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ORIGINAL ARTICLE

A GIS-based DRASTIC model for assessing groundwater vulnerability in the Ordos Plateau, China

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Abstract Groundwater plays a key role in arid regions as the majority of water is supplied by it. Groundwater pollution is a major issue, because it is susceptible to contamination from land use and other anthropogenic impacts. A study was carried out to build a vulnerability map for the Ordos Plateau using the DRASTIC model in a GIS environment. The map was designed to show the areas of the highest potential for groundwater pollution based on hydrogeological conditions. Seven environmental parameters, such as depth to water table, net recharge, aquifer media, soil media, topography, impact of the vadose zone media, and hydraulic conductivity of the aquifer, were incorporated into the DRASTIC model and GIS was used to create a groundwater vulnerability map by overlaying the available data. The results of this study show that 24.8 % of the study area has high pollution potential, 24.2 % has moderate pollution potential, 19.7 % has low pollution potential, and the remaining 31.3 % of the area has no risk of groundwater pollution. The regional distribution of nitrate is well correlated with the DRASTIC vulnerability index. In contrast to this, although the DRASTIC model indicated that the western part had no risk, nitrate concentrations were higher in some of these areas. In particular, higher nitrate concentrations were recorded along river valleys and around lakes, such as the Mulin River valley. This is mainly caused by the intensive agricultural development and favorable conditions for recharge along river valleys.

Keywords Groundwater vulnerability · DRASTIC model · Ordos Plateau

Introduction

Groundwater is the major source of water supply in arid regions due to its relatively low susceptibility to pollution in comparison to surface water (Navada et al. 1993; Jamrah et al. 2008). The quality of groundwater is generally under a considerable potential of contamination as it is susceptible to contamination from land use and other anthropogenic impacts, especially in agriculture-dominated areas with intense activities that involve the use of fertilizers and pesticides. Therefore, groundwater may be contaminated by the use of chemical fertilizers and the settlement of factories. In contrast to surface water pollution, groundwater contamination is difficult to detect and control, and may persist for years, decades, or even centuries (Todd 1980). Once contaminated, remediation of aquifers would be difficult and expensive. As a consequence, prevention of groundwater contamination is crucial for effective groundwater management. In order to protect groundwater resources from pollution, scientists have developed techniques for predicting which areas are more likely to be contaminated by activities at or near the land surface, such as the use of fertilizers and pesticides, and the leaching

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from mill tailings. This concept has been widely termed as "groundwater vulnerability to contamination". Groundwater vulnerability is considered as an intrinsic property of groundwater that relies on its sensitivity to human and natural impacts, and can be defined as the possibility of percolation and diffusion of contaminants from the groundwater surface into the groundwater system (Babiker et al. 2005). Groundwater vulnerability assessments are widely used to prevent groundwater contamination as they can provide valuable information for locating vulnerable areas (Antonakos and Lambrakis 2007; Sener et al. 2009). Based on the assessment of groundwater vulnerability, the vulnerability map can be drawn and be used to delineate areas with high levels of vulnerability. Groundwater vulnerability mapping is based on the idea that some land areas are more vulnerable to groundwater contamination than others (Piscopo 2001). Once these areas are identified, they can be targeted by proper land use and intensive groundwater monitoring (Mendoza and Barmen 2006). In these areas, lands cannot be used for agriculture with extensive use of chemical fertilizer, for industry and as solid-waste disposal sites.

The concept of groundwater vulnerability to contamination was developed by Margat (1968). Many methods have been developed to assess groundwater vulnerability. These methods can be classified into three types, i.e., process-based methods, statistical methods, and overlay/index methods (Tesoriero et al. 1998). Process-based methods use simulation models to predict contaminant transport, but the data these methods require are not often available and must be estimated by indirect means (Barbash and Resek 1996). Statistical methods use statistics to determine associations between the spatial variables and the actual occurrence of pollutants in the groundwater; however, they are usually region specific and not suitable for the transfer to other regions (Babiker et al. 2005) The overlay/index methods combine factors controlling the movement of pollutants from the ground surface into the saturated zone. Overlay/index methods are often preferred because the data they require are easily available over large areas, which make them suitable for regional-scale assessments (Jawed et al. 2012). Overlay/index methods include DRASTIC (Aller et al. 1987), EPIK (Doerfliger et al. 1999), SINTACS (Vrba and Zaporozec 1994), and GOD (Foster 1987). The DRASTIC method is one of the overlay/index methods and is a powerful tool for assessing groundwater vulnerability and is widely used (Knox et al. 1993; Kim and Hamm 1999; Adamat et al. 2003; Hamza et al. 2007; Rahman 2008; Leone et al. 2009). The data the DRASTIC method requires are easily available, which makes it suitable for regional-scale assessments (Thapinta and Hudak 2003). In addition, it is relatively simple and includes a high number of input data layers that limits the impacts of errors of the individual parameters on the final result.

Groundwater plays a crucial role in large-scale basins in arid regions, such as the Great Artesian Basin in Australian, the Ordos Plateau in China, and the Death Valley in the USA. Groundwater vulnerability assessment can provide valuable information for decision-makers for the strategic planning of these basins. For example, there are rich coal resources in the Ordos Plateau, and coal and chemical plants should not be built in highly vulnerable areas. However, the DRASTIC model is mainly used in small-scale basins covering an area of less than 1,000 km^2. The application of the DRASTIC model is seldom reported for large-scale basins with areas of over 10,000 km^2, where data are scarce relative to small-scale basins and limited information is available for assessing its validity to large-scale basins. Therefore, validation using groundwater chemical data is needed to assess the result of groundwater vulnerability. Regarding the studies of large-scale groundwater vulnerability assessments, Fritch et al. (2000) studied the groundwater vulnerability of a regional aquifer in central Texas and Al-Zabet (2002) conducted a groundwater vulnerability assessment for an unconfined shallow aquifer in the United Arab Emirates, but no validation was performed.

In this paper, the DRASTIC model was used to assess groundwater vulnerability of the Ordos Plateau that covers an area of 81,000 km^2. In the Ordos Plateau, groundwater is the major water resource because of the undeveloped surface water systems (Hou et al. 2006). Abundant mineral resources within the basin, such as coal, natural gas, petroleum and halite, make it one of the largest regions for energy and chemical production in China (Yin et al. 2010). With the construction of energy and industrial chemical plants, the development of local industry, and agriculture and urbanization, the possibility of groundwater contamination by these activities is increasing. The intrusion of pollutants from different sources to groundwater alters the water quality and reduces its value to consumers (Melloul and Collin 1994). The aim of this study is to assess the groundwater vulnerability of the Ordos Plateau using the DRASTIC model in order to manage groundwater effectively and to test the validity of the application of the DRASTIC model to the Ordos Plateau using nitrate concentrations in groundwater.

Study area

The Ordos Plateau is located between 37°10′and 40°30′N and 106°45′and 110°08′E. It extends 360 km in the N–S and 210–260 km in the E–W direction, covering an area of 81,000 km^2. The elevation of the Ordos Plateau decreases from 1,400 to 1,500 m in the central Sishi Ridge to 1,100–1,200 m above mean sea level in the eastern, western, and northern margins. The Baiyu Mt. at the southern margin has an elevation ranging from 1,500 to 1,800 m above mean sea level (Fig. 1).

The climate is considered to be arid to semi-arid in the Ordos Plateau, as precipitation decreases from 420 mm/year in the southeast to 160 mm/year in the northwest (Fig. 1). Rainfall occurs from March to October, but approximately 60–80 % of the rainfall occurs from July to September. The mean annual potential evaporation is very high, varying from 2,000 to 3,200 mm/year. The mean monthly temperature ranges between −4.6 °C in January and 20.7 °C in July, and the mean annual value is 6.5 °C.

There are three major rivers in the area, i.e., the Muolin River, the Dosit River, and the Wuding River. The first two are ephemeral rivers, while the latter is a perennial river (Fig. 1). These rivers are mainly fed by groundwater (Hou et al. 2006; Zhao et al. 2008). Numerous lakes occur in the study area as a result of surface run-off and groundwater discharge, of which 56 have a water area larger than 1 km^2. Lakes and wetlands are important features in the study area.

The major geological units are sandstones of the Cretaceous Bao'an Group that is overlain by the Tertiary mudstone and Quaternary sediments. The Bao'an Group is further divided into three formations from the oldest to the youngest, i.e., the Luohe sandstone, the Huanhe sandstone and the Luohaidong Formation. In the Ordos Plateau, the Cretaceous Bao'an Group is the major aquifer system. The Ordos Basin is an asymmetric syncline. The east limb is a flat monoclinal structure dipping westward at an angle of 1–2°while the western limb is steeper. The Sishi Ridge and Xizhao Ridge divide the study area into three groundwater basins that are named according to the major rivers in the basin, i.e., the Dosit groundwater basin, the Molin groundwater basin and the Wuding groundwater basin (Fig. 1).

Due to the lack of reliable surface water resources in the Ordos Plateau, groundwater serves as the major source for drinking, irrigation, and chemical industries (Hou et al. 2008). According to statistics, about 64 % of the water consumption derives from groundwater in the Ordos Plateau and it is the only water resource in some areas. Due to several anthropogenic activities in the study area, groundwater is showing signs of contamination (Wang 2006). Therefore, groundwater vulnerability assessments are required for the management of water resources, the design of monitoring networks, and the land use planning in order to protect the valuable resources from contamination (Vias et al. 2005). The vulnerability concept is implemented by classifying a geographical area with regard to its susceptibility to groundwater contamination.

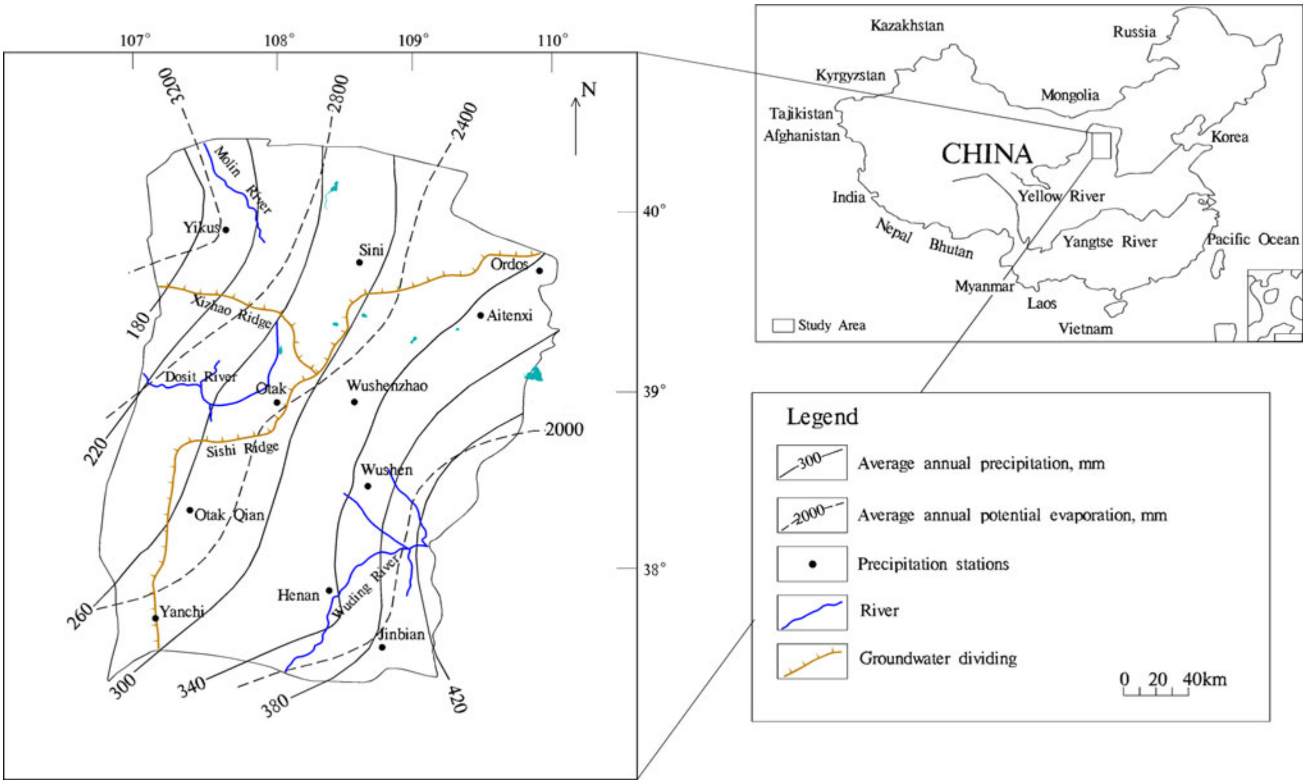


Fig. 1 Map of the Ordos Plateau showing average annual precipitation, potential evaporation, rivers, and sampling location

Methodology

DRASTIC was developed by the US Environmental Protection Agency to evaluate groundwater pollution potential for the entire USA (Aller et al. 1987). The acronym DRASTIC represents seven parameters used in the model, i.e., D (Depth to water), R (Net Recharge), A (Aquifer media), S (Soil media), T (Topography), I (Impact of the vadose zone media), and C (Hydraulic Conductivity of the aquifer) (Aller et al. 1987). Four assumptions of the DRASTIC model are (1) contaminants are introduced at the ground surface; (2) contaminants seep into the groundwater by precipitation; (3) contaminants have the mobility of water, and (4) the area of concern is at least 0.4 km^2. The DRASTIC model is used to produce results suitable for screening regions with respect to groundwater protection, monitoring, and clean-up efforts. The DRASTIC model evaluates pollution potential based on the weighted combination of these parameters. The typical ratings range from 1 (less contamination potential) to 10 (highest contamination potential). This rating is then scaled by a weighting factor varying from 1 (least significant) to 5 (most significant), and the DRASTIC index is made up of a sum of products rating and weights for the seven parameters (Sener et al. 2009). The DRASTIC index (D_i) is calculated by:

$$D_i = D_r \times D_w + R_r \times R_w + A_r \times A_w + S_r \times S_w + T_r \times T_w + I_r \times I_w + C_r \times C_w \quad (1)$$

where subscript r is the rating value and w is the weight assigned to each parameter. The higher the DRASTIC index, the more likely the aquifer is contaminated. In this study, the numerical weights, which were established using the Delphi technique (Aller et al. 1987), were used as shown in Table 1.

The DRASTIC model involves (1) the collection of hydrogeologic and geologic data (infiltration, soil, aquifer, slope, and hydraulic conductivity); (2) the construction of GIS maps for the DRASTIC model; (3) the calculation of DRASTIC index; (4) rating as to vulnerability of contamination. Recently, most studies have used the DRASTIC model within a GIS environment (Fritch et al. 2000; Hrkal 2001; Adamat et al. 2003; Babiker et al. 2005; Sener et al. 2009). The major advantage of GIS-based mapping is the combination of several types of data and a rapid change in the parameter values used to classify the groundwater vulnerability (Wang et al. 2007). In addition, GIS allows spatial data gathering and gives a way for data processing, such as integration, geo-referencing, and spatial analysis. In this study, the DRASTIC model was also used within a GIS environment.

To evaluate the influence of a single parameter on the assessment of groundwater vulnerability, the map removal sensitivity analysis was carried out. The map removal sensitivity, introduced by Lodwick et al. (1990), identifies the sensitivity (S) associated with removing one or more maps from the suitability analysis and is computed as follows:

$$S = \left(\frac{\frac{V}{N} - \frac{V'}{n}}{V} \right) \times 100\,\% \quad (2)$$

where V and V' are the unperturbed and perturbed vulnerability indices, respectively, and N and n are the number of maps used to compute V and V'. The actual vulnerability

Table 1 DRASTIC rating and weighting values for the hydrogeological parameter settings

DRASTIC parameters	Range	Rating	Weight
Depth to water table (m)			5
	<1	10	
	1–2	9	
	2–4	8	
	4–10	7	
	>10	5	
Net recharge			4
	<8	1	
	8–16	3	
	16–28	6	
	28–40	8	
	>40	9	
Aquifer media			3
	Sandstone	6	
	Fine sand	8	
Soil media			2
	Sand	10	
	Sandstone	6	
Topography (slope %)			1
	<2	10	
	2–6	9	
	6–12	5	
	12–18	3	
	>18	1	
Impact of the vadose zone			5
	Loam	1	
	Sandstone	3	
	Loess	5	
	Weathered sandstone	6	
	Sand	9	
Hydraulic conductivity (m/d)			3
	<0.5	1	
	0.5–1	3	
	1–1.5	6	
	>1.5	10	

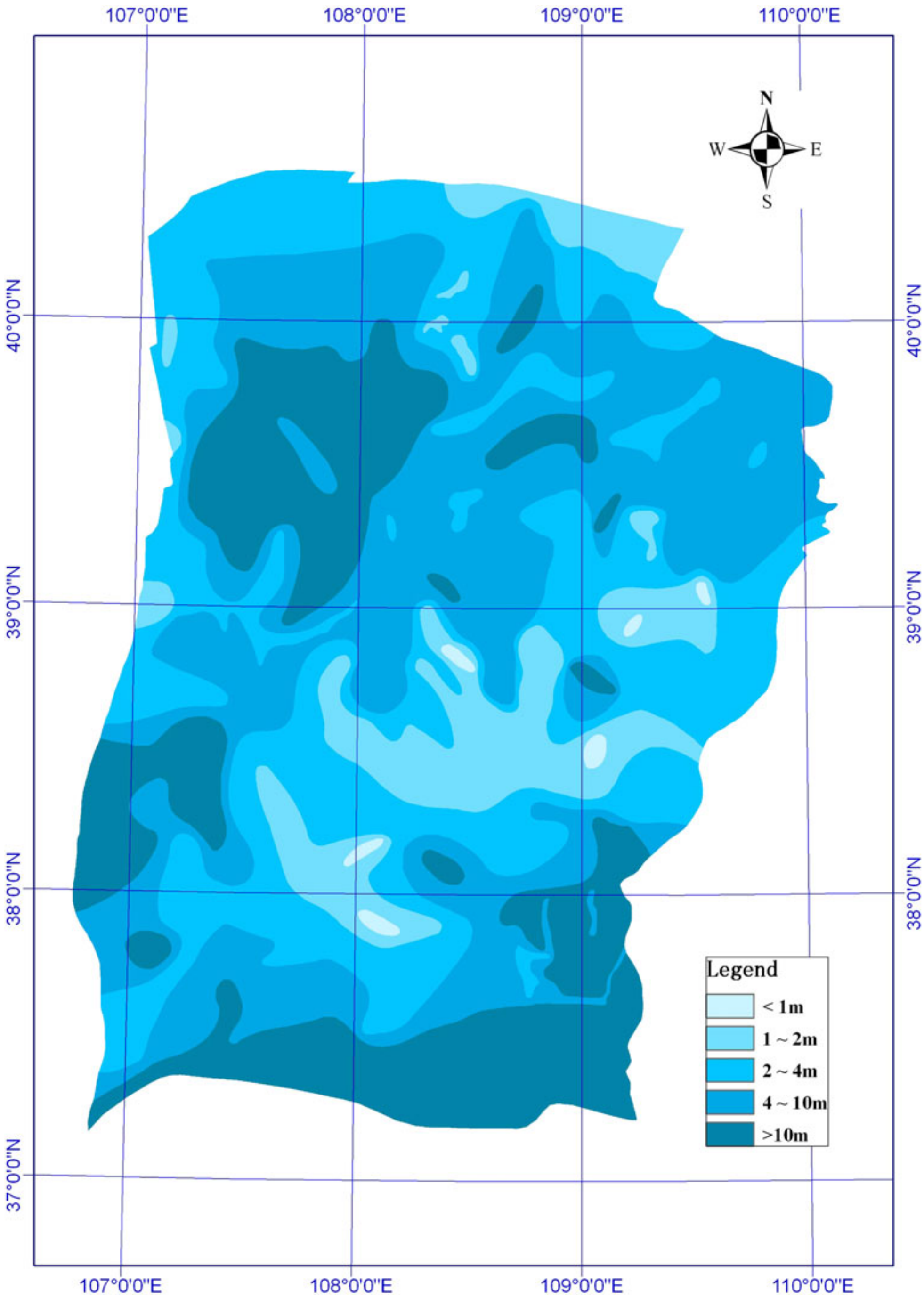


Fig. 2 Depth to water level map

index calculated using all the seven parameters was the unperturbed vulnerability, while the vulnerability obtained using six parameters was considered as a perturbed one.

Development of the DRASTIC vulnerability index

The seven maps required by the DRASTIC model were prepared and built using available hydrogeological data in a GIS environment. Finally, the DRASTIC index was calculated in ArcGis using Eq. 1.

Depth to water

Depth to water is the distance from the ground surface to the water table. Depth to water is important as it determines the depth of material through which infiltrating water must travel before reaching the saturated aquifer (Rahman

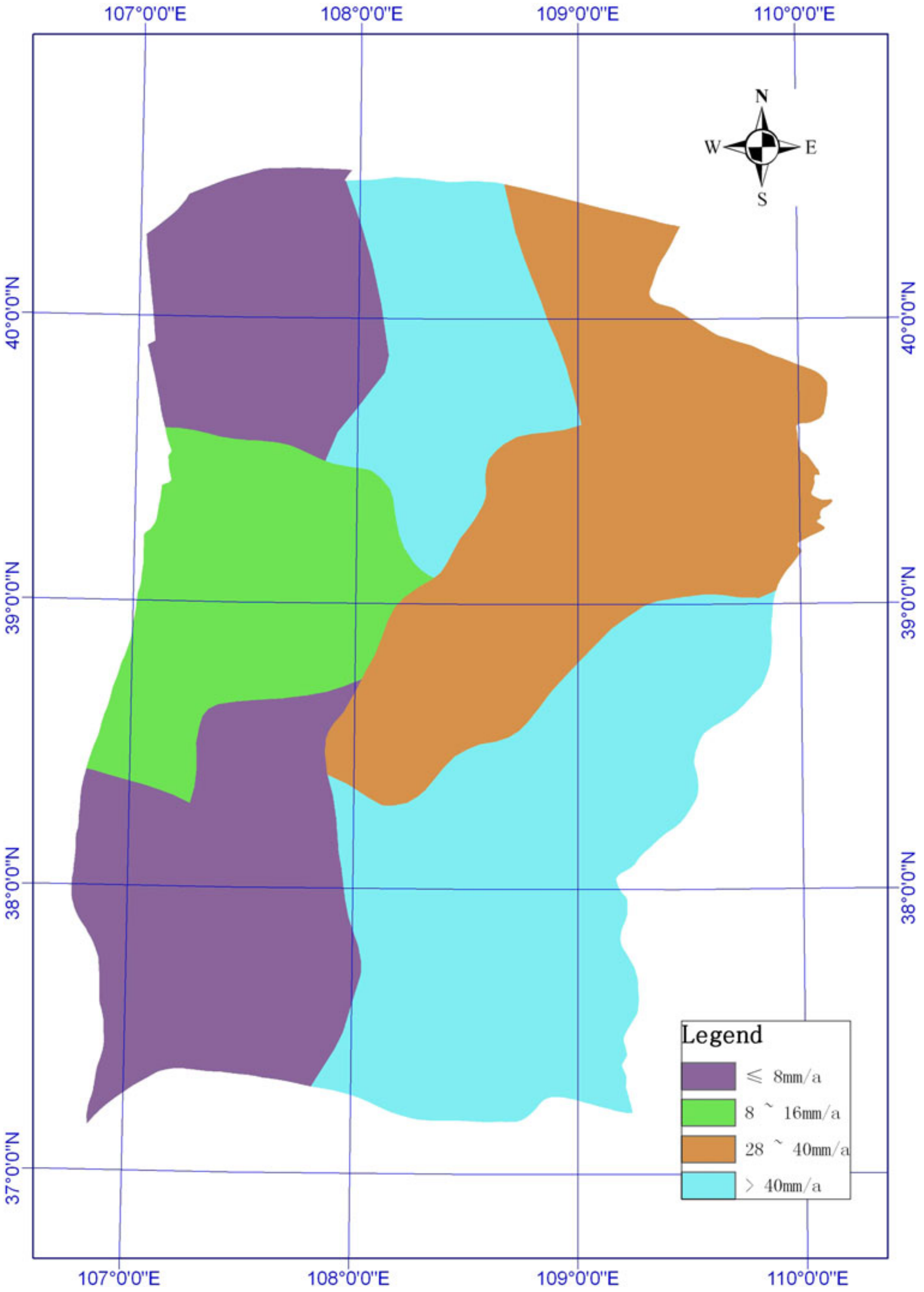


Fig. 3 Net recharge map

2008). In general, the potential of groundwater contamination decreases with the increase of depth to water. In this study, the maximum weight of 5 has been assigned to the depth to water parameter according to Aller et al. (1987).

In this study, groundwater heads were measured in 197 boreholes in June 2008 and the depth to water was obtained by subtracting the groundwater surface elevation from the groundwater elevation. Due to the extent of the study area, field work was completed in 3 weeks. For the investigated area, the annual fluctuation of water table is generally less than 1 m. Therefore, the variation of water table in the 3 weeks was small and would not bring much uncertainty to the study. These point data were contoured by the ordinary kriging interpolation method (Fig. 2). In this area, the depth to water is low in the mid-eastern part and high in the groundwater divide areas. The rating for the depth to water table ranges from 10 for small depths and 5 for depths larger than 10 m. The deeper the groundwater, the smaller the rating value. The depth to water table interval range, DRASTIC rating, and weight are listed in Table 1.

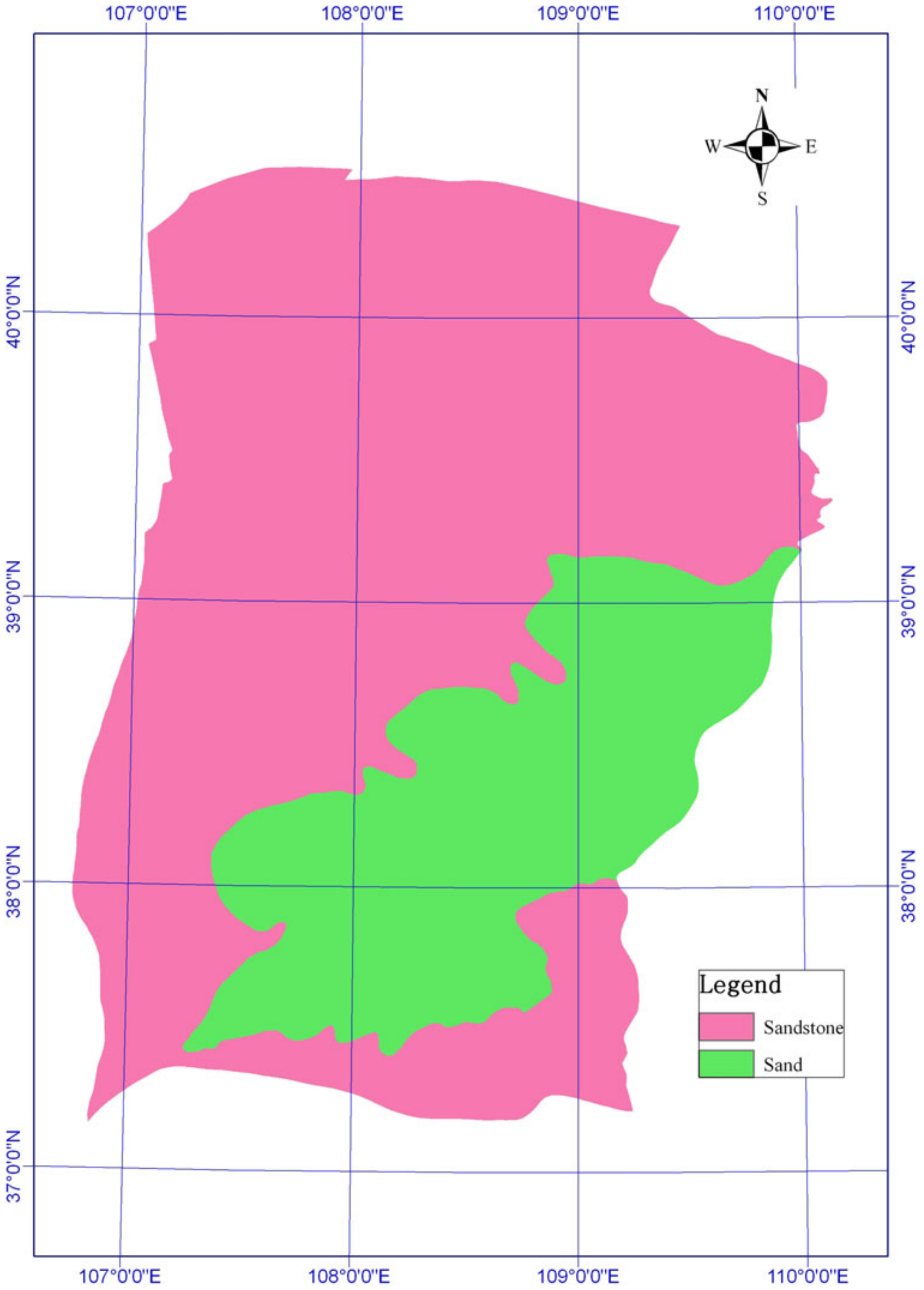
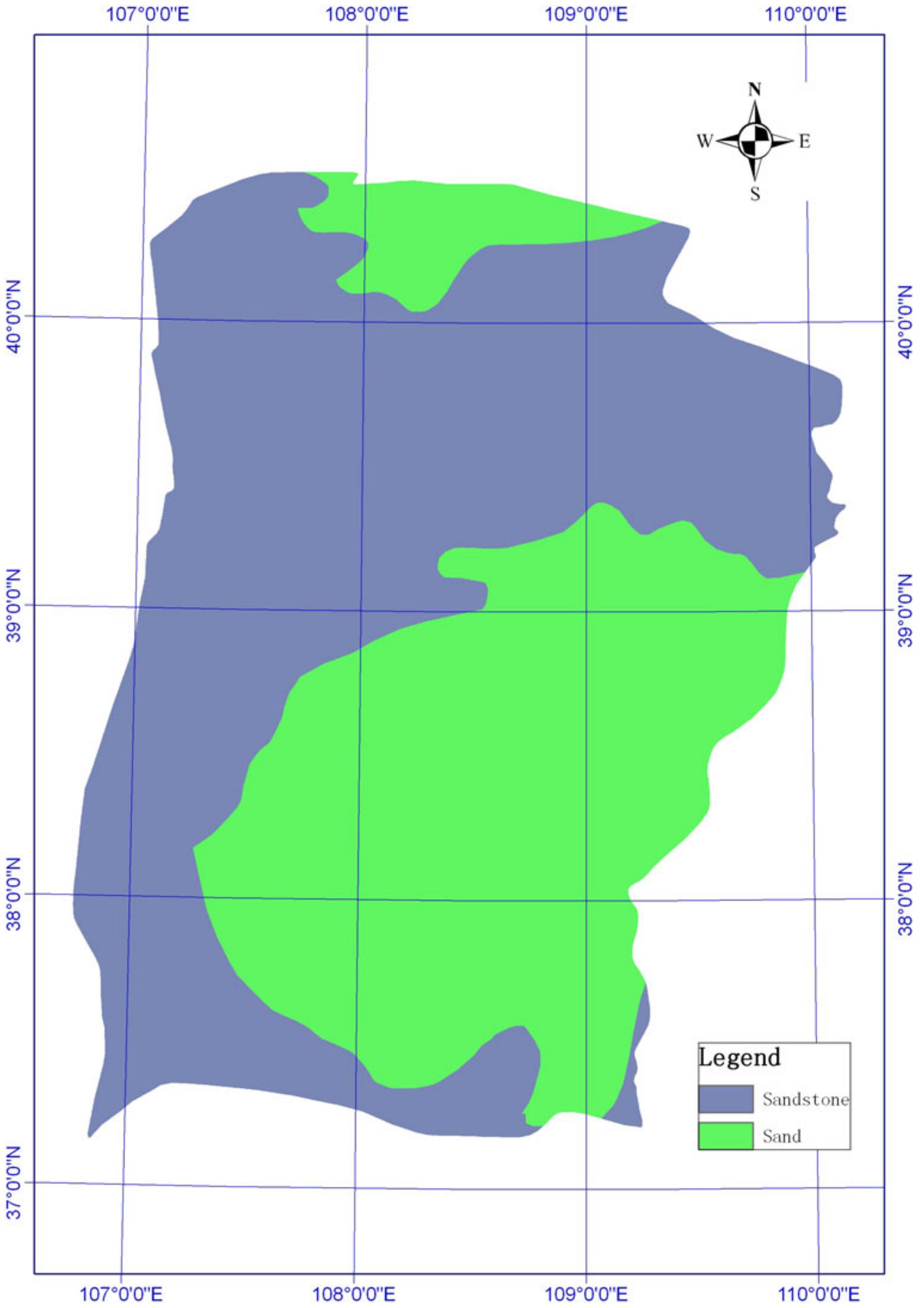


Fig. 4 Aquifer media map

Net recharge

The net recharge is the total quantity of water that percolates down to the groundwater on an annual basis. Net recharge includes the average annual amount of infiltration and does not account for the distribution and intensity of recharge events. Recharge water is a significant medium for transporting contaminants from vadose zones to saturated zones. In the Ordos Plateau, there are nine groundwater systems (Yin et al. 2010). Four methods were used to quantify the net recharge in each groundwater system, i.e., the empirical method (EMP) and Darcy's method for unsaturated zones (DLU) (Hou et al. 2006), the remote sensing (RS) method (unpublished data) and the chloride mass balance method (Yin et al. 2010). As each method has some uncertainty, the arithmetic average value is used in this study. The results show that the net recharge varies from 5.54 to 73.85 mm/year (Fig. 3) (Yin et al. 2010). The highest net recharge was found in sandy areas, whereas the areas with low recharge rates are located in the western part

Fig. 5 Soil media map

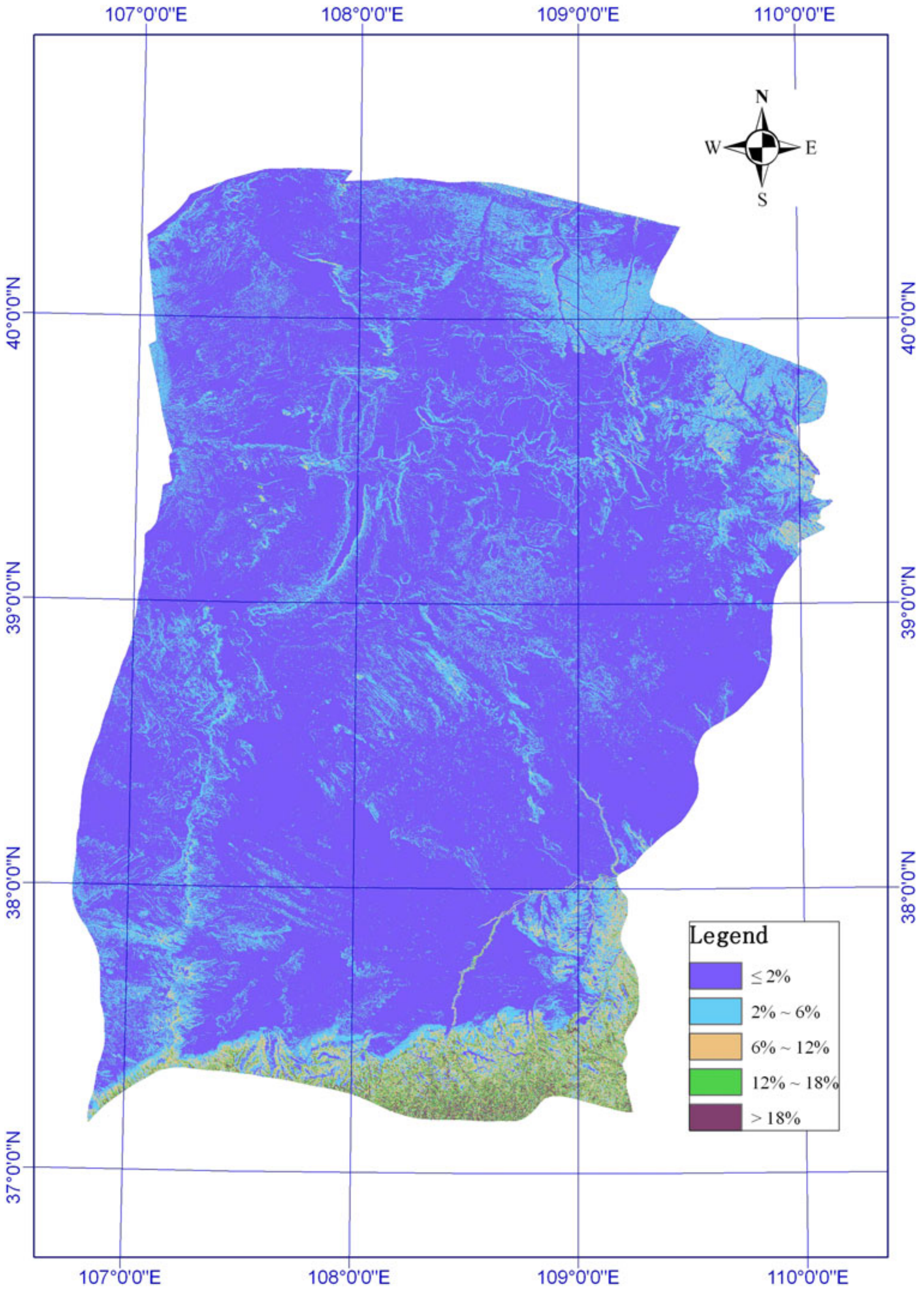


of the study area. DRASTIC assigns a rating of 1 for small recharge rates and a rating of 9 for large recharge values.

Aquifer media

Aquifer media controls the contaminant fate. High permeability generally leads to lower pollutant attenuation capacity. A hydrogeologic map of the study area was used to classify the aquifer media and was prepared from the field studies, borehole data from 63 hydrogeological boreholes, and borehole logging from 320 petroleum boreholes in the previous investigation (Hou et al. 2006). The aquifer media is mainly sandstone and fine sand in the Ordos Plateau (Fig. 4). The major aquifers are sandstones of the Cretaceous Bao'an Group that is further divided into three formations from the oldest to the youngest, i.e., the Luohe sandstone (K_{1l}), the Huanhe sandstone (K_{1h}), and the Luohaidong Formation (K_{1lh}). In the southeast, a

Fig. 6 Topographic map

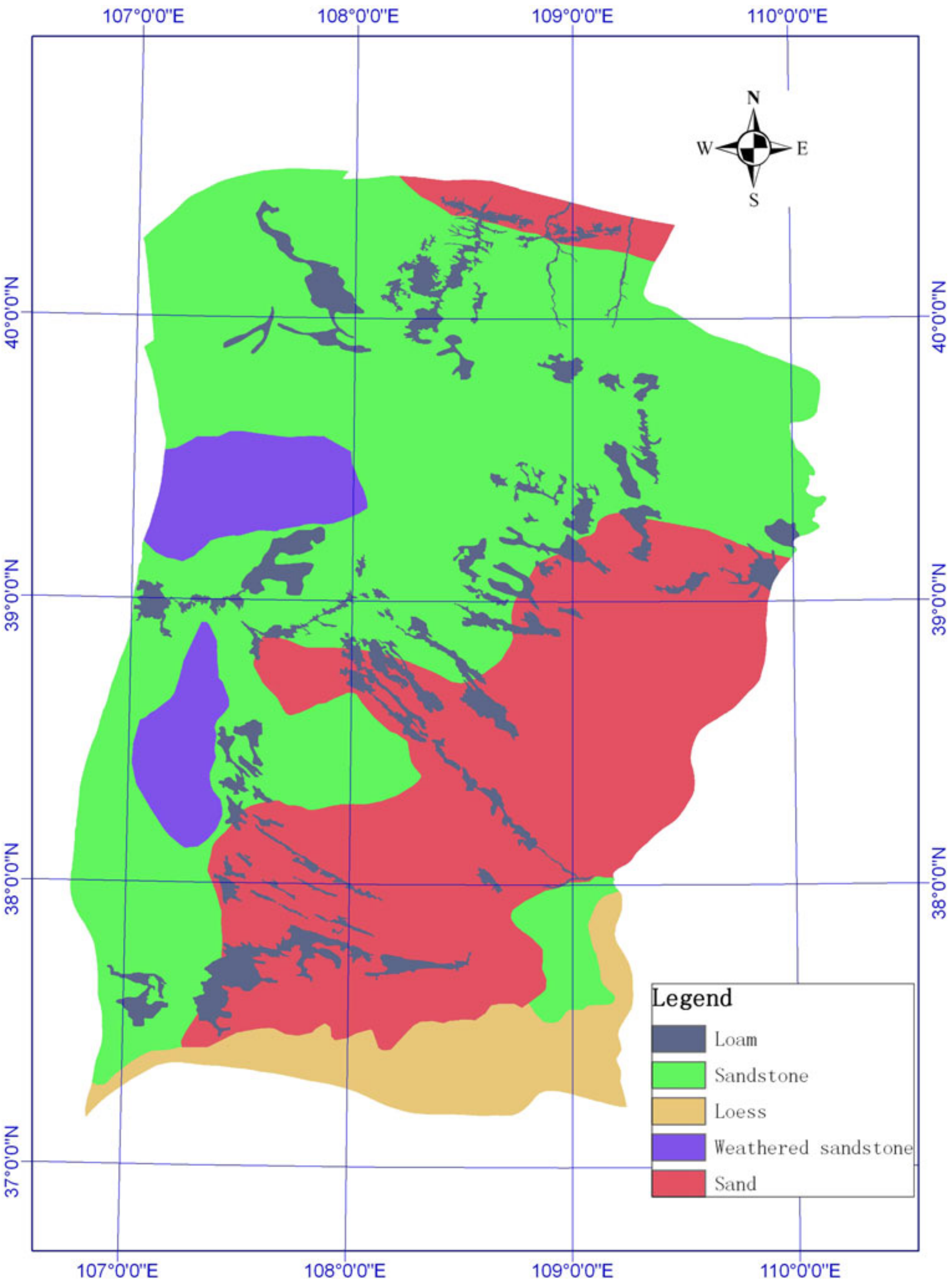


Quaternary aquifer is present and consists of mainly fine sand and is of lucustrine origin. Aquifer ratings were assigned a weight of 6 for sandstone and 8 for fine sand. The coarse media was assigned a high rating and the hard rock was assigned a lower rating.

Soil media

Soil has a significant impact on the amount of recharge, the amount of potential dispersion and the purifying process of contaminants (Lee 2003). Soil materials containing fine soil or organic matter can decrease intrinsic permeability and retard contaminant migration. A soil map was prepared using the geological maps from the previous study (Hou et al. 2006). Soil is either sand or sandstone in the study area (Fig. 5). According to the soil media layer, sand with high permeability is located in the mid-eastern part of the study area. The DRASTIC rating values of soils depend on their permeability and vary from 10 for sand and 6 for sandstone.

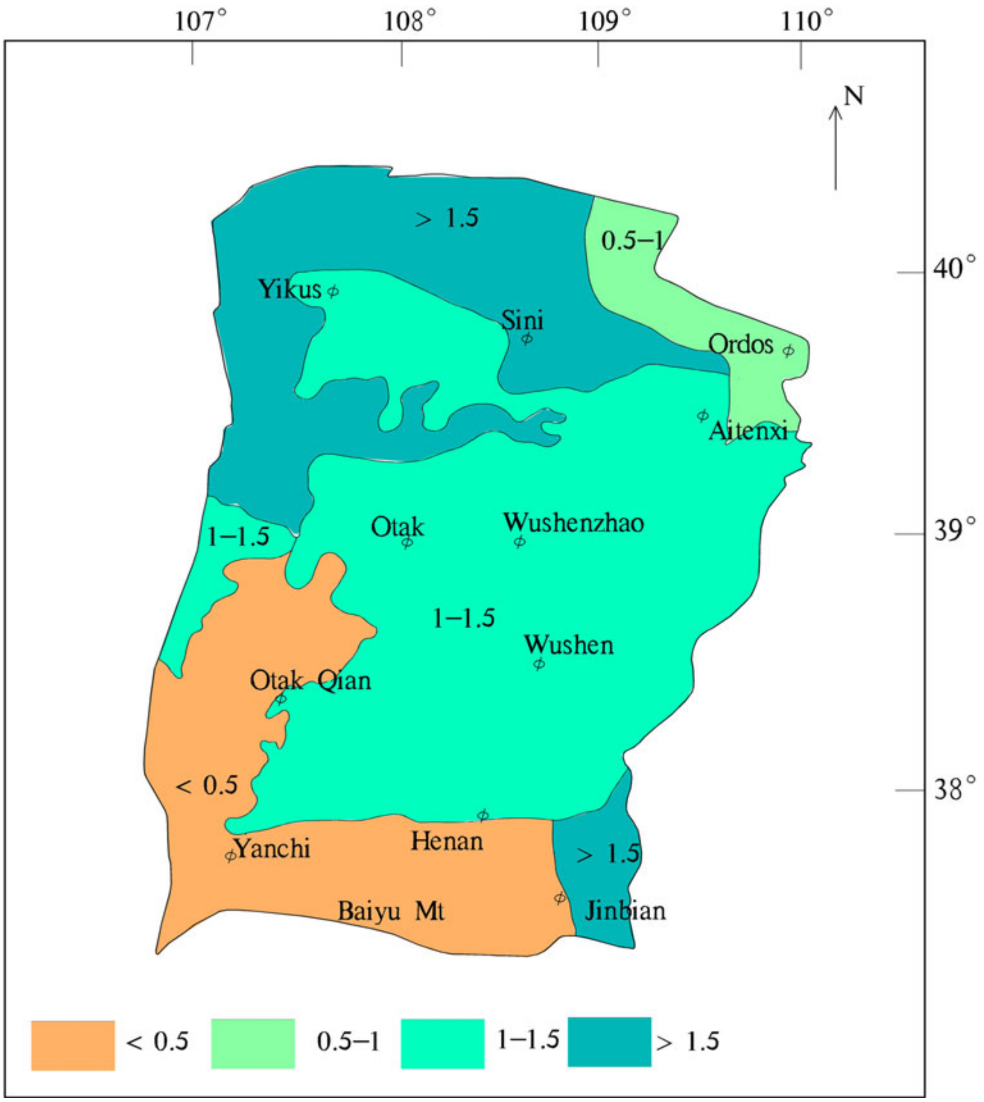
Fig. 7 Map of impact of the vadose zone



Topography

Topography is expressed in the form of slope in the DRASTIC model and areas with low slope tend to retain water for a longer period of time. Consequently, infiltration and contaminant migration increase in lower sloping areas. The slope map was developed from the topographic contour maps of 1:25,000 scale. The maps were first scanned and registered. The contour lines were digitized as well as the elevation points to be used in the interpolation. Then, a digital elevation model was prepared with a triangular irregular network using ArcGIS 3D Analyst. Finally, the slope was determined using the slope function of ArcGIS. Figure 6 reveals that the slope is less than 2 % in most parts of the study area, and areas with slopes ranging from 2 to 6 % are located in groundwater dividing areas. The slope values are highest in the south margin where the Baiyu Mt. is present. The slope was categorized into five groups and the rating was assigned from 1 to 10. The rating is high in flat areas as

Fig. 8 Hydraulic conductivity map



they slow down the run off allowing more time for the contaminant to infiltrate. The rating is lower in steep areas where there is lesser opportunity for a pollutant to infiltrate.

Impact of the vadose zone

The vadose zone's impact on the potential for aquifer contamination depends on its permeability and the attenuation characteristics of the media. Many processes that influence the pollution potential take place in vadose zones and control the passage and attenuation of the contaminated material to the aquifer. The impact of the vadose zone was obtained from the lithological cross sections from core data. The vadose zone media is loam, sand, sandstone, weathered sandstone and loess (Fig. 7). The rating of impact of vadose zone ranges from 1 to 9 as shown in Table 1. Lower rating values were given to materials with lower permeability.

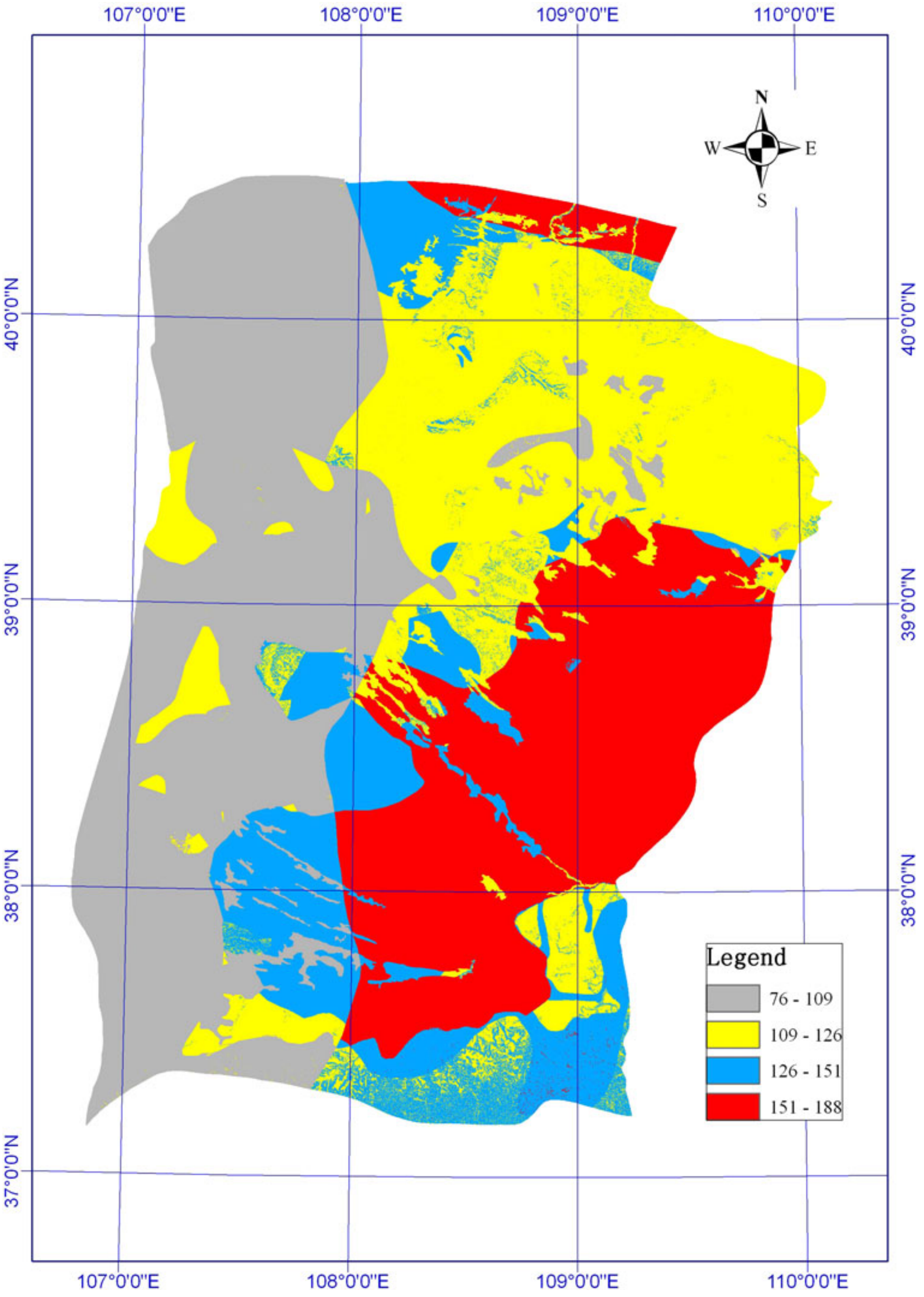
Hydraulic conductivity

Hydraulic conductivity is the ability of the aquifer to transmit water. It controls the rate of contaminant movement and dispersion from the injection point. Hydraulic conductivity values were calculated from pumping tests and have been divided into five zones as shown in Fig. 8. Then the hydraulic conductivity map was scanned and spatially registered. It can be seen that most parts of the study area have hydraulic conductivity values from 1 to 1.5 m/day. The rating values of the DRASTIC model for this parameter range from 1 to 10 as shown in Table 1. The higher the hydraulic conductivity, the higher is the rating value.

The DRASTIC index

Finally, the DRASTIC values were calculated using Eq. (1) and ranged from 76 to 188. In this study, the quantile classification method was used to classify the DRASTIC

Fig. 9 The DRASTIC aquifer vulnerability map



index. The quantile classification method distributes a set of values into groups that contain an equal number of values. Sener et al. (2009) state that this is the most suitable method for this kind of classification. The range is divided into four classes as follows (Fig. 9):

- High groundwater pollution potential (>150)
- Moderate groundwater pollution potential (126–150)
- Low groundwater pollution potential (110–126)
- No risk for groundwater pollution potential (<110)

The results of this study show that 24.8 % of the study area has high pollution potential, 24.2 % has moderate pollution potential, 19.7 % has low pollution potential, and the remainder of the study area (31.3 %) has no risk for groundwater pollution. This means that about one quarter of the Ordos Plateau is at high risk with respect to pollution potential. These areas are mainly located in the south-eastern part where physical factors such as gentle slope, high water table and the permeable vadose zone make

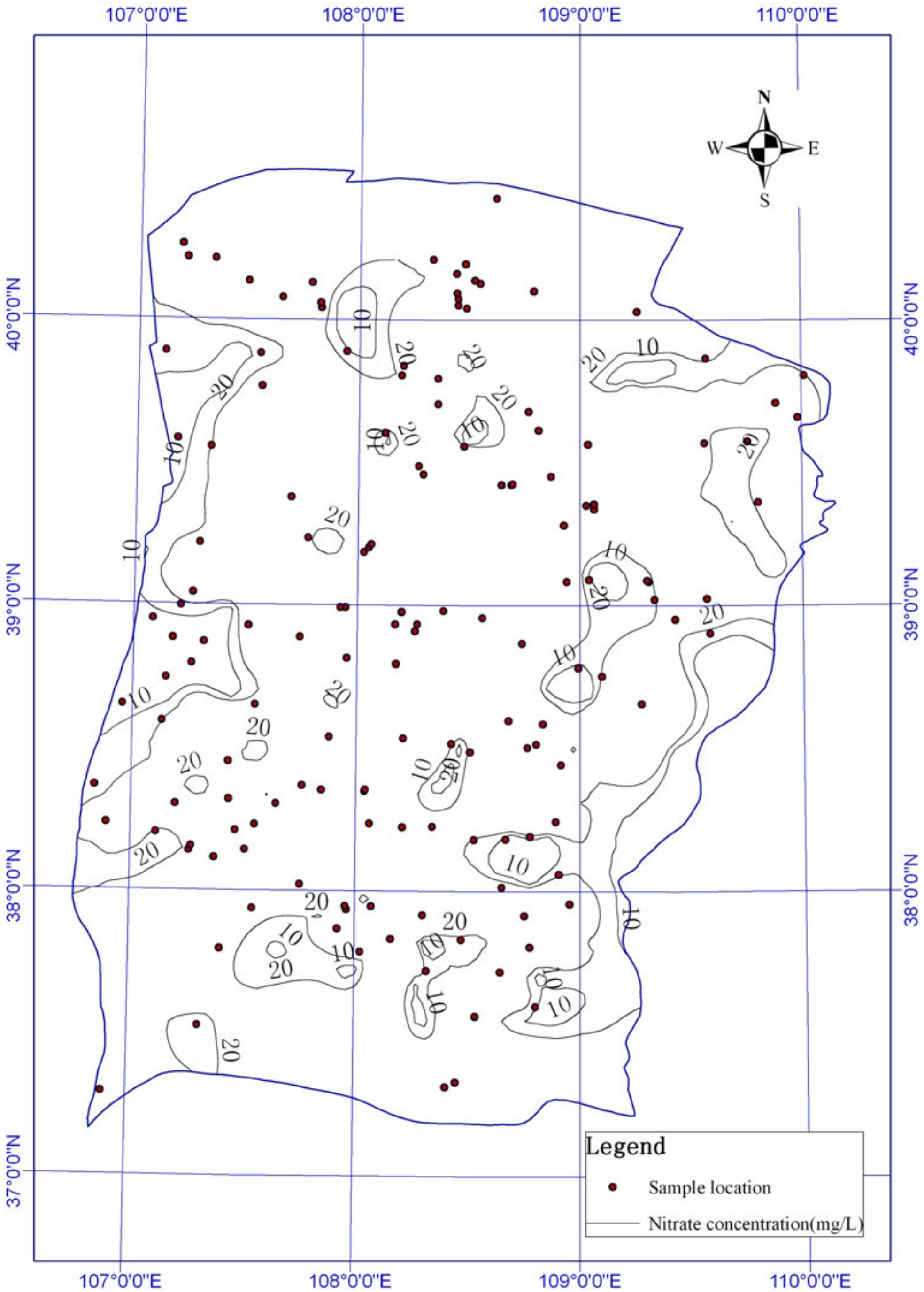


Fig. 10 Well location and nitrate concentration in groundwater

contamination of shallow groundwater easier. The western part displays no risk for pollution. This is due to the combination of the deep water table and the low permeability of the vadose zone.

Map removal sensitivity analysis

Table 1 shows the results of the map removal sensitivity analysis by removing one map at a time. The sequence of variation index is D > I > A > C > R > S > T. Variation of the vulnerability index is high when D and I are removed. It might be due to the relatively high weight assigned to this layer (Table 1). The vulnerability index varies greatly upon removal of soil media and topography maps. This could be attributed to their relatively high contamination risk. The results of the map removal sensitivity indicate that the removal of each parameter will influence groundwater vulnerability and it is really necessary to use all of the seven parameters to assess groundwater vulnerability in the Ordos Plateau.

DRASTIC index validation

A validation of the DRASTIC method is vital as it is an empirical model; thus, nitrate concentrations were applied to validate the results of the DRASTIC model. Nitrogen in fertilizers is very frequently applied to agricultural areas to enhance crop production, and there are no unknown geological sources for nitrate in the study area. Hence, nitrate can be a good water quality parameter to evaluate the DRASTIC index and has been widely used (Baalousha 2006; Jamrah et al. 2008). The correlation between the DRASTIC index and the nitrate concentrations in groundwater was investigated to check the efficiency of using this approach to assess groundwater vulnerability. Groundwater samples were collected in 353 wells and nitrate concentrations were measured (Wang 2006). Figure 10 shows the contour map of the concentration of nitrate in groundwater based on the ordinary kriging interpolation of measured data. By visual inspection of Fig. 10, high nitrate concentrations can be observed mostly in the high and moderate groundwater pollution potential areas, which have a good correlation with DRASTIC index (Fig. 9). Therefore, the results of vulnerability assessment using the DRASTIC model were confirmed. In contrast to this, although DRASTIC indicated that the western part was at no risk, nitrate concentrations were higher in some areas, particular along river valleys, such as the Mulin River valley. Along river valleys, there are some farmlands where fertilizers are used. In addition, the depth to water table is shallow in river valley areas. Hence, this anomaly may be caused by the combination of agricultural activities and favorable conditions for recharge along river valleys.

Conclusions

Groundwater resources in the Ordos Plateau are very important as they supply the majority of water resources. Therefore, a study was carried out to assess the groundwater vulnerability of the Ordos Plateau using the DRASTIC model in a GIS environment. Seven parameters were used to represent the natural hydrogeological conditions of the Ordos Plateau, i.e., depth to water table, net recharge, aquifer media, soil media, topography, impact of vadose zone, and hydraulic conductivity. The results of this study show that 24.8 % of the study area has high pollution potential, 24.2 % has moderate pollution potential, 19.7 % has low pollution potential, and the remainder of the study area (31.3 %) has no risk for groundwater pollution. The regional distribution of nitrate is well correlated with the DRASTIC vulnerability maps. In contrast to this, although DRASTIC indicated that the western part was at no risk, nitrate concentrations were higher in some areas, particularly along river valleys and around lakes. This is mainly caused by the intensive agricultural development and favorable conditions for recharge along river valleys. The map removal sensitivity analysis indicated that the vulnerability index was highly sensitive to the removal of net recharge, soil media, and topography layers, but least sensitive to the removal of the aquifer media layer. This study indicated that the GIS technique could provide an efficient way to deal with a large quantity of spatial data used in the DRASTIC model.

This study produces a very valuable tool for policy makers as it gives a very comprehensive indication of vulnerability to groundwater contamination. The knowledge about high vulnerable zones is important for local authorities to manage and monitor groundwater resources properly.

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