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ORIGINAL ARTICLE

A GIS-based DRASTIC model for assessing shallow groundwater vulnerability in the Zhangye Basin, northwestern China

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Abstract Groundwater vulnerability is a cornerstone in evaluating the risk of groundwater contamination and developing management options to preserve the quality of groundwater. Based on the professional model (DRASTIC model) and geographical information system (GIS) techniques, this paper carries out the shallow groundwater vulnerability assessment in the Zhangye Basin. The DRASTIC model uses seven environmental parameters (depth to water, net recharge, aquifer media, soil media, topography, impact of vadose zone, and hydraulic conductivity) to characterize the hydrogeological setting and evaluate aquifer vulnerability. According to the results of the shallow groundwater vulnerability assessment, the Zhangye Basin can be divided into three zones: low groundwater vulnerability risk zone (risk index <120); middle groundwater vulnerability risk zone (risk indexes 120–140) and high risk zone (risk index >140). Under the natural conditions, the middle and high groundwater vulnerability risk zones of the Zhangye Basin are mainly located in the groundwater recharge zones and the important cities. The high, middle and low groundwater vulnerability risk zones of the Zhangye Basin cover around 17, 21 and 62% of study area, respectively.

Keywords Vulnerability · Shallow groundwater · DRASTIC · GIS · Zhangye Basin · Northwestern China

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Introduction

Groundwater has been considered as an important source of water supply due to its relatively low susceptibility to pollution in comparison to surface water, and its large storage capacity (US EPA 1985). The quality of groundwater is generally under a considerable potential of contamination especially in agriculture-dominated areas with intense activities that involve the use of fertilizers and pesticides. The issue of protection of groundwater against pollution is of crucial significance. Groundwater vulnerability is a cornerstone in evaluating the risk of groundwater contamination and developing management options to preserve the quality of groundwater. Vulnerability assessment has been recognized for its ability to delineate areas that are more easily to be contaminated than others as a result of anthropogenic activities on/or near the earth's surface.

Zhangye Basin, located in the middle reaches of the Heihe River (Fig. 1), is an important agricultural and industrial center (Wang and Gao 2002). For the last few decades, surface water has been the main water supply for these industries. However, water demands have increased and groundwater is now used as a secondary source. The annual exploitation yield of groundwater was only 0.39×10^8 m^3 during the 1970s, and it became 2.17×10^8 m^3 in 1999. Due to excessive use of surface water and excessive abstraction of groundwater, local springs have dried up and water levels have been significantly lowered. The quality of groundwater has also been affected by over abstraction (Wang et al. 1999; Tang and Zhang 2001; Ding and Zhang 2002).Groundwater of the Zhangye Basin has encountered high nitrate concentration that exceeds 49 mg/l (Wen et al. 2007).

To ensure this aquifer to be a water source for the Zhangye Basin, it is necessary to estimate which locations in this groundwater basin are more susceptible to receive and transport pollutions. The main objective of this paper is to assess groundwater vulnerability to pollution in a shallow aquifer using the DRASTIC model and geographical information system (GIS) techniques in combination with hydro-geological data layers i.e. depth of water, net recharge, aquifer media, soil media, topography, impact of vadose zone and hydraulic conductivity.

Study area

The Heihe River in north-western China is one of the largest inland rivers in China, covering an area of 13×10^4 km^2. Its source is in the Qilian Mountains (Qinghai Province), it flows through the Zhangye basin (Gansu Province), and the lower reaches (also known as the Ejina Basin) are in the inner Mongolia Autonomous Region (Fig. 1). The Zhangye Basin itself covers an area of 1.08×10^4 km^2, extending from 38°30′–39°50′N and 99°10′–100°52′E, and including Zhangye City, Linze County and Gaotai County (Fig. 1), neighboring Shandan to the east and Yanchi to the west. The area has an arid continental climate with a mean annual temperature of 3–7°C. The average annual precipitation ranges from 50 to 150 mm, with the majority ($\sim$80%) falling from June to September. The average annual potential evaporation is 2,000–2,200 mm (Gao 1991).

Hydrogeology

The hydrogeological setting of the Zhangye basin has been outlined by Fan (1981) and Chen (1997), varying from south to north. The southern part of the basin is an area of extensive faulting, underlain by bedrock. Down-faulted bedrock (pediments) extends toward the northeast, overlain by Quaternary sediments. The uplift of the Qilian Mountains caused the accumulation of several thousand meters of alluvial fan and fluvial deposits in a north-south trending basin, and filled with large volumes of unconsolidated Quaternary sediments, to depths of 300–500 m (Fig. 2). The Zhangye basins can be divided into discrete geomorphologic units, including piedmont alluvial plain, alluvial plain, and desert. The sediments in the basins from south to north gradually change from coarse-grained gravel to medium and fine-grained sand and silt. These sediments along with aeolian and lacustrine deposits form the main aquifers. In the southern part of Zhangye basin, the aquifer is formed from highly permeable cobble and gravel deposits with a thickness of 300–500 m. From the northern edge of this diluvial fan, the aquifer becomes confined or semi-confined, with a thickness of 100–200 m, comprising interbedded cobble, gravel, fine sand and clay. Further north, the groundwater table becomes shallow (Fig. 2). A NW–SE thrust fault along the foot of the Qilian Mountains, it is difficult for groundwater to flow from the mountains into the basin laterally (Fan 1981; Chen 1997).The rivers originating from the Qilian Mountains are the main recharge source for these aquifers, under natural conditions, more than 70% of the surface water infiltrates into

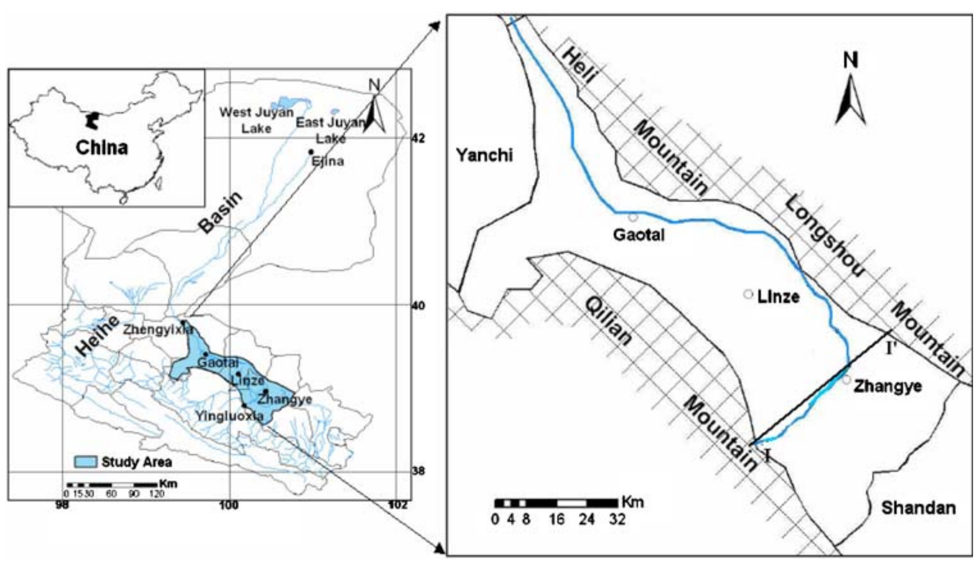

Fig. 1 Location map of study area

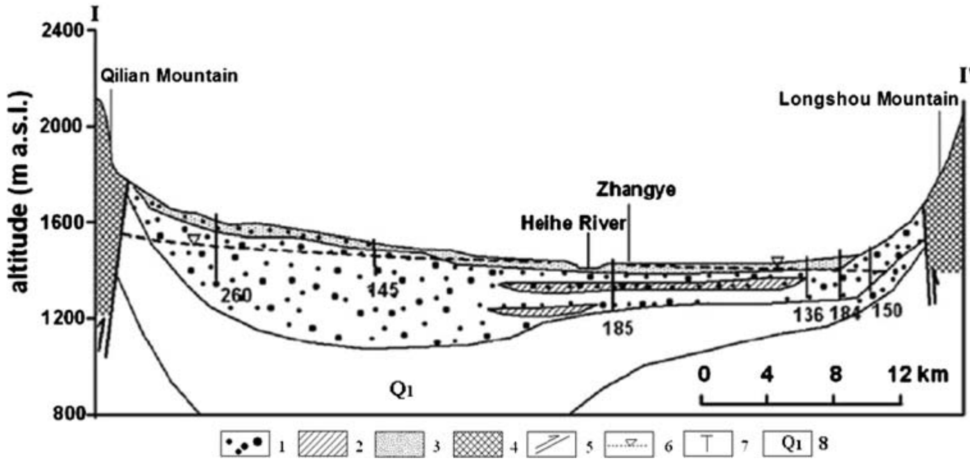

Fig. 2 Hydrogeological cross section along transect I–I′ indicated in Fig. 1 (after Chen et al. 2006). *1* Gravel, *2* clay, *3* sand, *4* base rock, *5* fault line, *6* groundwater table, *7* borehole and depth, *8* pleistocene sediments

the aquifer. Groundwater in the basin generally flows from the piedmont area towards the centre of the basin (Fig. 3). As the Longshou Mountains act as a barrier to groundwater flow, groundwater discharges at the middle and north part of this sub-basin by upward seepage and springs. The depths to the water table range from 50–200 m in the upper alluvial fan to 3–5 m in the north part of the floodplain.

Methods

A DRASTIC model applied in a GIS environment was used to evaluate the vulnerability of the shallow groundwater of Zhangye Basin. The DRASTIC model was developed by the US Environmental Protection Agency (EPA) to evaluate groundwater pollution potential for the entire United States (Aller et al. 1987). It was based on the concept Heights of the hydro-geological setting that is defined as a composite description of all the major geologic and hydrologic factors that affect and control the groundwater movement into, through and out of an area (Aller et al. 1987). The acronym DRASTIC stands for the seven parameters used in the model which are: depth to water, net recharge, aquifer media, soil media, topography, impact of vadose zone and hydraulic conductivity (Table 1). The model yields a numerical index that is derived from ratings and weights assigned to the seven model parameters. The DRASTIC Index is then computed applying a linear combination of all factors according to the following equation:

$$\text{DRASTIC Index} = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw$$

Where D, R, A, S, T, I, C represent the seven hydrogeologic factors, r is the notation value (1–10) and w is the weight value for a given parameter (1–5). The resulting DRASTIC index represents a relative measure of groundwater vulnerability.

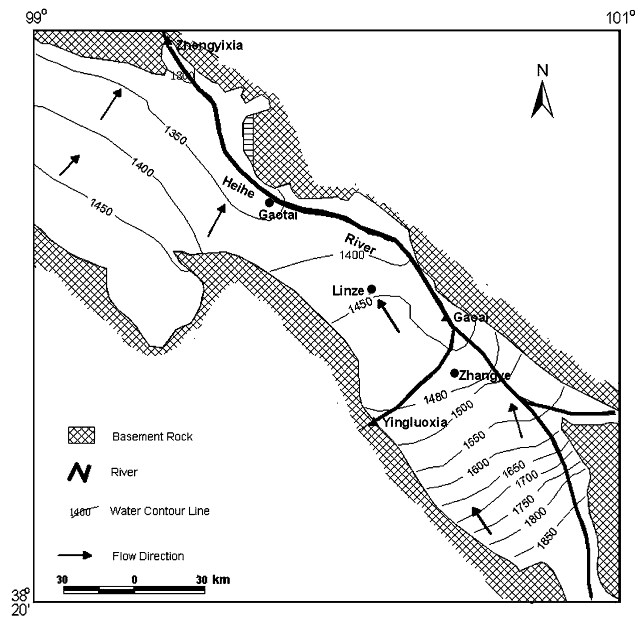

Fig. 3 Groundwater contours in the Zhangye Basin

This model was selected based on the following considerations. DRASTIC uses a relatively large number of parameters (seven parameters) to compute the vulnerability index, which ensures the best representation of the hydrogeological setting. The numerical ratings and weights, which are established using the Delphi technique (Aller et al. 1987), are well defined and used worldwide. This makes the model suitable for producing comparable vulnerability maps on a regional scale. The necessary information needed to build up the several model parameters was available in the study area or could easily be inferred. Data analyses and model implementation were performed using the GIS software of the ARCVIEW GIS 3.2.

Table 1 The DRASTIC model parameters

Factor	Description	Relative weight
Depth to water	Represents the depth from the ground surface to the water table, deeper water table levels imply lesser chance for contamination to occur.	5
Net recharge	Represents the amount of water which penetrates the ground surface and reaches the water table, recharge water represents the vehicle for transporting pollutants.	4
Aquifer media	Refers to the saturated zone material properties, which controls the pollutant attenuation processes.	3
Soil media	Represents the uppermost weathered portion of the unsaturated zone and controls the amount of recharge that can infiltrate downward.	2
Topography	Refers to the slope of the land surface, it dictates whether the runoff will remain on the surface to allow contaminant percolation to the saturated zone.	1
Impact of vadose zone	Is defined as the unsaturated zone material, it controls the passage and attenuation of the contaminated material to the saturated zone.	5
Hydraulic conductivity	Indicates the ability of the aquifer to transmit water, hence determines the rate of flow of contaminant material within the groundwater system	3

Preparation of the parameter maps

Depth to water (*D*)

Depth to water is important because it determines the depth of the material through which a contaminant travels before reaching the aquifer. The depth to water is defined as the distance (in meter) from the ground surface to the water table.

In this study, the location of the 37 observation wells was digitized from the accompanying digital elevation model (DEM) and was linked to an attribute table containing the depth to groundwater table. Essentially, the elevation of the well and the water level table were provided in January of 2000. The depth to water level was obtained by subtracting the water table level from the elevation of the well. The kriging algorithm was used to interpolate these values. The depth to water table map was then classified into ranges defined by the DRASTIC model and assigned rates ranging from 1 (minimum impact on vulnerability) to 10 (maximum impact on vulnerability) (Fig. 4).

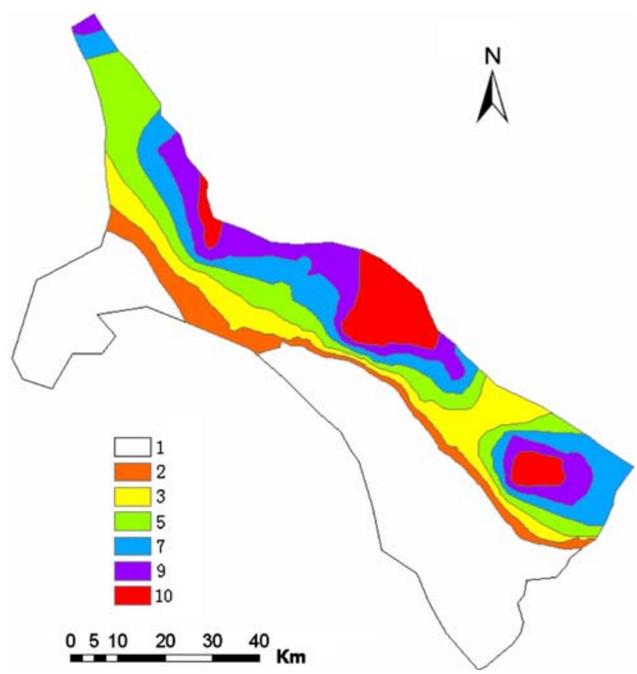

Fig. 4 Depth to water (*D*) of the study area

Net recharge(*R*)

Net recharge is the total quantity of water which infiltrates from the ground surface to the aquifer on an annual basis. In the study area, local recharge is inflow from the Heihe River, irrigation return flow and direct recharge. Leakage between Heihe River and the aquifer is the principal source of groundwater recharge. The data of the recharge obtained from the hydrogeologic report (Li et al. 2004). The average direct annual volume of recharge into the aquifer from the Heihe River is about 5.82×10^8 m^3 (Li et al. 2004). This value is estimated using the difference between river and groundwater levels. Considering the contribution of the canal to recharge in the area, the average direct annual

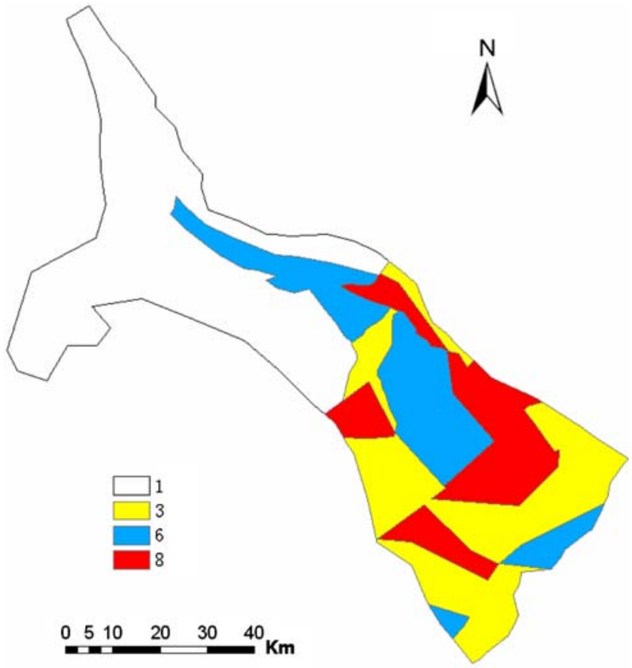

Fig. 5 Net recharge (*R*) of the study area

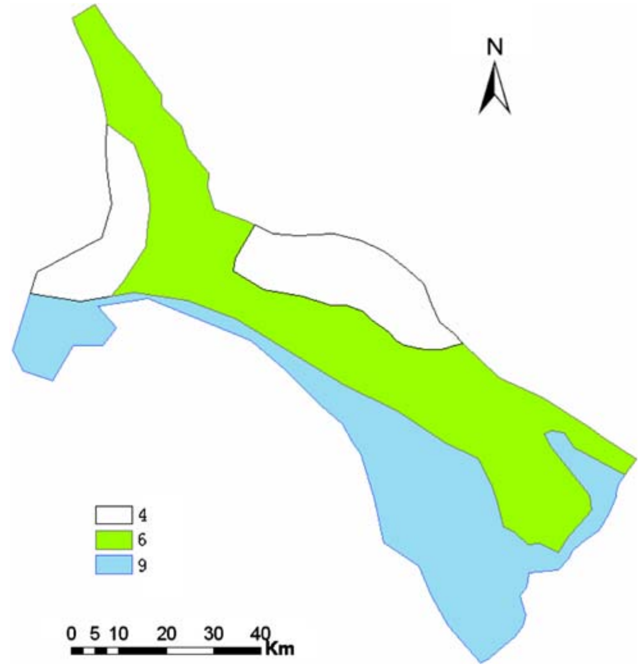

Fig. 6 Aquifer media (*A*) of the study area

volume of recharge into the aquifer from the irrigation canal is about 3.69 $\times$ 10^8 m^3.

Irrigation return flow replenishes groundwater based on rock and soil types, and occurs only in the regions where the groundwater depth is shallower than 10 m. The average direct annual volume of recharge into the upper aquifer from irrigation return flow is about 2.47 $\times$ 10^8 m^3 (Li et al. 2004). For recharge values based on rock and soil types, the average direct annual recharge into the upper aquifer from rainfall is about 0.54 $\times$ 10^8 m^3 (Li et al. 2004). The recharge map was then classified into ranges and assigned ratings from 1 to 8 (Fig. 5).

Aquifer media (*A*), soil media(*S*), impact of the Vadose zone (*I*)

The Aquifer media, soil media and the impact of vadose zone were obtained using a subsurface geology map, geological sections, and drilling profiles of the Zhangye Basin aquifer. The sediments in the basins from south to north gradually change from coarse-grained gravel to medium and fine-grained sand and silt. These sediments along with aeolian and lacustrine deposits form the main aquifers. In the southern part of Zhangye basin, the aquifer is formed from highly permeable cobble and gravel deposits. From the northern edge of this diluvial fan, the aquifer comprises interbedded cobble, gravel, fine sand and clay. The Aquifer media, soil media, impact of the vadose zone have been mapped as shown in Figs. 6, 7, 8.

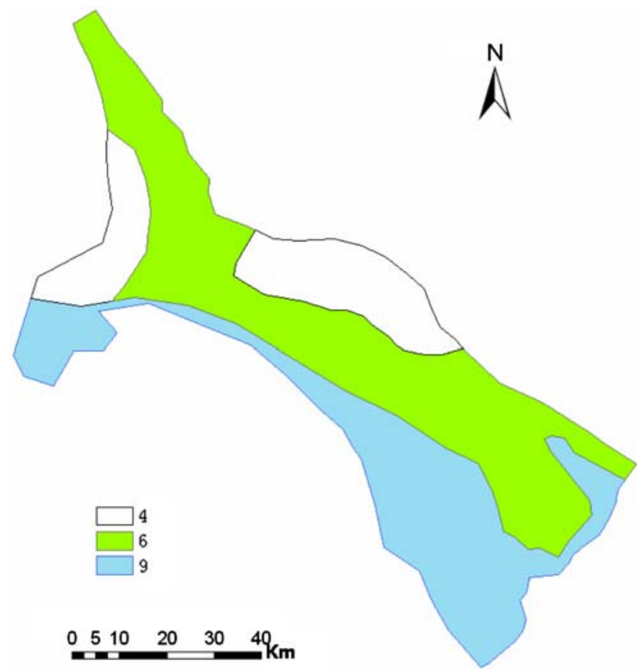

Fig. 7 Soil media (*S*) of the study area

Topography (*T*)

Topography here refers to the slope variability of the land surface. The degree of slope will determine the extent of runoff of the pollutant and settling long enough to infiltrate. The digital elevation model (DEM) was used to extract the slope of the study area. Within the study area, most of the

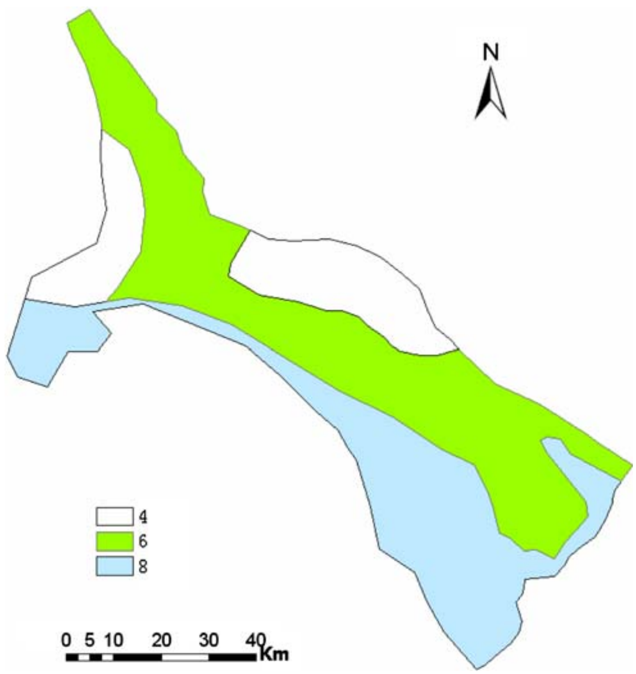

Fig. 8 Impact of the Vadose zone (*I*) of the study area

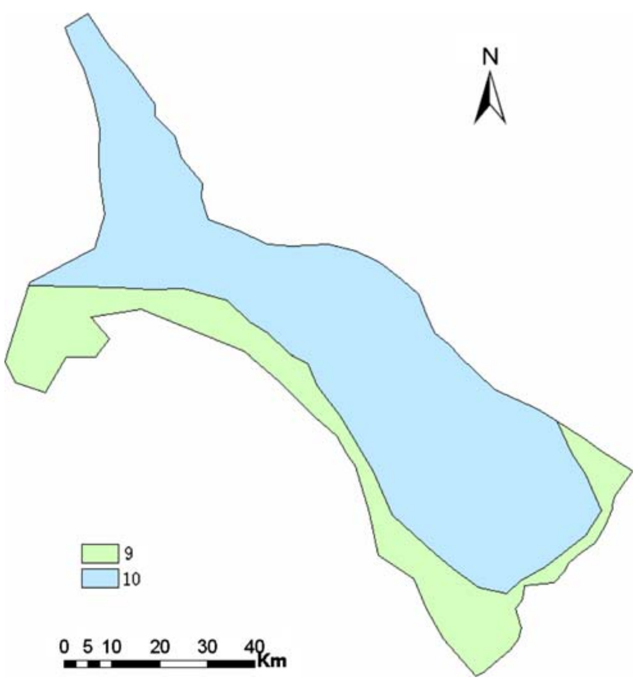

Fig. 9 Topography (*T*) of the study area

regions have a gentle, smooth slope in the range of 2–5% have been mapped as shown in Fig. 9.

Hydraulic conductivity of the aquifer(*C*)

The hydraulic conductivity is important because it controls the rate of groundwater movement in the saturated zone, thereby controlling the degree and fate of the contaminants. The hydraulic conductivity of the aquifer used in the model was derived from pumping tests. An initial spatial distribution of hydraulic conductivity was obtained from the available data (Li et al. 2004). The hydraulic conductivity of the aquifer was obtained from the available data (35 measurements). Data were spatially interpolated using Kriging method and the corresponding results were divided into arbitrary zones. The hydraulic conductivity of the aquifer ranging from more than 120 m/day in the south of the plain, and decreasing towards the north of the aquifer to less than 1 m/day. The Hydraulic conductivity of the aquifer(*C*) map was then classified into ranges and assigned ratings from 1 to 10 (Fig. 10).

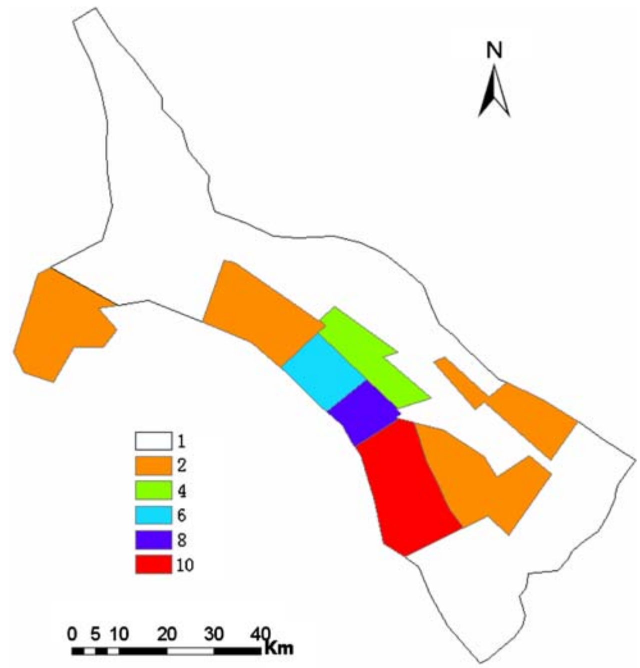

Fig. 10 Hydraulic conductivity of the aquifer(*C*) of the study area

The aquifer vulnerability maps

The final vulnerability map was obtained by running the model in the ArcView GIS software environment by using the seven hydro-geological data layers. The DRASTIC scores obtained from the model vary from 61 to 183. These values were reclassified into three classes using the quantile classification scheme i.e., low vulnerable zones, moderate vulnerable zones and high vulnerable zones. According to the results of the groundwater vulnerability assessment, the study area can be divided into three zones: low groundwater vulnerability risk zone (risk index <120); middle groundwater vulnerability risk zone (risk indexes 120–140), and high risk zone (risk index >140).

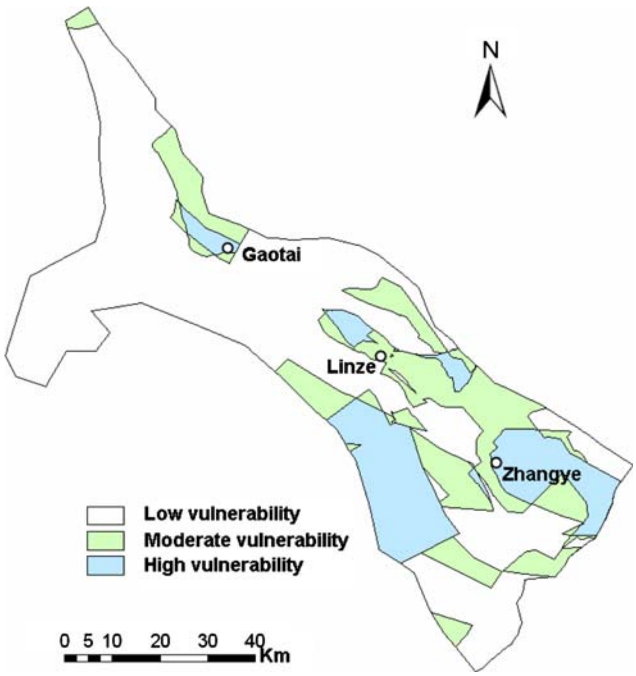

Fig. 11 Shallow groundwater vulnerability maps of the Zhangye Basin according to the DRASTIC models

Under the natural conditions, the high groundwater vulnerability risk zones of the Zhangye Basin are mainly located in the groundwater recharge zones and the important cities (Fig. 11). These vulnerable zones cover around 17% of studied area. Zhangye city and Gaotai Country were the high-value centers.

The middle groundwater vulnerability risk zones of the Zhangye Basin are mainly located in the around major cities and the part of the recharge area (Fig. 11), these vulnerable zones cover around 21% of studied area. The low groundwater vulnerability risk zones of the Zhangye Basin are mainly located in north of study area (Fig. 11), these vulnerable zones are cover 62% of studied area.

According to the analysis of nitrate in the study area, high nitrate concentrations were mainly near urban areas. The high concentration of nitrate is likely to be related to wastewater leakage from industrial activities, urbanization and agricultural practices. Nitrate concentration is also high in areas near major cities, reaching a maximum of 49.19 mg/l (Wen et al. 2007). Zhangye city was the high-value centre, and the nitrate concentration gradually decreased from Zhangye city to the Northwest (Zhang et al. 2004).

Conclusions

Zhangye Basin, located in the middle reaches of the Heihe River, is an important agricultural and industrial center. Groundwater is a major water source for these activities. Due to excessive abstraction of groundwater, the quality of groundwater has been deteriorated. In this paper, the empirical index DRASTIC model and GIS technique were employed to assess the aquifer vulnerability of the shallow aquifer of Zhangye Basin. Seven environmental parameters including Depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone, and hydraulic Conductivity were used to represent the natural hydrogeological setting of the Zhangye Basin. According to the results of the groundwater vulnerability assessment, the study area can be divided into three zones: low groundwater vulnerability risk zone (risk index <120); middle groundwater vulnerability risk zone (risk indexes 120–140) and high risk zone (risk index >140). Under the natural conditions, the middle and high groundwater vulnerability risk zones of the Zhangye Basin are mainly located in the groundwater recharge zones and the important cities. The high, middle and low groundwater vulnerability risk zones of the Zhangye Basin cover around 17, 21 and 62% of studied area, respectively. According to the analysis result in the study area, high nitrate concentrations were mainly near urban areas. Zhangye city was the high-value centre, and the nitrate concentration gradually decreased from Zhangye city to the Northwest. The results of this study indicate that groundwater vulnerability and risk mapping is an efficient tool to assist with planning and decision-making processes.

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