ORIGINAL ARTICLE

Geostatistical analysis of temporal and spatial variations in groundwater levels and quality in the Minqin oasis, Northwest China

Lijuan Chen · Qi Feng

Abstract Recognition of the temporal and spatial variations in groundwater levels and quality has become a prerequisite of formulating strategies for the sustainable development and utilization of water resources. In this study, data were obtained from 51 observation wells of depth to groundwater from 1999 to 2008 and 30 sampling wells of hydrochemical characteristics of groundwater in the Minqin oasis. The Kolomogorov–Semirnov test revealed that all data followed normal or log-normal distribution. A set of well-structured semivariograms also confirmed that the data had moderate (only for Mg^{2+} and K^+) or strong spatial dependence. Based on spatial distribution, maps drawn using the ordinary Kriging interpolation method in different periods, the declining trend of the groundwater table was found to have been relieved since 2007, with the mean water table dropping 4.65 m from 1999 to 2008. Spatial comparison results further showed that the variations in groundwater levels in Baqu and Quanshan were more evident than those in Huqu, with mean decline rates of 0.64, 0.93, and 0.41 m/year, respectively. The mean value of total dissolved solids (TDS) was 3.34 g/L, and the groundwater in 76.2 % of the study area was brackish (TDS $\geq$ 1.0 g/L). From south to north, the groundwater types can be classified into three obvious zones based on the major ion distributions: SO_4^{2-}–HCO_3^-–Na^+–Ca^{2+} type in Baqu, SO_4^{2-}–Na^+–Ca^{2+} type in Quanshan, and SO_4^{2-}–Cl^-–Na^+ type in Huqu. TDS increased from the 1970 to 2005 and gradually decreased thereafter.

Introduction

For arid and semi-arid regions, groundwater is a vital part of the total water resources and plays an important role as a water supply both for clean drinking and irrigation. This is increasingly the case in the regions of over-dependence on groundwater resources caused by the shortage of surface water supply (Edmunds 2003). Driven by rapid population growth and economic development, the high demand for water in these regions can easily result in groundwater withdrawals and quality decline. Consequently, understanding of the temporal and spatial variations in groundwater levels and quality has become an essential prerequisite for groundwater management and sustainable water use.

The Minqin oasis is located between the Badain Jaran and Tengger deserts in the lower reaches of the Shiyang River. It is an ecologically fragile area characterized by low and irregular rainfalls, high temperatures and evaporation, as well as notable drought periods (Ma et al. 2005). Because of clear lack of precipitation and gradually decreasing inflow from the upper reaches of the Shiyang River, a series of adverse consequences on the hydrogeological regime have been occurred in recent years (Gu 2002; Feng et al. 2000; Ma and Gao 2000). As one of the driest regions in China, research on groundwater factors (levels and quality) in the Minqin oasis has a representative significance for most areas in northern China.

Direct measurements of water levels and quality have been used in many studies over the past decades (Shi et al. 2001; Feng et al. 2004; Zhang et al. 2005). However, such

L. Chen (✉) · Q. Feng
Cold and Arid Regions Environmental and Engineering
Research Institute, Chinese Academy of Sciences,
Lanzhou 730000, China
e-mail: chenlj2001@126.com

measurements are inadequate for most applications in water resource research and management. For this reason, groundwater surfaces based on these measurements are needed. A proven method of generating accurate surfaces is using multivariate geostatistical algorithms. Geostatistical techniques such as variogram analysis and kriging are commonly applied in oil, gas and mineral exploration, in groundwater research, and for marine or terrestrial habitat mapping (Bonham-Carter 1996; Isaaks and Srivastava 1992; Rivoirard and Wieland 2001; Schlüter 1996). These techniques allow the computation of regional patterns and contour plots under consideration of the spatial distribution of the input data.

The aim of this study was to employ Geostatistical techniques to identify the spatial distribution patterns of variables (depth to groundwater, TDS, Cl^-, HCO_3^-, SO_4^{2-}, Na^+, K^+, Ca^{2+} and Mg^{2+}) and, accordingly, analyze temporal and spatial variations in groundwater levels over the past 10 years in the Minqin oasis, get a better understanding of the groundwater quality and discuss the developing trend of groundwater quality over the past 40 years. The results of the analysis can be used for technical developments related to applied Geostatistics and instruction of sustainable management of groundwater resources to meet future water requirements in the Minqin oasis as well as other similar arid and semi-arid regions.

Materials and methods

Study area

The Minqin oasis is located in the lower reaches of the Shiyang River, Gansu province, northwest China (Fig. 1). The area covers approximately 2,868 km^2 (102°54′ to 103°49′ E and 38°27′ to 39°07′N, altitude from 1,309 to 1,459 m). Situated in the interior of an inland river basin, this area has an extremely arid climate and is one of the driest regions in China. This area is characterized by scanty precipitation (about 110 mm), strong evaporation (more than 2,664 mm), frequent wind (the days with strong winds of more than 17 m/s exceed 25), abundant sources of sand and long sunshine hours (3,028 h). The annual average temperature is 7.8 °C, and winter temperature minima can fall to −27.3 °C whereas summer maxima rise to 41.1 °C. The annual average wind speed is about 2.8 m/s.

In the Minqin oasis, agricultural water use accounts for more than 95 % of the total water consumption. Farmland has been continuously developed since 121 BCE. At present, cultivated land occupies 47,900 ha and the main soil type is silt clay. Principal crops include cereals (spring wheat and summer maize) and cash crops (cotton, seed melon and fennel) (Fang et al. 2005). Native vegetation is mainly drought-resistant shrubs, salt-resistant shrubs and perennial sand-loving herbaceous plants (Kang et al. 2004). Based on the agricultural development history and socio-economic characteristics, the oasis can be mainly divided into three irrigation districts: Baqu, Quanshan and Huqu (Fig. 1).

The only surface water resource in the oasis comes from the Shiyang River. Over the past 60 years, due to over-consumption of water resources in the upper reaches of the Shiyang River, the water discharged into the Minqin oasis has gradually decreased. The water volume at Hongyashan Reservoir (surface water entrance of the oasis) was 573 million m^3 in the 1950s, but decreased to 445 million m^3 in the 1960s, 225 million m^3 in the 1980s, 148 million m^3 in the 1990s and 86 million m^3 in 2000 (Gansu Water Management Bureau 2007). As a result, farmers in this region now depend on pumping groundwater for both irrigation and drinking water. Recently, groundwater has begun to be exploited in the vicinal desert region, i.e. the Tengger desert. There can be little doubt that the groundwater is being extracted much more rapidly than it is being replaced. In 1965, there were only 165 shallow wells but by 1976, there were 10,000 wells with over 14,000 by the end of the last century to a maximum depth of 320 m and groundwater abstraction had reached 11.6×10^8 m^3/year, far exceeding the groundwater natural recharge (Edmunds et al. 2006).

Geology and hydrogeology

The Minqin oasis is geomorphicly characterized as an alluvial plain. Its headstream—Shiyang River originates from the Qilian Mountains. From the end of the Palaeozoic and continuing through the Mesozoic era, the uplift of the Qilian Mountains created the embryonic Hexi Corridor. Followed by a complex tectonic stage, the Longshoushan–Hongyashan structural zone was formed, cutting the Hexi Corridor into two parts: the southern Wuwei Basin and the northern Minqin Basin. From the late Tertiary, especially from the end of the Pliocene and at the beginning of the early Pleistocene, the Tibetan mountains uplifted rapidly (Li et al. 1979) and the basins subsided further. At the same time, erosion from the mountains led to significant transfer of clastic material to the basin depression. The deposition of these clastics formed the Quaternary diluvial and alluvial sediments, as well as some aeolian and lacustrine sediments, which form the main aquifer system (Fig. 2).

Since Pliocene, this area filled with Pliocene and Quaternary sediments with thicknesses of several hundred meters. The Pliocene and early Pleistocene sediments in the oasis are inter-bedded, poorly consolidated fluvio-lacustrine sandstones with thickness averaging 200–300 m. The later Middle and Late Pleistocene sediments are
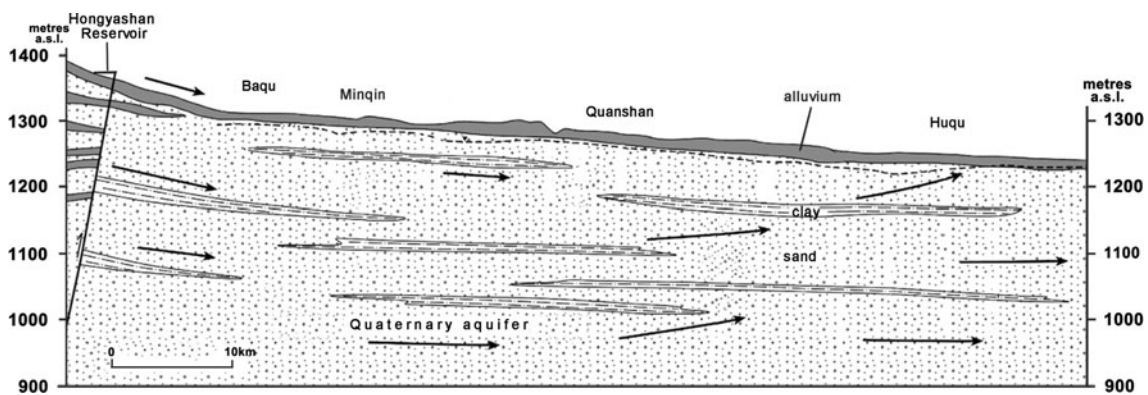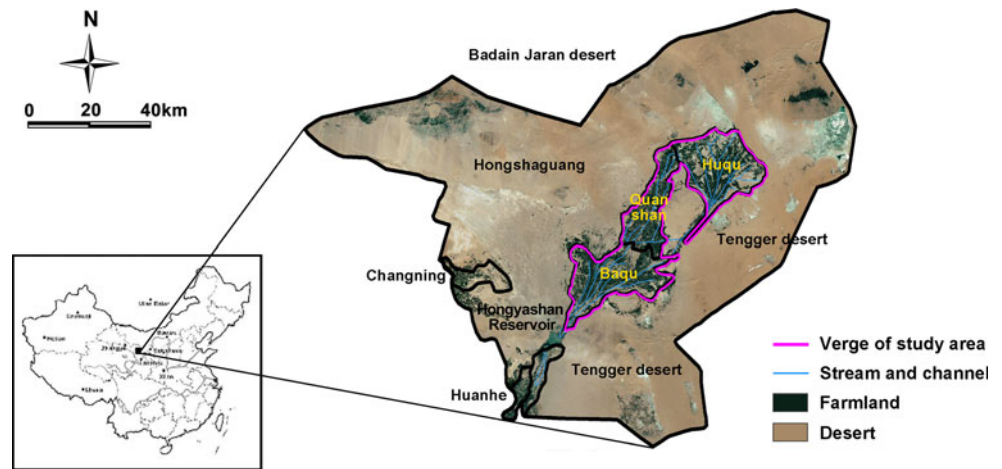
Fig. 1 Location of the study area

Fig. 2 Schematic hydrogeological cross-section of the Minqin oasis

composed of fluvial sands in the south but inter-bedded sandy-clay and clay in the north, with a thickness among 80–130 m.

The groundwater systems are basically divided into two groups in this area: the shallow phreatic aquifer and the deep confined aquifer. The 70–100-m thick shallow phreatic aquifer forms the main aquifer, which is composed of middle and late Pleistocene sediments. The specific capacity is about 10–1 L/(s m) and the coefficient of permeability is about 70–10 m/day along the groundwater flow direction (from south to north) (Qu 1991). The buried depth of groundwater in the deep confined aquifer is more than 100 m. The aquifer is made up of the Late Pleistocene sediments.

According to Edmunds et al. (2006), continuous groundwater recharge in the oasis mainly occurred during the cold and wet phases of the late Pleistocene and early Holocene with a minimum groundwater velocity of around 2 m/a. As the limited precipitation accounts for <5 % of the total recharge (Feng and Li 1997) and recharge to the aquifer from the Shiyang River is considered to have been of minor importance compared with

regional groundwater flow, the modern groundwater in the Minqin oasis is mainly recharged by limited surface water via river infiltration, canal system seepage and farmland irrigation water seepage. According to the utilization rates of water resources, irrigation infiltration occupies over 90 % of the total recharge of the aquifers. The groundwater discharge is mainly via evapotranspiration and artificial abstraction.

Data collection

Data for groundwater level analysis were provided by the Minqin Water Conservancy Bureau, which included the longitude and latitude coordinates for each of 51 groundwater observation wells and the monthly observed depth to groundwater from 1999 to 2008. The locations of the 51 observation wells are shown in Fig. 3. Based on the monthly average depth, a dataset of the average annual depth was established for each observation well and its geodetic coordinates. Within this dataset, the depth to groundwater in 1999 and 2008 was selected for the spatial variation analysis of groundwater levels.
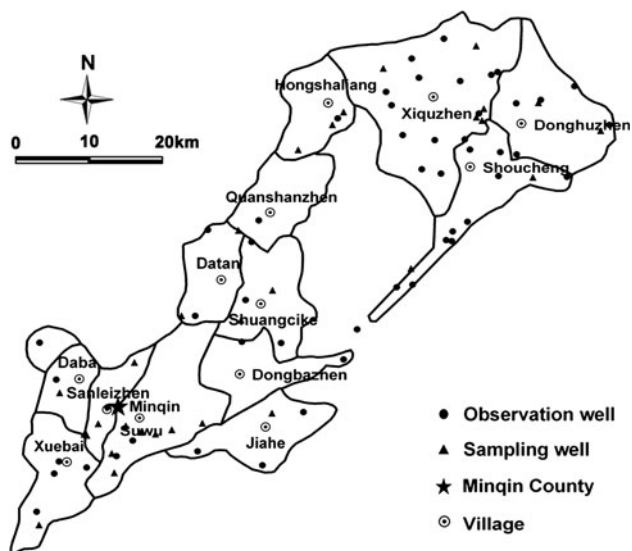
Fig. 3 Location of observation wells and sampling wells in the study area

Data for groundwater quality analysis were obtained from field investigations carried out during in August and September, 2010. Based on the geodetic coordinates of 8,000 active agricultural water supply wells provided by the bureau, 30 wells were selected for sampling (Fig. 3). Global positioning system was used to define the location. Each sample was taken after intensive pumping to avoid any local contamination or evaporative concentration. Sealed samples were then taken to the Key Lab in Cold and Arid Regions Environmental and Engineering Research Institute of the Chinese Academy Sciences for chemical analysis. The concentrations of anions (Cl^- and SO_4^{2-}) were analyzed by ion chromatography (Shimadzu) and HCO_3^- was analyzed by titration at pH 4.8. The concentrations of major cations (Ca^{2+}, Mg^{2+}, Na^+ and K^+) were analyzed by inductively coupled plasma (ICP-1,000 III C, Shimadzu).

Data analysis

Exploratory statistical analysis

Descriptive statistics, including the mean, maximum, minimum, median, standard deviation and coefficient of variation (CV) were calculated using SPSS 15.0. The statistical distribution of each dataset was evaluated using the kurtosis, skewness and Kolmogorov–Smirnov methods; when the distribution was not normal, the data were log-transformed.

Geostatistical analysis

A geostatistical method was used to study the spatial variability of the elements of groundwater levels and quality.

Geostatistics uses an experimental semivariogram to measure the spatial variability of a regionalized variable, and provides the input parameters for the spatial interpolation of kriging. The value of the experimental semivariogram for a separation distance of h (referred to as the lag) is half the average squared difference between the components of data pairs:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(x_i + h) - z(x_i)]^2 \qquad (1)$$

where $\gamma(h)$ is the experimental semivariogram value at distance interval h; $N(h)$ is the number of sample pairs within the distance interval h; $z(x_i)$, $z(x_i + h)$ is the sample value at two points separated by the distance interval h.

Several standard models are available to fit the experimental semivariogram, e.g., spherical, exponential and Gaussian models. The appropriate model is chosen by matching the shape of the curve of the experimental semivariogram to that of the mathematical function. The fitted model provides information on the spatial structure as well as the input parameters such as nugget (the variance at zero distance), sill (the constant value of the variogram when the variables do not influence each other) and range (the distance at which the value of one variable becomes spatially independent of another) for Kriging interpolation. In this study, the fitted spherical, exponential and linear models were selected.

Maps of the spatial distributing patterns of all elements were generated by Kriging interpolation. The Kriging is regarded as the best linear unbiased estimator and is based on the assumption that the parameter being interpolated can be considered as a localized variable (Matheron 1963). It is assumed that, given an adequate population, variables will exhibit a degree of continuity within a finite region. The Kriging can be classified into simple Kriging, ordinary Kriging, and universal Kriging. In this study, ordinary Kriging was selected.

Normality analysis and statistical tests were carried out using SPSS 15.0. Semivariogram analysis and the definition of the theoretical model were performed with version 7 of GS$^+$ software. Interpolation and spatial distribution maps were obtained by using the ArcGIS 9.2 (ESRI) software.

Results and discussion

Descriptive statistics and normality test

To evaluate the raw data, descriptive statistics for all data sets are presented in Table 1. The coefficients of kurtosis

Table 1 Descriptive statistics of the sample dataset in the study area

Variable	Number	Mean	Minimum	Maximum	Median	SD	CV	Skewness	Kurtosis	K–S p	Distribution
Depth to groundwater (m)											
1999	51	15.87	2.09	28.51	16.61	7.39	0.47	−0.27	−0.99	0.728	Normal
2000	51	16.74	2.32	30.47	17.52	7.73	0.46	−0.17	−0.89	0.934	Normal
2001	51	17.19	2.38	30.47	18.78	7.68	0.45	−0.33	−0.88	0.755	Normal
2002	51	17.70	2.43	32.25	18.86	7.87	0.44	−0.31	−0.82	0.778	Normal
2003	51	18.39	2.46	32.71	20.28	8.12	0.44	−0.37	−0.82	0.664	Normal
2004	51	19.05	2.57	33.75	21.73	8.50	0.45	−0.37	−0.89	0.222	Normal
2005	51	19.61	3.10	33.14	21.37	8.43	0.43	−0.44	−0.95	0.220	Normal
2006	51	20.39	3.25	34.63	22.90	8.71	0.43	−0.50	−0.89	0.375	Normal
2007	51	20.36	3.41	34.53	22.92	8.69	0.43	−0.45	−0.94	0.237	Normal
2008	51	20.52	3.67	32.61	23.17	8.37	0.41	−0.61	−0.91	0.059	Normal
Chemical composition of groundwater (mg/L)											
HCO_3^-	30	341.48	92.00	699.00	260.50	205.74	0.60	0.74	−0.91	0.055	Normal
Cl^-	30	650.77	29.00	2,906.00	168.75	934.25	1.44	1.66	1.48	0.000	Lognormal
SO_4^{2-}	30	1,500.24	150.00	7,061.00	572.00	2,073.33	1.38	1.83	2.17	0.000	Lognormal
Ca^{2+}	30	182.12	38.00	511.00	117.25	137.48	0.75	1.07	0.07	0.003	Lognormal
Mg^{2+}	30	219.47	14.00	1,043.00	66.00	325.07	1.48	1.88	2.27	0.000	Lognormal
Na^+	30	601.19	50.00	2,655.00	182.25	840.15	1.40	1.67	1.39	0.000	Lognormal
K^+	30	9.45	2.30	33.60	6.58	8.95	0.95	2.04	3.11	0.000	Lognormal
TDS	30	3,343.56	424.30	14,783.50	1,375.38	4,473.39	1.28	1.71	1.69	0.000	Lognormal

SD standard deviation, *CV* coefficient of variation

and skewness of the series of groundwater levels and HCO_3^- in groundwater were close to zero revealing that these variables had near normal distributions. The Kolomogorov–Semirnov test confirmed that they all followed a normal distribution (K–S $p < 0.05$) and the other variables (Cl^-, SO_4^{2-}, Ca^+, Mg^{2+}, Na^+, K^+ and TDS) followed non-normal distribution. Transformation was required for those variables prior to the next analysis. After logarithmic transformation, all data sets followed normal distribution or lognormal distribution (Table 1). Although normality is not a prerequisite for Kriging, it is a desirable property. Kriging would only generate the best absolute estimate if the random function fits a normal distribution (Goovaerts 1997).

The CV values of depth to groundwater ranged from 0.41 to 0.47, and those for HCO_3^-, Ca^+ and K^+ were 0.60, 0.75 and 0.95, respectively, indicating that these variables had moderate variations. TDS and other ions (Cl^-, SO_4^{2-}, Mg^{2+} and Na^+) showed higher variability and characterized by CV > 1.0 suggesting that these ions would had the highest possibility of being influenced by historical factors such as groundwater evolution.

Spatial structure

As ordinary Kriging was chosen as the optimum interpolation algorithm for all variables, experimental

semivariograms were computed. Theoretical spherical, exponential and linear models provided the best fit for the variables (Fig. 4; Table 2).

In this work, the semivariograms showed a lower nugget effect on both groundwater levels and chemical composition of groundwater (Table 2), indicating that the sampling density was adequate to reveal the spatial structures. According to Cambardella et al. (1994), the ratio of nugget to sill ($C_0/(C + C_0)$) can be used to denote the spatial dependence of regionalized variables (ratio <25 % indicates strong spatial dependence; between 25 and 75 % denotes moderate spatial dependence; >75 % indicated weak spatial dependence). The values of this ratio for groundwater levels in 1999 and 2008 were 6.04 and 0.11 %, respectively, indicating that the spatial dependence of groundwater level was strong. Regarding groundwater ions, the values of this ratio for Mg^{2+} and K^+ were 33.33 and 34.38 %, respectively, indicating that the spatial dependence of these two cations was generally moderate. Considering the few factories in the Minqin oasis, the strong spatial dependence of other ions can be attributed to intrinsic factors (groundwater formation). The range of the depth to groundwater in 1999 and 2008 were 21.68 and 24.79 km, respectively, which implies that the length of the spatial autocorrelation is much longer than the investigation wells' average interval of 4.8 km. The range of groundwater chemical contents varied from 8.96 to
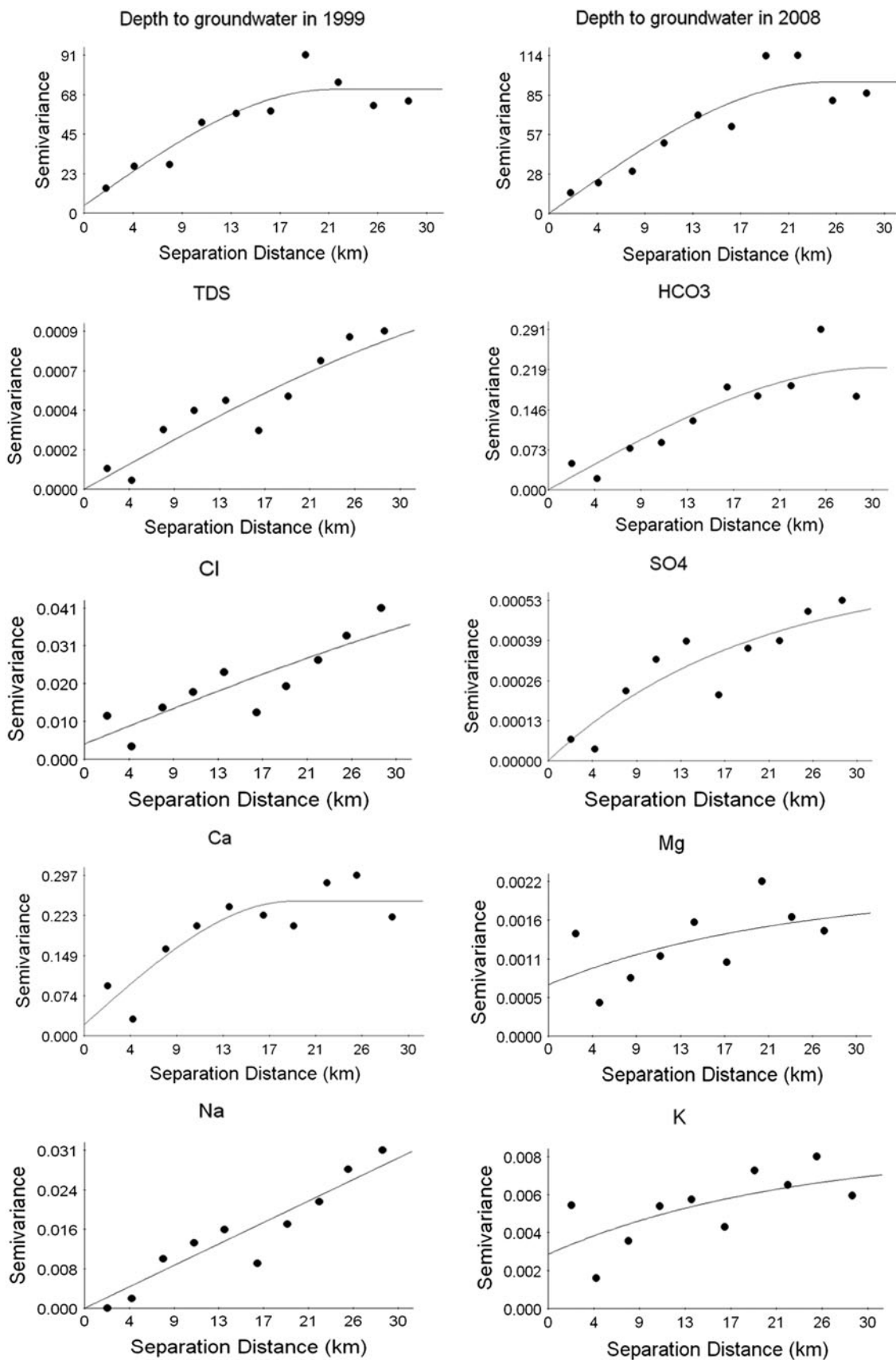
Fig. 4 Semivariograms model of all variables

Table 2 Semivariogram models and parameters of the sample dataset

Variable	Model	Nugget (C_0)	Sill $(C + C_0)$	$C_0/(C + C_0)$ (%)	Range (km)
Depth to groundwater					
1999	Spherical	4.30000	71.140	6.04	21.68
2008	Spherical	0.10000	94.600	0.11	24.79
Chemical composition of groundwater					
HCO_3^-	Spherical	0.00010	0.2222	0.05	30.61
Cl^-	Spherical	0.00410	0.0509	8.06	62.60
SO_4^{2-}	Exponential	0.00001	0.0006	1.67	58.98
Ca^{2+}	Spherical	0.02060	0.2492	8.27	19.27
Mg^{2+}	Spherical	0.00070	0.0021	33.33	68.52
Na^+	Linear	0.00001	0.0089	0.11	8.96
K^+	Exponential	0.00300	0.0087	34.48	66.27
TDS	Spherical	0.00002	0.0011	1.82	50.12

68.52 km, indicating that groundwater chemical contents depended on the groundwater parent material.

Groundwater levels

Temporal variation in depth to groundwater

The statistical analysis results for groundwater levels from 1999 to 2008 are shown in Table 1. The mean depth to groundwater declined from 15.87 m in 1999 to 20.52 m in 2008, with a mean decline rate of 0.52 m/year. This result agreed with those of studies conducted in arid and semi-arid regions in northern China, which concluded that groundwater levels were falling at alarming rates (Liu and Jun 2004). The minimum depth to groundwater declined year after year, revealing that extraction in shallow groundwater areas increased year after year and recharge of groundwater was always slower than extraction. However, the maximum depth to groundwater was fluctuant, as elevating 0.61 m in 2005, 0.10 m in 2007 and 1.92 m in 2008. And, the decline rate in 2006–2007 was −0.03 m/year and 0.16 m/year in 2007–2008, much smaller than the mean and previous decline rates (the smallest decline rate before was 0.45 in 2000–2001). This phenomenon demonstrated that the decline range has relieved to a certain degree since 2007, which maybe profited from the water resource management policies implemented in the Minqin oasis since 2004. Such policies include a water transfer project (from Jingtai in Gansu province), farmlands conversion to forests, withdrawals of some agricultural water supply wells and enforcement of efficient irrigation modes. Although all these policies had played some positive effects on relieving groundwater table decline, they are insufficient for solving the crisis in the Minqin oasis.

Spatial variation of depth to groundwater

Figure 5 is the spatial distribution map generated based on the semivariograms of depth to groundwater in 1999 and 2008 within the study area. From this map, an intuitionistic comparison of variations in groundwater levels in 1999 and 2008 can be observed. Areas with different depths to groundwater were obtained by GIS methods. The depths to groundwater in the study area were mainly between 10–20 m in 1999 and 20–30 m in 2008. In 1999, areas with depth to groundwater among 10–20 m accounted for 61.7 % of the study area while >20 m accounted for 27.3 %. By 2008, areas with depth to groundwater among 10–20 m had dwindled to 19.4 % while >20 m grew to 62.6 % (>30 m grew to 8.5 %). In addition, in 1999, the sites with depth to groundwater below 10 m were surrounding Zhenbao, Fengqing, Huangan, Xinhua, Liuyu, Waixi, Wangzhi, Yanghe, Xinlong and Fuzhi (Fig. 5, 1999). In 2008, however, the sites with depth to groundwater below 10 m were only occurred near Wangzhi, Zhenbao, Yanghe, Xinlong, Huangan, Fengqing and Fuzhi (Fig. 5, 2008). In 2008, three obvious deep cones of depression (center of Baqu, Hongshaliang in Qushan and center of Huqu) had formed in the study area and the overall area with depth to groundwater among 28–35 m were 14,000 ha. The biggest cone appeared in Baqu, covering 50 villages and occupying 10,300 ha, with a mean drop in the center groundwater level of 1.4 m/year.

Regional differences among the decline rates of groundwater level were observed in the Minqin oasis. Different decline rate was corresponding to different terrain, physiognomy, exploitation conditions, and hydrogeology. The variations in groundwater levels in Baqu and Quanshan were more violent than that in Huqu. Over the past 10 years, the mean decline rates in Baqu and Quanshan were 0.64 and 0.93 m/year, respectively, with a maximum drop of 14.4 m (Sanxin in Fig. 5). In Huqu, however, the mean decline rate was 0.41 m/year and the maximum drop was 7.3 m, the decline rate was mainly slow-paced. In recent years, many policies, e.g. prevailing population migration in Huqu, favorable planting structure adjustment, have ameliorated the water utilization environment in Huqu. As a result, the groundwater exploitation speed in Huqu decreased.

Although some studies consider that natural climate fluctuations reduce groundwater recharge (Xia and Zhang 2008), the main cause of the groundwater decline on a more local scale is closely linked to human activities (Ma et al. 2005). Affected by the overgrowing population and rapid agricultural development, the total domestic water consumption in the Minqin oasis increased from 2.03 million m^3 per year in 1999 to 2.96 million m^3 per year in 2008. The population has significantly increased
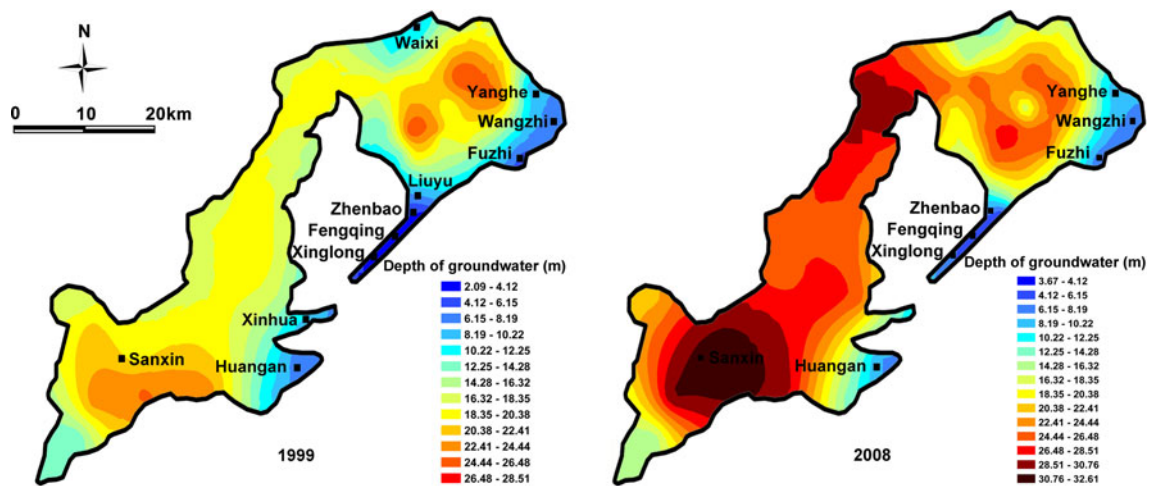
Fig. 5 Spatial distribution of depth to groundwater for 1999 and 2008

from 234,000 in 1999 to 273,000 in 2008. The population density was 95.19 per km^2 in 2008. Increasing population inevitably induced the increasing need for drinking and living water consumption, which amounted to 0.30 million m^3 per year. In addition, overgrowing population has also encouraged intensive agricultural development, which plays an important role in the economic development of this area. Farmland increased from 39.000 ha in 1999 to 47,900 ha in 2008. Consequently, widespread water consumption for agriculture was engendered.

Groundwater quality

Hydrochemical characterization

Groundwater quality mainly depends on physicochemical parameters and their concentrations. The mean value of the concentrations of TDS is 3.34 g/L with a range 0.42–14.78 g/L (Table 1), nearly 76.2 % is higher than 1.0 g/L. According to the World Health Organization (1993), the maximum permissible concentration of TDS for drinking water is 1.0 g/L. Thus, about 50 % of the population in the oasis where almost 70 % of the population depends on groundwater as a source of drinking water are facing acute drinking water crisis. WHO also noted that the TDS concentrations more than 1.0 g/L can make scales in water pipes, heaters, boilers and household appliances, indicating that the groundwater are not good even for irrigation. The high concentrations of chloride can give a salty taste to drinking water. According to World Health Organization (1993), the taste thresholds for chloride are in the range of 0.2–0.3 g/L and the maximum permissible concentration for drinking water is 0.6 g/L. In the present study, the chloride values of groundwater ranged within 0.03–2.91 g/L (Table 1). WHO suggested that the maximum value of sulfate in drinking water is 0.4 g/L. The

sulfate values of samples ranged within 0.15–7.06 g/L. About 60 % of samples showed higher sulfate values than the standard values. About 26.7 % of water samples had higher chloride values than the prescribed limit for drinking water. A guideline value of 0.2 g/L for sodium was established by WHO based on taste considerations. In the study area, the sodium value of groundwater samples ranged within 0.05–2.66 g/L. About 46.7 % of water samples showed higher Na values than the standard prescribed by WHO.

The spatial distribution of the concentrations of TDS and major ions are represented in Fig. 6. Due to higher ambient temperature, water–rock interaction and greater length of flow path, the values of these variables are all low in the southern part of the study area and gradually increased along the groundwater flow path. According to Fig. 6, the groundwater types can be spatially classified into three obvious zones. The SO_4^{2-}–HCO_3^-–Na^+–Ca^{2+} type occurred in most areas of Baqu where replenishment for most of the groundwater comes from the rapid seepage flow of river water. The mean value of the concentrations of TDS in this area was mostly <1.38 g/L, belonging to fresh water or slight saline water. In Quanshan, the water type transformed into SO_4^{2-}–Na^+–Ca^{2+}. This type of water belonged to slight saline or moderate saline water with the concentrations of TDS ranging from 0.80 to 3.23 g/L. The SO_4^{2-}–Cl^-–Na^+ type of water was dominant in the Huqu. The concentrations of TDS were mainly higher than 2.79 g/L, belonging to very saline or briny water.

The spatial distribution of chemical elements is useful for assessing the possible sources of evolution of groundwater and for identifying regional hydrochemical types in the study area. According to Fig. 6, the concentrations of SO_4^{2-}, Cl^- and Na^+ increased more prominently than the others along the groundwater flow path. Sulfate ions

Fig. 6 Spatial distribution of the chemical concentrations of groundwater
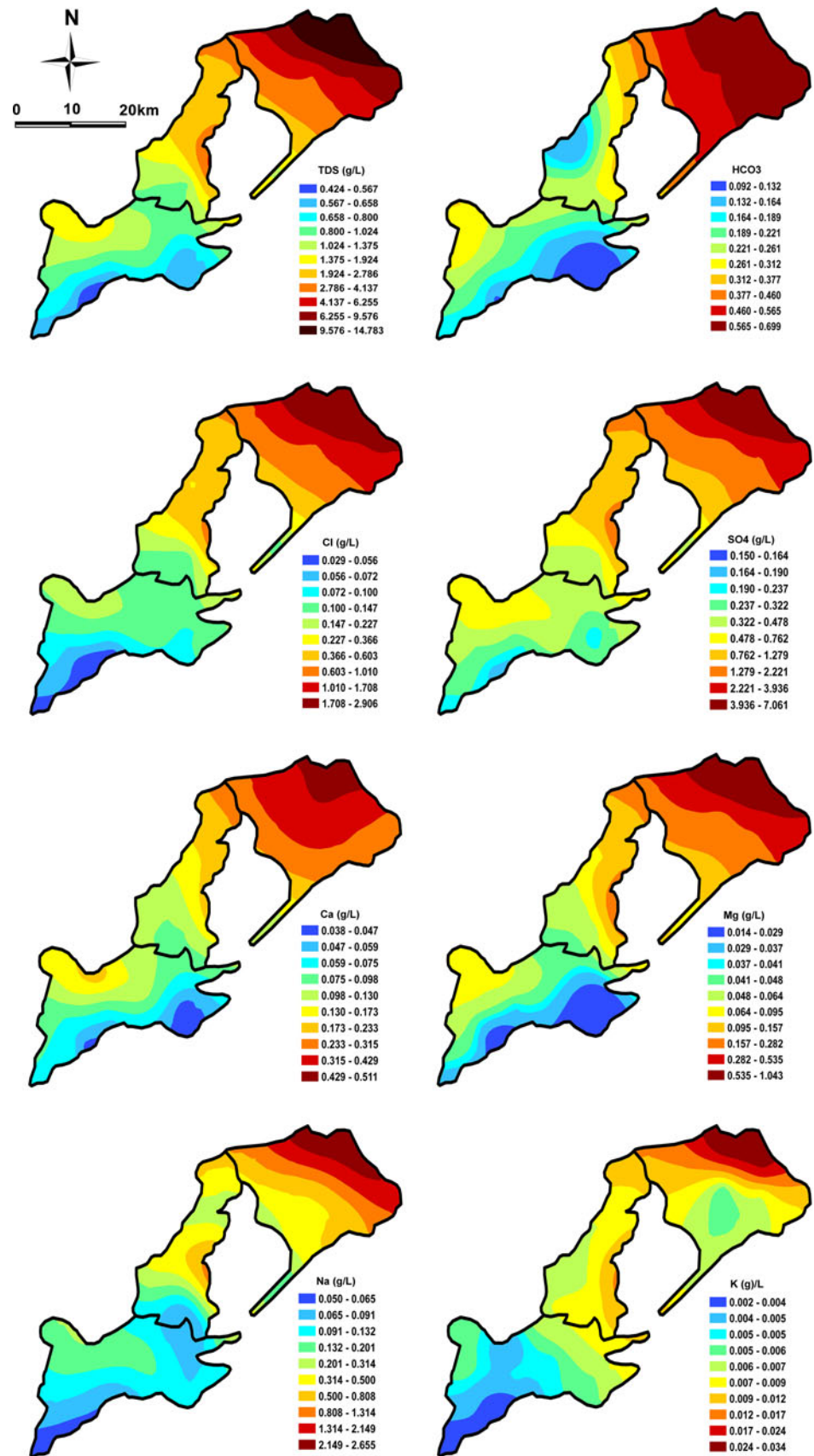
(SO_4^{2-}), the dominant anion in the whole study area, are primarily derived from gypsum ($CaSO_4 \cdot 2H_2O$) or anhydrite ($CaSO_4$), both of which are present as thick deposits in the study area (Shi et al. 2004). The values of chloride concentrations for about half the areas of Huqu exceeded 1.0 g/L are considered to be the result of some irrigation return waters and mixed evaporated waters from the original lake basin in north Huqu. This result suggested that an internal Cl^- source is required to produce the higher Cl^- values in Huqu, since these values are too high to be derived directly only from rainfall recharge. Among the cations, the mean value of the ratio of Na^+ to total cations was 51.04 %, revealing that Na^+ was dominant all over the study area. The primary source of most sodium ions is the release of soluble products during the weathering of plagioclase feldspars, which is common in the evaporite deposits and argillaceous sediments that are common in the study area. One significant characteristic of the groundwater in the study area was very the low K^+/Na^+ ratio (from 0.62 to 7.81 %). The low levels of potassium in natural waters are a consequence of its tendency to be fixed by clay minerals and to participate in the formation of secondary minerals. The main source of magnesium in groundwater is the dissolution of dolomite which is common in sedimentary rocks in the Minqin oasis. The aquifer and recharge areas in the study area are almost exclusively composed of siliceous clastic, metamorphic or granitic rocks with an absence of carbonate minerals. According to Edmunds, the virtual absence of carbonate minerals and silicate in the study area is predominantly caused by the weathering process and the groundwaters being close to dolomite saturation were caused by the weathering of reactive mafic minerals in the sediments derived from diorites in Qilian Shan source rocks (Edmunds et al. 2006).

Variation in groundwater quality

According to previous research (Liu and Chang 1992; Zhao et al. 2004; Liu et al. 2009), from the 1970 s to 2005, the concentrations of TDS mainly presented an increasing trend in the Minqin oasis year by year. As shown in Fig. 7, above 50 % of the study area had increased TDS of 0.1–0.5 g/L and the decrease only occurred in south Huqu and other small scattered places from 1977 to 1980. The highest increase in TDS concentrations (>1.0 g/L) was observed in north Huqu, indicating that the high TDS in Huqu is the result of a long-term historical accumulation process. In the 1970s, the TDS concentrations in Huqu were mostly 2.0 g/L, with increments above 1.0 g/L in Shoucheng and 3.0 g/L in other parts of Huqu by the 1980s (the locations of villages are shown in Fig. 1). By the end of 1990, the total area with TDS concentrations >5.0 g/L reached 250 km². In 1990s, at the northern-most point
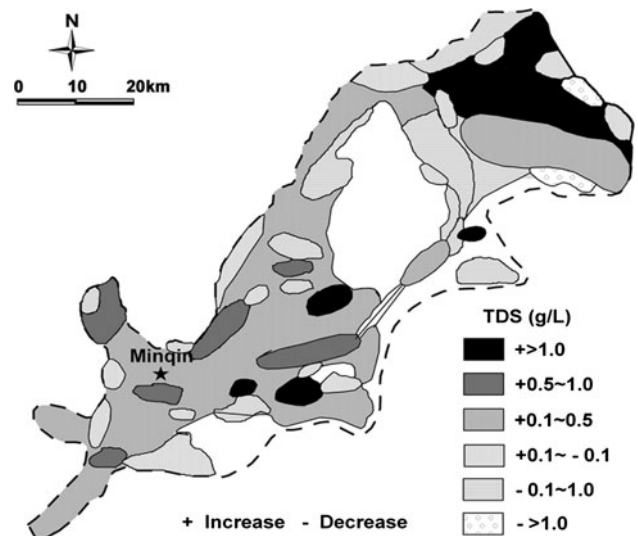

Fig. 7 Variation of the concentrations of TDS in 1980, using 1977 as reference year

Huqu, the TDS concentrations were mainly higher than 4.0–6.0 g/L and some places in the north even exceeded 16.0 g/L. As for Baqu, the TDS concentrations in most villages reached 1.0–3.0 g/L in 1980s. The increments of TDS from 1970s were 0.5–1.0 g/L in west Baqu, 1.0–3.0 g/L in Jiahe and Dongbazhen, and 0.2–0.5 g/L in Xuebai. In 1991, groundwater with TDS > 2.0 g/L was found mostly in Jiahe and Dongbazhen. However, by 2000, the TDS levels in Jiahe, Dongba, and Xuebai all exceeded 2.0 g/L and saline groundwater gradually fused together. For Quanshan, in the 1980s, the highest increments in TDS were 1.0–3.0 g/L in Shuangcike as well as 0.5–1.0 g/L in Datan, Quanshanzhen, and Hongshaliang. By the end of 1989, the TDS concentration reached 2.0–4.0 g/L and the increment in the 1990s was 0.12 g/L. In addition, compared with 2002, TDS concentrations in 2005 increased by 67, 20, 81, 18, 3 and 6 % in Xuebai, Daba, Datan, Quanshanzhen, Hongshaliang and Xiqu, respectively (Liu et al. 2009).

From 2005 until now, groundwater quality has gradually improved because of a series of water and soil management practices implemented in the Minqin oasis. Liu et al. (2009) reported that the concentrations of TDS in 2008 decreased by 35, 34, 71, 32, 8 and 5 % in the abovementioned villages than in 2005. Our results conformed with this conclusion, showing that the concentrations of TDS in Baqu, Quanshan and parts of Huqu all decreased. This phenomenon can be ascribed to the improved water resource management. Water reserves in Hongyashan reservoir has been increasing from 2004; thus, recharge from freshwater is endless and groundwater quality is bound to improve.

Our research showed that groundwater in most parts of the Minqin oasis is undesirable for drinking, and groundwater in some parts can even be harmful to human health. Given its location in the lower reaches of the Shiyang River, the oasis is destined to be a salt depository. Considering the special climate, terrain, and physiognomy in the Minqin oasis, the occurrence of high TDS concentration in groundwater is inevitable. Human activities have also contributed to the groundwater quality deterioration, including the following: continual agricultural activities, which are the main sources of elevated solute concentrations in groundwater (Hudak 2000; Harter et al. 2002); increased water consumption, which accelerates the transfer of water between surface water and groundwater stores; as well as increased reuse of water resources and decreased surface water runoff, which have led to the significant salinization of groundwater. Ma et al. (2009a, b) proposed that substances released by humans (e.g., industrial wastes, domestic sewage, rubbish, organic and inorganic fertilizers, as well as pesticides, which include a range of harmful substances) also affect groundwater quality both directly and indirectly.

Conclusions

Using a series of data on the study area, the temporal and spatial variations in groundwater levels and quality were analyzed using geostatistical techniques. All data followed a normal or log-normal distribution. Well-structured semivariograms were obtained, and the variables chosen were considered to have moderate (only for Mg^{2+} and K^+) or strong spatial dependence. Based on the spatial distribution maps in different periods drawn using the ordinary kriging interpolation method, the following conclusions were drawn.

The groundwater levels declined from 1999 to 2008 in the Minqin oasis. The mean depth to groundwater dropped 4.65 m from 1999 to 2008 with a mean decline rate of 0.52 m/year. The consumption of shallow groundwater increased, although the decline rate had slowed down since 2007. Spatially, the variations in groundwater levels were remarkable in 1999 and 2008. The depth to groundwater ranged from 10 to 20 m in 1999 (61.7 % of the study area) and exceeded 20 m (62.6 % of the study area) in 2008. The largest depression cone covered 50 villages in the oasis, with a mean drop in center groundwater level of 1.4 m/year. The variations in groundwater levels in Baqu and Quanshan were more evident than that in Huqu, with mean decline rates of 0.64, 0.93 and 0.41 m/year, respectively.

Groundwater is undesirable for drinking in most parts of the oasis, and can even be harmful to human health in some parts. The concentrations of TDS and major ions showed great variations along the groundwater flow path. The mean TDS was 3.34 g/L, and groundwater in 76.2 % of the study area was unsuitable for drinking. From south to north, the groundwater types were classified into three obvious zones based on the major ion distributions: SO_4^{2-}–HCO_3^-–Na^+–Ca^{2+} type in Baqu, SO_4^{2-}–Na^+–Ca^{2+} type in Quanshan, and SO_4^{2-}–Cl^-–Na^+ type in Huqu. From the 1970s to 2005, TDS mainly presented an increasing trend in the study area: 4.0–6.0 g/L at the northern-most point of Huqu and >16.0 g/L in some areas; >2.0 and 2.0–4.0 g/L in most villages in Baqu and Quanshan, respectively. From 2005 until now, the concentrations of TDS has gradually decreased.

The results this study have important implications for groundwater management in the Minqin oasis as well as in the Shiyang River basin, probably the most water stressed of all basins in northwest China (a region destined for rapid development under China's West Development Strategy) (Ma et al. 2005; Edmunds et al. 2006). Given the alarming rates of groundwater level decline in the Minqin oasis, the patterns of groundwater resource utilization in the region must be reconsidered. The first target must be the development of a culture of water conservation across the region to conserve and protect groundwater resources. Meanwhile, groundwater management in the Minqin oasis is inevitably coupled with salt management. Given that agricultural water use accounts for >95 % of total groundwater consumption in the Minqin oasis, reduction of the irrigated area or changes in the vegetation can reduce the consumption of groundwater and salt accumulation. Modern irrigation technologies and new irrigation regulations for cover groundwater resource management and allocation within the oasis are urgently needed to achieve sustainable development. The bulk of groundwater resource in some villages in the Minqin oasis is predicted to be very limited. Thus, continuing exploitation of this groundwater is strongly inadvisable. Otherwise, groundwater protection zones should be defined to prevent absolute destruction of groundwater resources. The conclusions of this paper serve as a step toward this direction. New water laws are also warranted to ensure the adherence of water users and enable unified water resource development and allocation within the oasis.

In addition, the results are also very useful for groundwater resource management in terms of groundwater quality assessments, mapping its vulnerability, and developing risk-based protection measures. An organization tasked with protecting public health by setting threshold levels for drinking water can be formed. This task may be thought of as straightforward, i.e., carrying out a risk assessment and setting the threshold level that determines public health safety. Given that groundwater is partly undesirable for drinking, new approaches to obtaining

sufficient quantities of good-quality drinking water should be identified. The limited surface water should be guaranteed safe for drinking, and the water transfer project is probably the most effective measure for this purpose.

References

Bonham-Carter GF (1996) Geographic Information Systems for Geoscientists: Modelling with GIS. In: Computer Methods in Geoscience. Pergamon, Ontario, p 414

Cambardella CA, Moorman TB, Novak JM et al (1994) Field-scale variability of soil properties in Central Iowa soils. Soil Sci Soc Am J 58:501–1511

Edmunds WM (2003) Renewable and non-renewable groundwater in semi-arid regions. Dev Water Sci 50:265–280

Edmunds WM, Ma JZ, Aeschbach-Hertig W et al (2006) Groundwater recharge history and hydrogeochemical evolution in the Minqin basin, North West China. Appl Geochem 21:2148–2170

Fang SM, Qian ZT, Li YP (2005) Comparison of four precipitation spatial interpolation methods in Gansu. J Arid Land Resour Environ 19:47–50

Feng G, Li PC (1997) Defects of natural distribution and strategies of sustainable development and utilization of water resources in northwest China. Agric Res Arid Area 15:64–71

Feng Q, Cheng GD, Masao MK (2000) Trends of water resource development and utilization in arid northwest China. Environ Geol 39:831–836

Feng Q, Liu W, Su YH et al (2004) Distribution and evolution of water chemistry in Heihe river basin. Environ Geol 45:947–956

Gansu Water Management Bureau (2007) The programming report for key measures of Shiyang River Basin. The Government of Gansu Province, Lanzhou (in Chinese)

Goovaerts P (1997) Geostatistics for natural resources evaluation. Oxford University Press, New York

Gu BS (2002) Sandstorm coming from here: on-the-spot record of Minqin basin ecological deterioration. China Disaster Reduc 44:13–15 (in Chinese)

Harter T, Davis H, Mathews M et al (2002) Shallow ground water quality on dairy farms with irrigated forage crops. J Contam Hydrol 55:287–315

Hudak PF (2000) Regional trends in nitrate content of Texas ground water. J Hydrol 228:37–47

Isaaks EH, Srivastava RM (1992) An introduction to applied geostatistics. Oxford University Press, New York

Kang SZ, Su XL, Tong L et al (2004) The impacts of water-related human activities on the water-land environment of Shiyang river basin, an arid region in Northwest China. Hydrol Sci J 49:413–427

Li J, Wen S, Zhang Q (1979) Study on times, extent and form of Tibet plateau upheaving. Sci China 9:608–616

Liu YC, Chang HC (1992) Utilization of brackish water resources and environment in arid zones. Gansu Science and Technology Press, Lanzhou (in Chinese)

Liu C, Jun X (2004) Water problems and hydrological research in the Yellow River and the Huai and Hai River basins of China. Hydrol Process 18:2197–2210

Liu WJ, Su YZ, Yang R et al (2009) Hydrochemical characteristics and spatial-temporal variation of mineralization for the groundwater in Minqin Oasis. Environ Sci 30:2911–2917 (in Chinese)

Ma JZ, Gao QJ (2000) The groundwater evolution and its influence on the fragile ecology in the South Edge of Tarim Basin. J Desert Res 20:145–149 (in Chinese)

Ma JZ, Wang XS, Edmunds WM (2005) The characteristics of groundwater resources and their changes under the impacts of human activity in the arid Northwest China—a case study of the Shiyang River Basin. Arid Environ 61:277–295

Ma JZ, Ding ZY, Wei GX (2009a) Sources of water pollution and evolution of water quality in the Wuwei basin of Shiyang river, Northwest China. J Environ Manage 90:1168–1177

Ma JZ, Ding ZY, Edmunds WM (2009b) Limits to recharge of groundwater from Tibetan plateau to the Gobi desert, implications for water management in the mountain front. J Hydrol 364:128–141

Matheron G (1963) Principles of geostatistics. Econ Geol 58:1246–1266

Qu H (1991) Assess of groundwater resources in the arid and semiarid land of China. Science Press, Beijing, p 349

Rivoirard J, Wieland K (2001) Correcting for the effect of daylight in abundance estimation of juvenile haddock (*Melanogrammus aeglefinus*) in the North Sea: an application of kriging with external drift. ICES J Mar Sci 58:1272–1285

Schlüter M (1996) Einführung in geomathematische Verfahren undderen Programmierung. Enke Verlag, Stuttgart

Shi JA, Wang Q, Chen GJ et al (2001) Isotopic geochemistry of the groundwater system in arid and semiarid areas and its significance: a case study in Shiyang River Basin, Gansu Province, Northwest China. Environ Geol 40:557–565

Shi PZ, Ma JZ, Zhao H (2004) Simulation of geochemical evolution of groundwater beneath the Minqin Basin, Gansu Province. Arid Land Geogr 27:305–309 (in Chinese)

World Health Organization (WHO) (1993) Guidelines for drinking water quality. Recommendations. Geneva, p 130

Xia J, Zhang Y (2008) Water security in north China and countermeasure to climate change and human activity. Phys Chem Earth Parts A/B/C 33:359–363

Zhang YH, Wu Y, Su J et al (2005) Groundwater replenishment analysis by using natural isotopes in Ejina basin, northwestern China. Environ Geol 48:6–14

Zhao H, Ma JZ, Zhu GF et al (2004) Study on the change of the groundwater environment and its causes in the Minqin Basin, Gansu Province. Arid Zone Res 21:210–214 (in Chinese)