated into four indexes of *D* (groundwater depth), *R* (net recharge of aquifer), *A* (aquifer characteristics) and *V* (lithology of vadose zone) and normalized to get the corresponding weights, as shown in Table 1.

Based on the above, in the DRAV model, the normalized weights of indexes such as *D*, *R*, *A* and *V* are taken as the arithmetic averages of the above-mentioned corresponding normalized weights, or 0.20, 0.15, 0.31 and 0.34, respectively, as shown in Table 1. Such results are consistent with the long-term working experience of the authors and colleagues in groundwater development and protection in the arid area, in Xinjiang, China.

Scores of groundwater vulnerability

Groundwater depth (*D*)

Depth of groundwater determines the contact time of pollutants with vadose medium and controls various hydrogeochemical and physicochemical processes the pollutants undergo before reaching the aquifers, therefore, it is closely related to the possibility of pollutants' entering into the

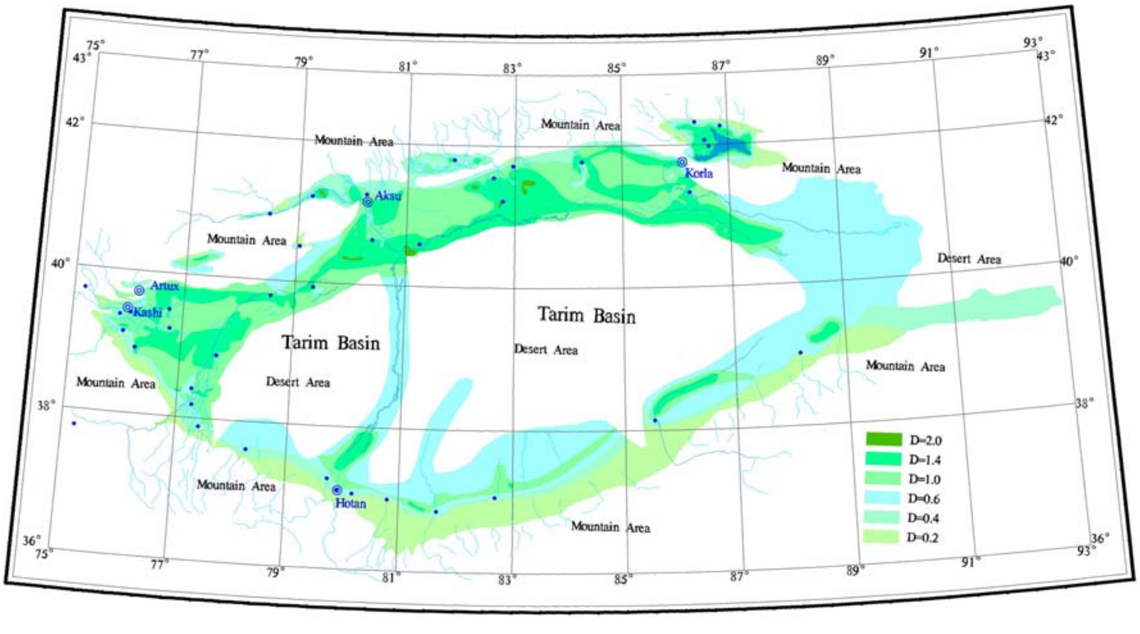

Fig. 1 Vulnerability scores of groundwater depth

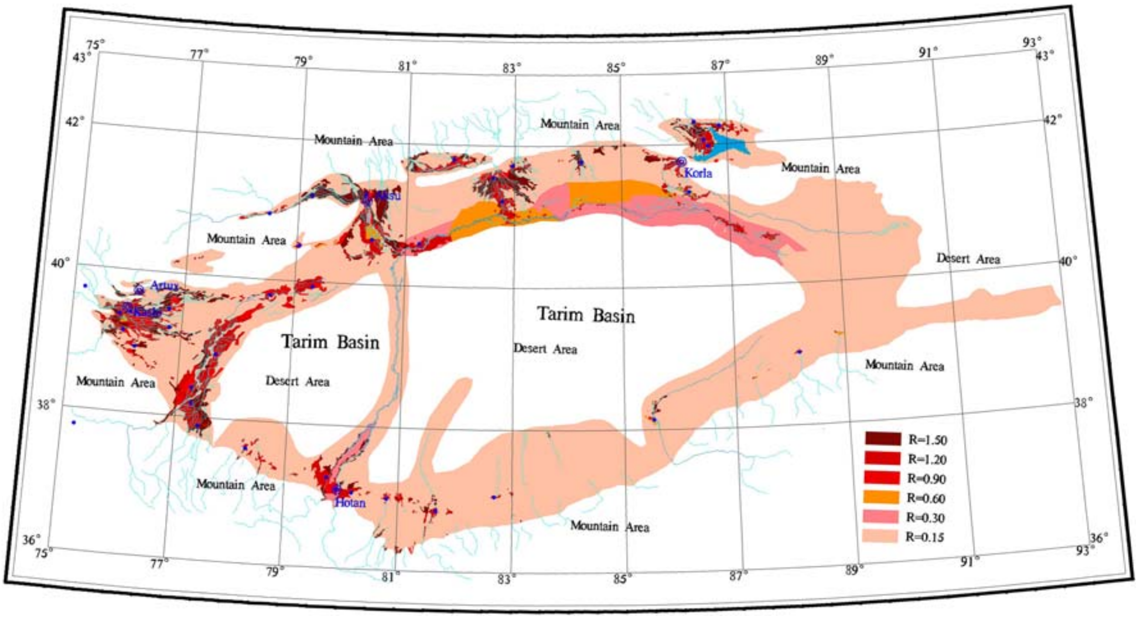

Fig. 2 Vulnerability scores of net recharge

Table 4 Vulnerability scores of aquifer characteristics

	Storativity (m^3/day/m)					
	≤2	2–20	20–200	200–1,000	>1,000	Total
Scores	1	3	5	7	10	
Weighted scores	0.31	0.93	1.55	2.17	3.1	
Area/km^2	30,504	84,729	143,107	31,784	2,769	292,894
% of Area	10.4	28.9	48.9	10.9	0.9	100

groundwater system. Generally, the deeper the groundwater, the longer the time it takes for the surface pollutants' to reach the aquifers and the greater the possibility for the pollutants' dilution, adsorption, and degradation in the process of transmission, and hence the smaller the chances for the pollutants to reach groundwater system and the lower the groundwater vulnerability.

According to Dong et al. (2005), there is a big variation of pore phreatic water depth in Tarim Basin and phreatic water is deeper at the edge of the basin, normally more than 30 m, while in the center of the basin, the depth is normally less than 3–6 m. In line with the grading principle of DRAV model (Table 2), vulnerability scores of groundwater depth in Tarim Basin are set as between 1 and 10, and the weighted scores are between 0.2 and 2.0, as shown in Table 2 and Fig. 1.

Net recharge to aquifers (*R*)

In the DRAV model, net recharge refers to the amount of vertical water infiltration per unit area of the ground surface. Recharge water is the major carrier of pollutants to aquifers. It not only vertically transmits pollutants in vadose zone, but also controls the dispersion and dilution of the pollutants in vadose zone and aquifers. As a result, the more the net charge is, the greater the possibility of groundwater pollution will be. However, when net recharge reaches an amount that it can dilute the pollutants, the possibility of groundwater pollution will become less.

According to Dong et al. (2005), the net recharge in Tarim Basin includes mainly three parts, surface irrigation seepage, groundwater seepage and rainfall infiltration. The net recharge in the plain area is normally less than 300 mm/a, with which it is impossible to dilute pollutants. Based on the grading principle of DRAV model (Table 3), vulnerability scores of the net recharge of phreatic water in Tarim Basin are set between 1 and 10, and the weighted scores are between 0.15 and 1.5, as shown in Table 3 and Fig. 2.

Aquifer characteristics (*A*)

Groundwater flow controls the transmission route of the pollutants, while aquifer characteristics (i.e. medium type of aquifer or hydraulic conductivity or unit yield) have profound impact on groundwater seepage route. For a specific type of aquifer, bigger hydraulic conductivity is, bigger unit yield (units of m^3/day/m) is. There is a good consistency between hydraulic conductivity and unit yield. In general, unit yield zoning map of groundwater is one of the hydrogeological survey maps of the watershed or region at different scales, so the unit yield can be used as a

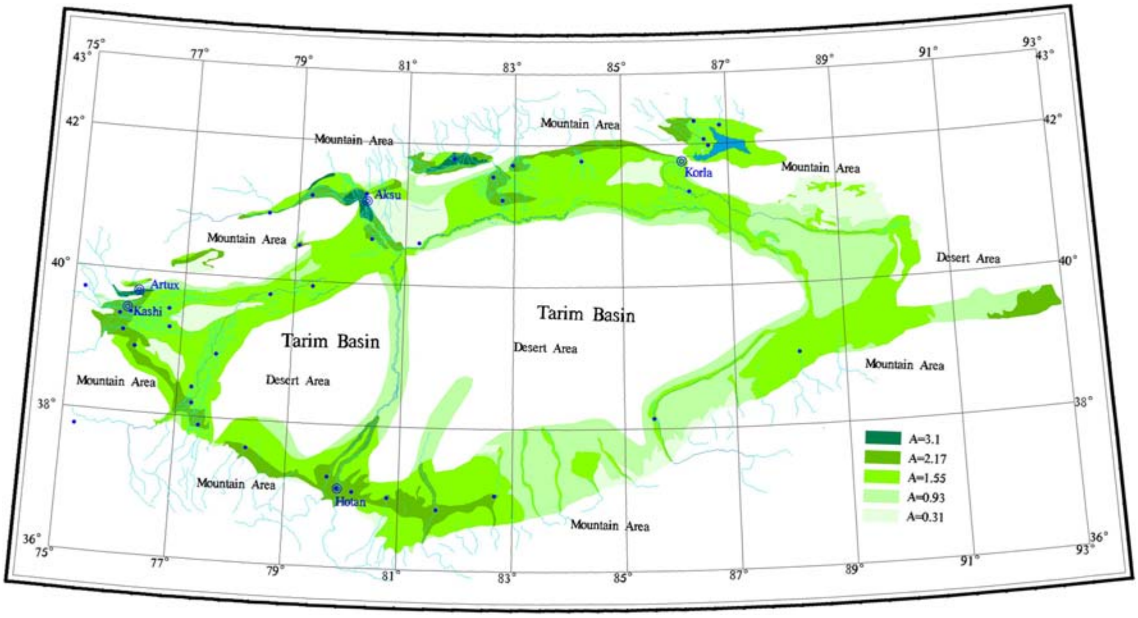

Fig. 3 Vulnerability scores of aquifer characteristics

Table 5 Vulnerability scores of lithology of vadose zone

	Lithology of vadose zone				
	Sandy gravel	Silty and fine sand	Sandy loam	Sandy clay	Total
Scores	10	7	4	2	
Weighted scores	3.4	2.38	1.36	0.68	
Area (km^2)	58,261	206,920	23,292	4,421	292,894
Area (%)	19.9	70.6	8	1.5	100

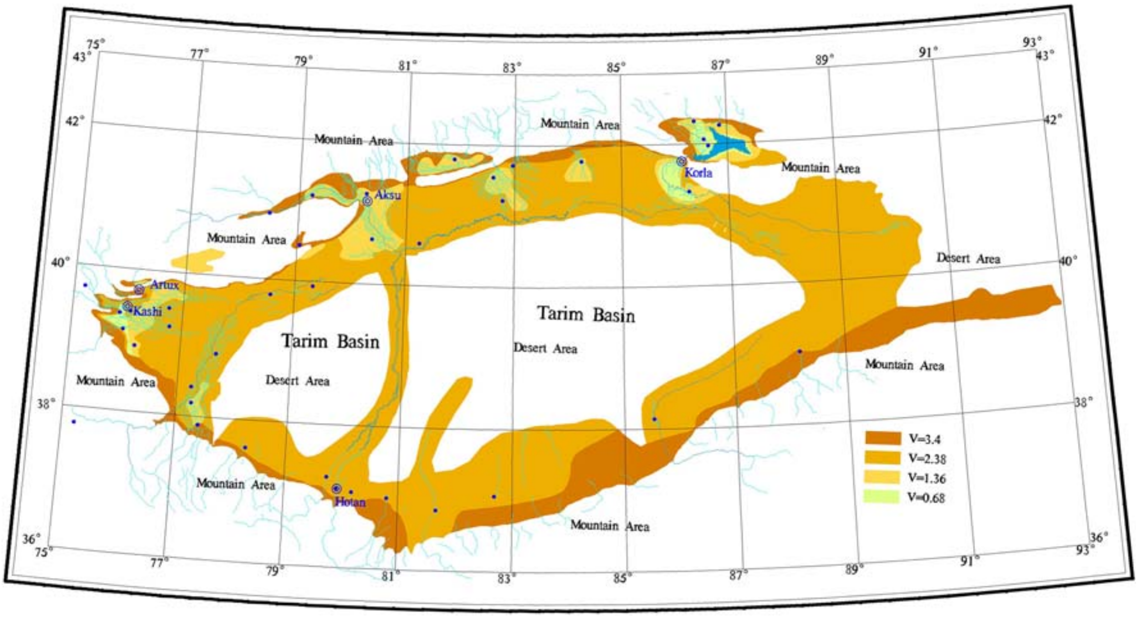

Fig. 4 Vulnerability scores of vadose zone

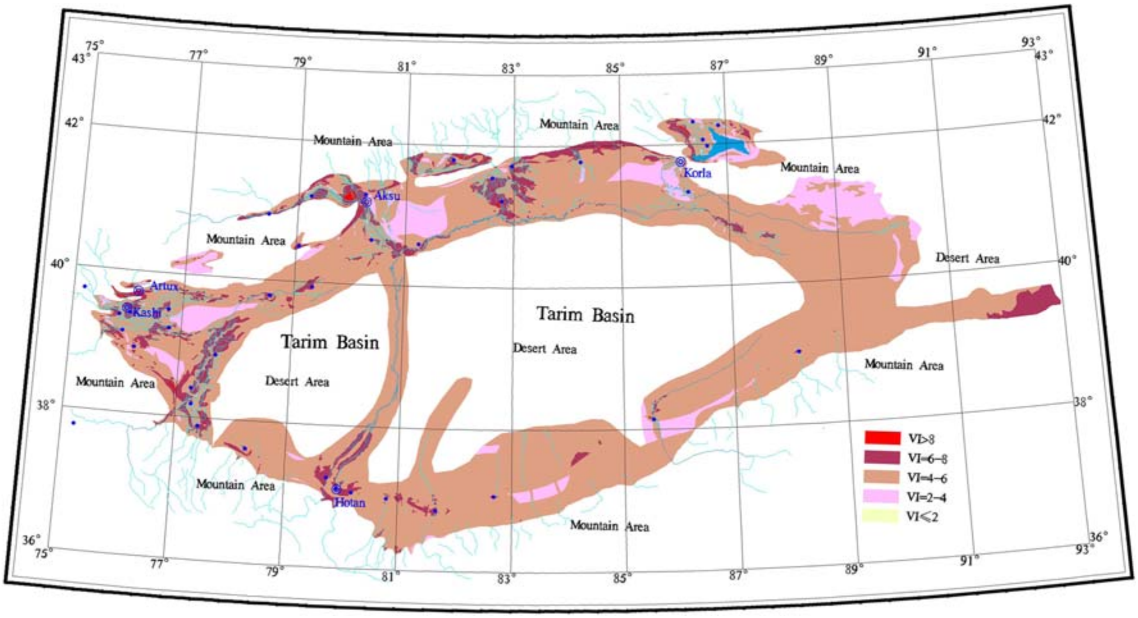

Fig. 5 Sketch map of vulnerability of phreatic water

Table 6 Grading of vulnerability of phreatic water

	VI_i					
	>8	6–8	4–6	2–4	≤2	Total
Vulnerability status	Extremely high vulnerability	High vulnerability	Medium vulnerability	Low vulnerability	Extremely low vulnerability	
Area (km^2)	707	26,991	235,582	29,613	0	292,894
Area (%)	0.2	9.2	80.4	10.1	0	100

comprehensive reflection of the indicators of aquifer characteristics. Bigger unit yield is weaker degradation capacity of the aquifer media, longer seepage route of the pollutants and higher sensitivity of groundwater to pollution. Therefore, aquifer characteristics are of great importance in assessment of groundwater vulnerability.

In this study, Groundwater Unit Yield Zoning Map of Xinjiang (1:1,500,000) (Bureau of Geology and Mineral Resources Exploration of Xinjiang, 2005) is used. The unit yield of phreatic water in the plain area of Tarim Basin is divided into five grades. According to the grading principle of DRAV model (Table 4), vulnerability scores of aquifer characteristics of phreatic water in Tarim Basin are set between 1 and 10, and the weighted scores are between 0.31 and 3.1, as shown in Table 4 and Fig. 3.

Lithology of vadose zone (*V*)

Lithology of vadose zone controls various physico-chemical processes (such as degradation, adsorption, deposition, complexation, neutralization, and biological degradation) of seepage water in the vadose zone. The smaller the medium particle is, the smaller the amount of pollutants reaching aquifer and thus the lower the vulnerability of groundwater. According to the size of particle, lithology of vadose zone can be divided into pebbles, gravel, coarse sand, medium sand, fine sand, silt, loam, sandy clay, and clay. For the phreatic water aquifer, when there is multiple layers of media, the group of medium with thickest layer, or the group with finest particles and thickest layer should be selected as medium of vadose zone.

According to Dong et al. (2005), silt and fine sand, sandy gravel, sandy loam and sandy clay are the major media in the vadose zone of phreatic water aquifer areas in the plain of Tarim Basin. According to the grading principle of DRAV model (Table 5), vulnerability scores of lithology of vadose zone in Tarim Basin are set between 1 and 10, and the weighted scores are between 0.34 and 3.4, as shown in Table 5 and Fig. 4.

Determination of vulnerability indexes

After obtained the scores of the four indexes included in the DRAV model, GIS platform is used to overlap the four figures and prepare the zoning map of pore water in Tarim Basin (Fig. 5), totally 5,001 delineations are obtained with vulnerability indexes ranging from 2.14 to 9.4. In Fig. 5, totally five ranges (≤2, 2–4, 4–6, 6–8 and >8) of vulnerability scores are defined for the groundwater in Tarim Basin, as shown in Table 6. It should be noted that such equal spacing grading of vulnerability is helpful to understand the relative degree (Jiang and Guo 2008) of vulnerability of groundwater in various areas.

Conclusions and recommendations

Results of this study (Fig. 5) explicate feasibility of use of DRAV model in assessing the intrinsic vulnerability of groundwater in arid area represented by Tarim Basin of Xinjiang:

1. Areas of phreatic water with vulnerability index ranges of 2–4, 4–6, 6–8 and >8 account for 10.1, 80.4, 9.2 and 0.2 of the total plain area of Tarim Basin, respectively.
2. Areas with the latter two vulnerability ranges (6–8 and >8), with relatively higher vulnerability, are mainly located in the irrigation districts with thin soil layer (20–30 cm surface soil and with underlying sandy gravel) and with silt and fine sand layer. It generally lacks sandy loam and clayey soil and has larger recharge by seepage of irrigation water.
3. In the plain area of Tarim Basin, phreatic water with low vulnerability is mainly located in the non-irrigation areas with sandy loam and clayey soil layers. Because of the thick layers of low-permeability soils in the vadose zone, almost no seepage of irrigation water occurs in those areas, while recharge by precipitation is extremely limited there.

While conducting groundwater environmental protection in Tarim Basin, principles of “prevention first and combination of prevention and control” should be maintained. Industrial layout and irrigation planning should exclude areas with high groundwater vulnerability, so as to reduce pollution to groundwater caused be some improper planning; seepage/leakage prevention measures should be well planned and applied if underground natural gas pipes and/or oil delivery pipes pass through areas of high groundwater vulnerability; environmental protection needs to be well implemented in oil exploration and production areas with high groundwater vulnerability. Irrigation areas with high groundwater vulnerability should actively encourage the use of efficient water saving irrigation techniques (such as drip irrigation beneath the agricultural membrane, etc.), to reduce infiltration seepage of irrigation water and reduce or avoid deep seepage of water and fertilizers.

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