

Groundwater simulation using a numerical model under different water resources management scenarios in an arid region of China

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Abstract Groundwater plays an important role in the economic development and ecological balance of the arid area of northwest China. Unfortunately, human activity, for example groundwater extraction for irrigation, have resulted in excessive falls in groundwater level, and aquifer overdraft in the oasis, disrupting the natural equilibrium of these systems. A groundwater numerical model for Minqin oasis, an arid area of northwest China, was developed using FEFLOW software to simulate regional groundwater changes under transient conditions. The vertical recharge and discharge (source/sink terms) of the groundwater models were determined from land-use data and irrigation systems for the different crops in the different sub-areas. The calibrated model was used to predict the change for the period from 2000 to 2020 under various water resources management scenarios. Simulated results showed that under current water resources management conditions groundwater levels at Minqin oasis are in a continuous drawdown trend and groundwater depth will be more than 30 m by 2020. Reducing the irrigation area is more effective than water-saving irrigation to reduce groundwater decline at Minqin oasis and the annual groundwater budget would be $-0.978 \times 10^8 \text{ m}^3$. In addition, water-diversion projects can also reduce the drawdown trend of groundwater at Minqin oasis, and the groundwater budget in the Huqu sub-area would be in zero equilibrium if the annual inflow into the oasis was enhanced to $2.51 \times 10^8 \text{ m}^3$. Furthermore, integrative water resources management including water-diversion projects, water-saving irrigation, and reducing the

irrigation area are the most effective measures for solving groundwater problems at Minqin oasis.

Keywords Groundwater simulation · Numerical model · Water resources management

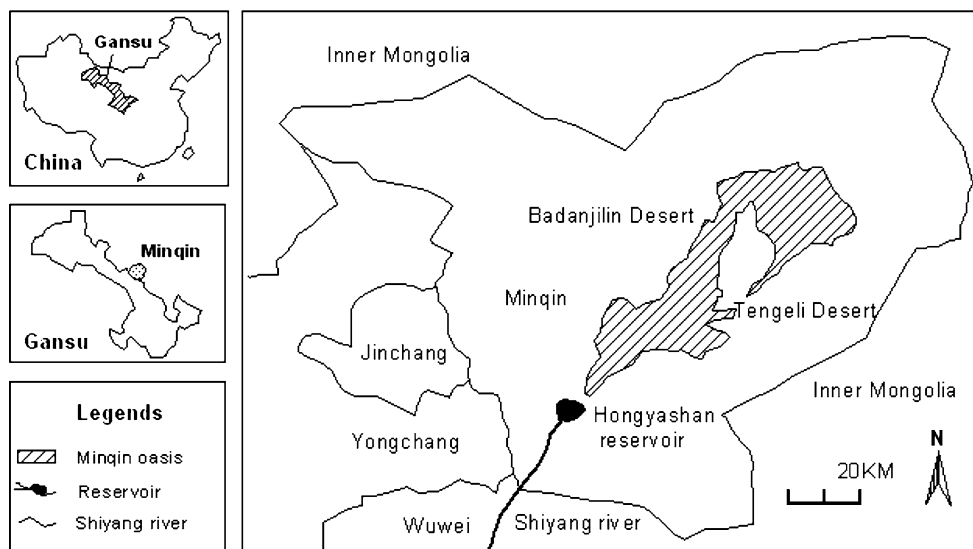
Introduction

Water resources shortages have become an increasingly serious problem, particularly in arid Northwest China, which is an ecologically fragile environment. The total water resources deficit in arid Northwest China was projected to be about 15 billion m^3 at the beginning of the 21st century (Feng and Li 1997). The arid inland watersheds of the Hexi Corridor are among the driest zones in the world (Wang et al. 2002) and water resources in this area are not only essential for agricultural and economic sustainability, but also a critical environmental component of the dry climate (Ji et al. 2006; Ma et al. 2005). The shortage of water resources and the induced degeneration of the ecological environment of this once lush and highly productive agricultural region have attracted much research (Ji et al. 2006; Jia et al. 2004; Kang et al. 2004; Ma et al. 2005; Ma and Wei 2003; Wang and Cheng 1999a, b; Wang et al. 2002, 2003; Zhu et al. 2004).

With population growth and economic development, combined with the arid climate conditions, surface water has not satisfied requirements. As a result, groundwater also plays an important role in the economic development and ecological balance in the area. Unfortunately, human activities, such as groundwater extraction for irrigation, have resulted in excessive groundwater level declines and aquifer overdraft in the some oases, disrupting the natural equilibrium of these systems (Hu

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Fig. 1 Location of the study area



et al. 2002). This overexploitation of water has had many adverse effects on the local environment, including soil salinization, vegetation degeneration, and land desertification (Ma et al. 2007). Because of this, agricultural yields have diminished, forcing many farmers to abandon their ancestral homeland.

In the past, many researchers focused on the impact of human activities on groundwater systems in arid and semi-arid areas, leading them to conclude that overexploitation of these systems has caused excessive decreases in groundwater levels (IAHS 2001; Fan et al. 2001; Horton et al. 2001; Kang et al. 2004; Cui and Shao 2005; Ma et al. 2005; Wang et al. 2002). However, these studies have only analyzed the relationships between groundwater levels and human activities on a qualitative level.

Numerical models have been used successfully for simulating and predicting groundwater levels for many years (Zhao et al. 2005; Matej et al. 2007; Wen et al. 2007; Huo et al. 2007b). In arid areas, the agricultural sector is by far the major user of water resources, and groundwater is an important water resource for irrigation. Land use, irrigation methods, and the surface water from outer regions can affect groundwater exploitation, and, furthermore, changes in regional groundwater levels. Increasing demand for groundwater will require effective management of water resources. Thus, modeling groundwater levels dynamics with numerical models under various possible water resources management scenarios can help to decide options for sustainable groundwater management.

In this work Minqin oasis, located in northwest China, was selected for study. The objectives of the study were:

- 1 to develop a numerical model, considering land use and agricultural irrigation, for predicting regional groundwater dynamics; and

- 2 to simulate the effect of various water resources management scenarios on groundwater levels and to analyze groundwater budgets.

Study area

Minqin oasis, encompassing an area of 160,000 km², is surrounded by the Badanjilin and Tengeli Deserts (Fig. 1) and is located within the lower reach of the Shiyang River basin in the Hexi Corridor of northwest China; it supports a population of about 307,000. Minqin oasis has an arid climate, with average annual precipitation and evaporation values of 109.5 and 2,646.2 mm, respectively, per year over the last 50 years. The agricultural sector is by far the major user of water resources, up 93.3% of the total water consumed in this region. Because the size of the effective irrigation area in the study region has increased from 4.6×10^4 hm² in 1980 to 5.5×10^4 hm² at present, groundwater extraction has increased (Feng et al. 2008). In the year 2000 there were more than 9,000 known extraction wells at Minqin oasis, with the estimated quantity of groundwater extracted via these wells more than 4.00×10^8 m³, substantially exceeding that of natural replenishment, estimated to be 1.0×10^8 m³ (Huo et al. 2007a). Because this groundwater usage is not sustainable, groundwater levels at the oasis have declined substantially (Fig. 2).

In the study area, the Shiyang River is the only source of surface water, and has been used for irrigation at Minqin oasis, with the Hongyashan reservoir established within the lower reach in 1958. Unfortunately, with the development of industry and agriculture in the neighboring city of Wuwei, large diversions from Shiyang River have significantly

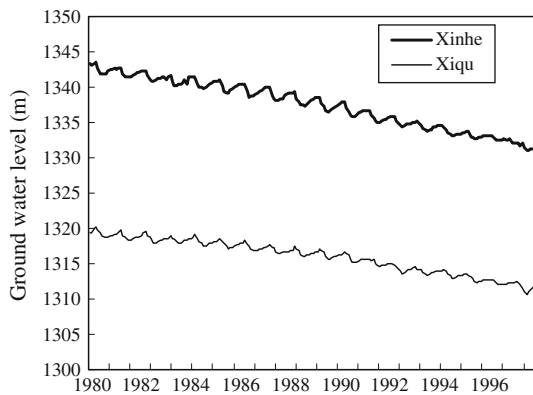


Fig. 2 Change of groundwater levels from 1980 to 2000 in Xinhe and Xiqu

reduced inflows into Hongyashan reservoir from $5.4 \times 10^8 \text{ m}^3$ in the 1950s to $1.2 \times 10^8 \text{ m}^3$ in the 1990s and less than $1.0 \times 10^8 \text{ m}^3$ in 2000 (Huo et al. 2007a). Because groundwater storage at Minqin oasis is highly affected by surface water conditions, Hongyashan reservoir has an important effect on transient groundwater levels. Recently, inflows into the reservoir have not been enough for agricultural irrigation and also result in the over-exploitation of groundwater at Minqin oasis. Excessive groundwater level decreases have caused serious ecological problems, for example land desertification and soil salinization, displacing inhabitants from their ancestral homeland (New York Times 2006).

Groundwater model

Numerical model

The groundwater system at Minqin oasis is a highly complex multilayered system consisting of 10–15 layers, or zones, of thickness ranging from 2 to 20 m. The upper unconfined aquifer consists predominantly of sand and gravel, and the lower aquifers exist under semi-confined conditions with vertical interconnections. Except for the upper unconfined aquifer, there are no continuous aquifers or hydrogeology units within this system. As a result, the aquifer of this domain is assumed to be an unconfined aquifer. The groundwater system is mainly affected by the source and sinks vertically, with relatively minor lateral fluxes into the system. A more detailed description of the hydrogeological system can be found in Ma et al. (2005).

Hydrogeology models have been developed on the basis of the characteristics of aquifer formation and groundwater flow at Minqin oasis. Considering the non-obvious changes of the media in the phreatic aquifers and changes in the alluvial plains, it can be assumed that the local media are

homogeneous. The following assumptions can be made for the two-dimensional phreatic flow on the plane of the horizontal impervious layers:

- 1 the change with z of head values at all the points of any section can be neglected; and
- 2 the horizontal current velocity does not change with z .

On the basis of these assumptions, the equations governing the horizontal two-dimensional phreatic flow in a homogeneous anisotropic medium are (Bear 1977):

$$\begin{cases} \frac{\partial}{\partial x} \left(Kh \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left(Kh \frac{\partial H}{\partial y} \right) + w(x, y, t) = \mu \frac{\partial H}{\partial t} \\ H(x, y, t)|_{t=t_0} = H_0(x, y), (x, y) \in \Omega \\ H(x, y, t)|_{\Gamma_1} = h_1(x, y, t), (x, y) \in \Gamma \\ h \frac{\partial H}{\partial n} |_{\Gamma_2} = q(x, y, t), (x, y) \in \Gamma_2 \end{cases} \quad (1)$$

where Ω is the domain of the simulated scope, Γ_1 and Γ_2 the boundaries of the first type and the second type, n the direction of the outer normal line of the second boundary, $H_0(x, y)$ the initial conditions, i.e. the initial head distribution (m), $h_1(x, y, t)$ the first type boundary conditions (m), $q(x, y, t)$ the second type boundary conditions with inflow being negative and outflow positive (m^3/day), H the groundwater level (m), h the distance between the bottom elevation of the phreatic aquifer (z) and the phreatic free surface (m), K the permeation coefficient of the aquifer (m/day), μ the water recharge, and $w(x, y, t)$ denote the source/sink factors of groundwater, i.e. the intensities of vertical water pumping and of percolation recharge per unit area (m/day).

Solution of the governing equation is achieved by the finite element method using FEFLOW software (Diersch and Kolditz 1998). According to the hydrogeological features in the study region, it was determined that the study area, general area $3,198 \text{ km}^2$, is from the southern boundary of the Hongyashan reservoir to the northern boundary of the desert zone. The domain was divided into 5,895 triangular meshes and 3,006 total nodes.

Boundary conditions

Groundwater flow in the aquifer is governed by the boundary conditions of the regional system. Boundary conditions are shown in Fig. 3. A no-flow boundary was defined between points B–C and C–D in the basin, because a groundwater divide is present at this boundary. Constant flux cells were defined between points D–E where groundwater flows outside. Along the boundary E–A, groundwater flows from the desert into the oasis. The boundary E–A is in the desert far from the oasis, and groundwater level varies slightly. Consequently, constant flux cells are also defined between points E–A. The

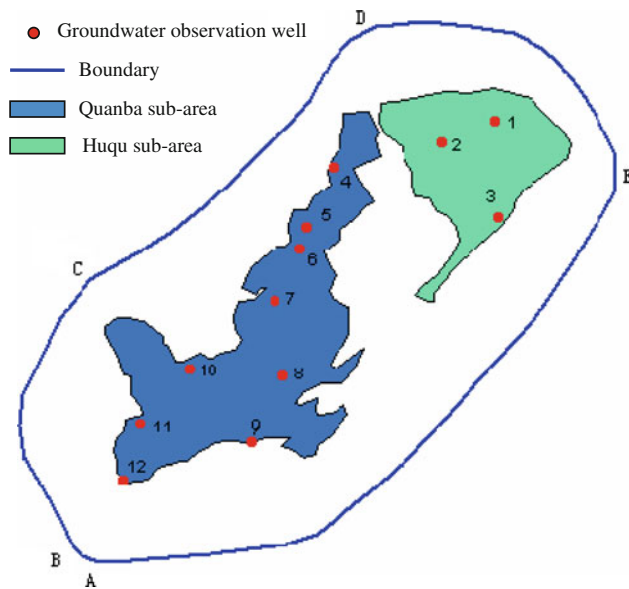


Fig. 3 Boundaries, observation well of groundwater levels, and the two sub-areas of the study area

boundary A–B is near the Hongyashan reservoir. Hydrogeology investigations have shown that groundwater flows through this boundary into Minqin oasis. A constant flux was defined at this boundary. The detailed groundwater fluxes at the boundaries of the domain are listed in Table 1.

Source/sink terms of groundwater

In the model, the source/sink factors represent vertical groundwater recharge and discharge. The source/sink factors in different land-use patterns are different. At Minqin oasis the land-use pattern includes irrigation field, forest land, shrub land, desert, and unused land.

With regard to groundwater pumping, irrigation field is the main land-use type which affects groundwater change. The effect of evapotranspiration and precipitation on groundwater is decided by groundwater depth. Some research has shown that groundwater recharge from precipitation and condensed water and groundwater discharge from evaporation can be neglected when the groundwater depth is deeper than 5 m. At Minqin oasis, groundwater depth has declined to 10–20 m and the effect of precipitation, water condensation, and evaporation on

groundwater can be neglected. So, the land-use patterns affecting groundwater include irrigation field, forests, and shrub.

Irrigation has the biggest effect on groundwater at Minqin oasis and is the dominant source/sink factor of groundwater. The sources term in the irrigation field includes the recharge volume by percolation from canals and fields. The sink term in the irrigation field is mainly the pumping groundwater volume. Because the irrigation schedule and surface distribution is different between the upper reaches and the lower reach of Minqin oasis, the study area was divided into two sub-regions including the Quamba area and the Huqu area for determining the source/sink terms in the irrigation field. The irrigation year in the Minqin oasis lasts from winter irrigation, using water from the reservoir, in mid October, until the next October. The irrigation systems are determined on the basis of the several species of crops and their growing areas. The volumes of well water and reservoir water used for irrigation in the whole sub-region are calculated according to the growing areas of crops, irrigation schedule of crops, and the irrigation systems. The pumped groundwater volume is then calculated on the basis of the utilization coefficients of the canal systems.

Because of the climate at Minqin oasis, the main growing period of plants covers eight months from March to October, so evapotranspiration is significant during this period and its seasonal difference is dramatic. Accordingly, groundwater losses are caused by the evapotranspiration in these eight months. The average annual groundwater losses caused by evapotranspiration from the forest and shrub lands are 270 and 38 mm respectively.

Model calibration

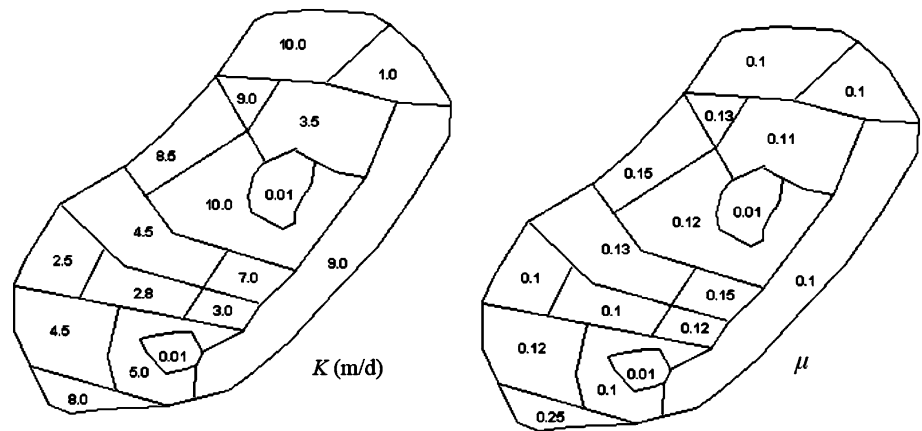
Criteria for evaluation of the model

In this study, statistical indices were used for quantitative evaluation of modeling performance. R^2 measures the degree to which two variables were linearly related. *RMSE* and *RE* provided different types of information about the predictive capabilities of the model—*RMSE* measured the goodness of fit relevant to high groundwater levels whereas

Table 1 Boundary conditions of the study area

Boundaries	AB	BC	CD	DE	EA
Water fluxes (10^8 m ³ /year)	0.060	0	0	0.073	0.355
Boundary length (km)	7.4	45	70	35	110
Aquifer thickness (m)	150	120	120	120	150
Groundwater flow speed at boundaries (m/day)	0.0148	0	0	0.0038	0.0059

Fig. 4 Distribution maps of the permeation coefficient (k) and of the degree of groundwater recharge (μ)



RE yielded a more balanced perspective of the goodness of fit at moderate groundwater levels. $RMSE$, RE , and R^2 were defined as:

- (a) the root mean square error ($RMSE$):

$$RMSE = \sqrt{\frac{\sum_{i=1}^m (y_i - O_i)^2}{m}} \quad (2)$$

where m is the number of observations, and O_i and y_i are, respectively, the i th observed and predicted data (using the ANN procedures).

- (b) the relative error (RE):

$$RE = \frac{1}{N} \sum_{i=1}^N \left(\frac{|y_i - O_i|}{\max(O_i) - \min(O_i)} \right) \times 100\% \quad (3)$$

where \bar{O} is the average value for O_i with $i = 1, 2, \dots, m$

- (c) the coefficient of determination, R^2 :

$$R^2 = \frac{[\sum (y_i - \bar{y})(O_i - \bar{O})]^2}{\sum (y_i - \bar{y}) \sum (O_i - \bar{O})} \quad (4)$$

where \bar{y} and \bar{O} are the averages of the data arrays of y_i and O_i .

Calibration results

Before the model was used to simulate future groundwater levels, calibration was carried out using historical data for groundwater levels. The hydrogeological properties permeation coefficient (K) and water recharge (μ), were calibrated in this groundwater model. The study area was divided into several sub-areas according to hydrogeology, and K and μ were constant for each sub-area. The values used in the models are calibrated according to the four fitting criteria above and the models are modified by using the land-use maps and the measured data for groundwater levels in 1998. The calibration makes the results calculated by the model match the measured groundwater level data as much as possible. The calibrated values are presented

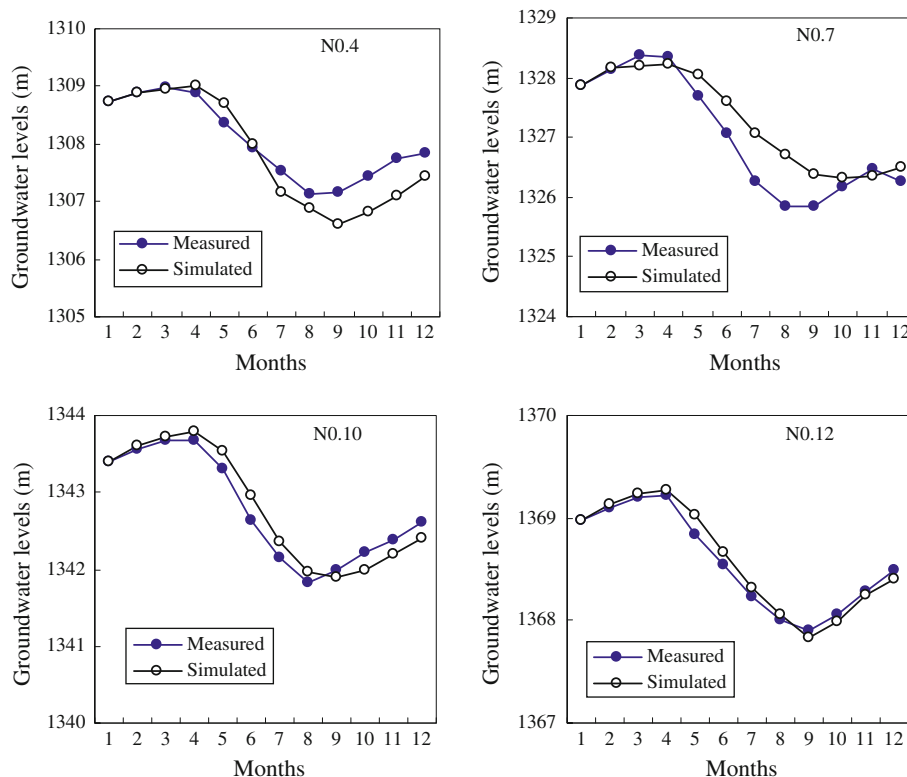
in Fig. 4. Comparison of simulated and the measured groundwater levels from 12 monitoring wells shows similar groundwater level trends with the hydrogeological situation at Minqin oasis, which indicates that the generalized models of the hydrogeological conditions mentioned above are reasonable. The models were verified by use of groundwater level data measured in 1999. Figure 5 shows comparisons between simulated and measured values of groundwater level from four monitoring wells in 1999.

Overall, precision is high for the groundwater with $RMSE$ of 0.71 m, RE of 17.96%, and R^2 of 0.84. However, the different groundwater level errors are significant between the two sub-areas. The $RMSE$, RE , and R^2 between simulated and measured groundwater levels are respectively 0.32 m, 12.7%, and 0.94 in the Quanba area. Comparatively, the groundwater model has higher error with $RMSE$ of 1.05 m, RE of 21.7%, and R^2 of 0.76 in the Huqu area. This can be attributed to the strong exploitation of groundwater in the Huqu area where there is almost no surface water to use and the change of groundwater is large with an average value of 4.13 m. Relative to the change of groundwater levels, the groundwater model has low error and the RE changes between 7.37 and 22.14%. Overall, the results show that the trend of changes of simulated groundwater levels basically matches that of the measured values. So the models can be used to simulate the effect of agricultural activities on groundwater levels.

Groundwater simulation under different water management scenarios

To cut the decline of groundwater levels and protect the ecological environment at Minqin oasis, several measures are proposed to reduce groundwater exploitation including agriculture water-saving projects, reducing the agricultural irrigation area, and possible water-diversion projects. The calibrated model was used to evaluate plans for potential exploitation of groundwater at Minqin oasis, with the

Fig. 5 Comparison of simulated and observed groundwater levels for four monitoring wells



objective of predicting aquifer drawdown. Simulations were made for the period 2000–2020. First, the current water resources management scenario including irrigation area $5.5 \times 10^4 \text{ hm}^2$, available surface water $0.9 \times 10^8 \text{ m}^3$, and traditional irrigation was simulated. Furthermore, two scenarios including water-saving irrigation and reducing the irrigation area were simulated. There are several possible water-diversion projects from outside the basin and the corresponding inflows of the Hongyashan reservoir are 1.45 , 2.91 , 2.93 , and $3.40 \times 10^8 \text{ m}^3$ respectively. In this study, groundwater at Minqin oasis after completion of different water-diversion projects was also simulated. There are, in addition, four scenarios assuming simultaneous water-diversion, water-saving irrigation, and reduction of the irrigation area. Altogether 11 scenarios were considered in this study; the detailed plans are listed in Table 2.

Scenarios 1–3: current conditions, water-saving irrigation, reducing irrigation area

At present there are $5.5 \times 10^4 \text{ hm}^2$ of irrigated fields at Minqin oasis, but the surface water flow into the Hongyashan reservoir is only about $0.9 \times 10^8 \text{ m}^3 \text{ year}^{-1}$. However, the crops are mainly wheat and cotton, etc., for which evapotranspiration is high and which are irrigated by flooding. The simulated results indicated that groundwater levels have a significant trend of decline at Minqin oasis

under current conditions (Fig. 6). Specifically, groundwater levels will decline with a velocity of 1.8 m year^{-1} in the Huqu sub-area and groundwater depth in the centers of the sub-areas will drop to 48 m in 2020. Because the Honyashan reservoir is near, some fields in Quanba sub-area can be irrigated with surface water and then the groundwater level will decline by 1.1 m year^{-1} and groundwater depth will drop to 35 m in 2020. This can be attributed to much pumping of groundwater. According to data measured by the local water-management department, groundwater exploitation increased from $3.73 \times 10^8 \text{ m}^3$ in the 1980s to $4.57 \times 10^8 \text{ m}^3$ in 2000. The calculated groundwater budget volume based on the simulated results for groundwater is $-3.029 \times 10^8 \text{ m}^3$ (Table 3). It is therefore necessary to determine a rational volume for groundwater exploitation and a distribution scheme for surface water at Minqin oasis.

Cutting down the irrigation area is an important measure for reducing groundwater exploitation at Minqin oasis. Simulation results showed that reducing the irrigation area can reduce drop speed of groundwater levels in the Minqin oasis. When the irrigation area decreased from $5.5 \times 10^4 \text{ hm}^2$ to $3.75 \times 10^4 \text{ hm}^2$, groundwater levels drop 0.46 and 0.27 m every year, respectively, in the Quanba and Huqu sub-areas and groundwater depths are between 15 and 30 m by 2020 (Fig. 6). The groundwater levels after cutting the irrigation area would be obviously higher than current conditions. Around the margin of the oasis, groundwater levels will decline by only 0.1 m every year

Table 2 Scenarios sets of water resources management for reducing groundwater exploitation in the Minqin oasis

Scenario	Surface water (10 ⁸ m ³)	Irrigation area (10 ⁴ hm ²)	Water-saving irrigation (yes or no)
Current conditions	0.9	5.4	No
Water-saving irrigation	0.9	5.4	Yes
Cutting down irrigation area	0.9	3.75	No
Water-diversion projects -1	1.45	5.4	No
Water-diversion projects -2	2.51	5.4	No
Water-diversion projects -3	2.93	5.4	No
Water-diversion projects -4	3.4	5.4	No
Integrative measures -1	1.45	3.75	Yes
Integrative measures -2	2.51	3.75	Yes
Integrative measures -3	2.93	3.75	Yes
Integrative measures -4	3.4	3.75	Yes

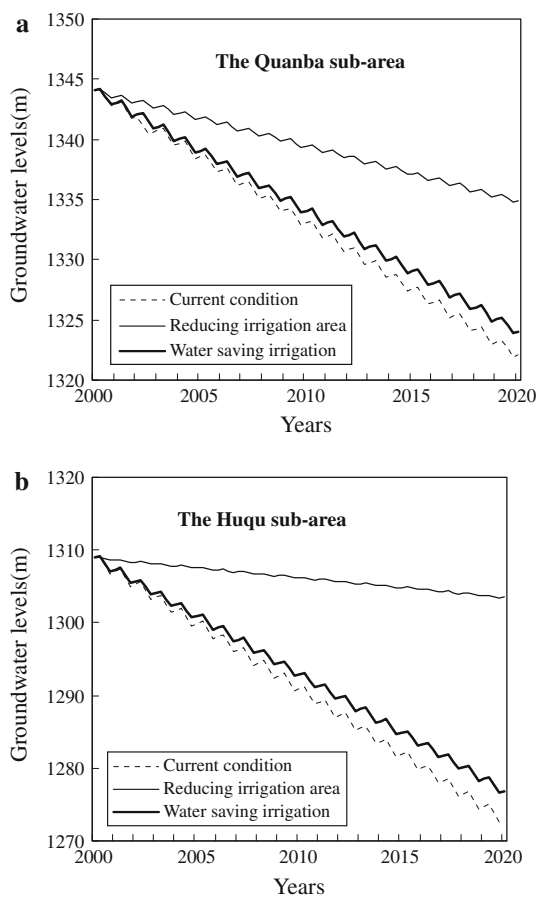


Fig. 6 Changes of groundwater levels in the Huqu and Quanba sub-areas of Minqin oasis under current conditions, after reducing the irrigation area, and after use of water-saving irrigation conditions

when the irrigation area is reduced to 3.75×10^4 hm². In addition, annual groundwater budget would be -0.978×10^8 m³ at Minqin oasis and the value is distinctly lower than that under current conditions (Table 3). So, reducing the irrigation area is an effective measure to reduce groundwater overexploitation.

In addition, water-saving irrigation is also a measure to reduce agricultural water usage which is favorable to groundwater renewal. According to local water-saving irrigation experiments and instructions from government, for the Quanba and Huqu sub-areas, irrigation water will decrease by 5,130 and 5,235 m³ hm⁻², respectively, every year as a result of water-saving projects, use of modern irrigation technology, and change of planting crops. However, simulation results showed the effect of water-saving irrigation on groundwater would not significantly alter the budget of the oasis change from -3.029×10^8 m³ to -2.791×10^8 m³. This can be attributed to lined canals which would reduce the leakage recharging groundwater. Groundwater levels would drop by 1.0 and 1.6 m, respectively, per year in the Quanba and Huqu sub-areas, and groundwater depths would be between 25 and 40 m by 2020. Although water-saving irrigation does not obviously reduce draw-down of groundwater, it can enhance the water utilization efficiency of plants. This is especially significant for arid areas where water is short.

Scenarios 4–7: different water-diversion projects

There are four water-diversion projects for protecting the ecological environment of Minqin oasis and corresponding inflows at Hongyashan reservoir are 1.45, 2.91, 2.93, and 3.40×10^8 m³. Surface water was allocated first to satisfy the irrigation demand of Quanba sub-area in winter and the Huqu sub-area, and then to satisfy the summer and autumn irrigation demand of Huqu sub-area where the ecology is frangible. The results indicated that water-diversion projects can reduce the decline of groundwater at Minqin oasis (Fig. 7; Table 4). When the surface water is 1.45×10^8 m³, groundwater will drop by 0.86 m every year and the groundwater budgets will be -2.322×10^8 m³ in the Quanba sub-areas. Furthermore, groundwater will decline

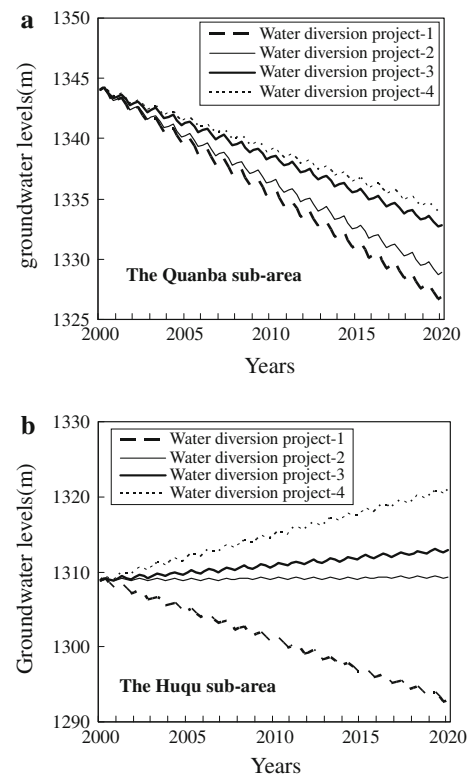
Table 3 Groundwater budgets in the study area and two sub-areas under current conditions, after reducing the irrigation area, and after use of water-saving irrigation (10^8 m³/year)

Scenarios	The study area	Quanba area	Huqu area
Current conditions			
Lateral recharge	0.472	0.390	0.052
Lateral discharge	0.016	0.089	0.013
Vertical recharge	0.306	0.140	0.158
Vertical discharge	3.791	2.704	0.946
Total	-3.029	-2.263	-0.749
Cutting down irrigation area			
Lateral recharge	0.472	0.313	0.037
Lateral discharge	0.016	0.099	0.015
Vertical recharge	0.431	0.101	0.317
Vertical discharge	1.865	1.328	0.444
Total	-0.978	-1.014	-0.105
Water-saving irrigation			
Lateral recharge	0.430	0.379	0.050
Lateral discharge	0.016	0.091	0.013
Vertical recharge	0.152	0.077	0.071
Vertical discharge	3.357	2.513	0.773
Total	-2.791	-2.148	-0.664

by 0.57 m every year and the groundwater budget will be -1.522×10^8 m³ in the Quanba sub-area when surface water is 2.93×10^8 m³. The trend in the drop of groundwater levels under surface water of 3.40×10^8 m³ is similar to that under surface water of 2.93×10^8 m³ and showed that surface water of 2.93×10^8 m³ can satisfy winter irrigation in the Quanba sub-area.

As the objective of the projects is to protect the Huqu sub-area where water resources are comparatively more scarce, the effect of increasing surface water is more obvious on groundwater in the Huqu sub-area than in the Quanba sub-area. When surface water is 1.45×10^8 m³, groundwater will drop by 0.80 m every year and the groundwater budgets will be -0.331×10^8 m³ in the Huqu sub-area. It should be noted that groundwater will be in plus equilibrium of 0.028×10^8 m³ and groundwater levels will climb in to Huqu sub-area when surface water is 2.51×10^8 m³. Specifically, groundwater levels will rise by 0.60 m every year and groundwater budget will be 0.519×10^8 m³ in the Huqu sub-area when the surface water is 3.40×10^8 m³. Groundwater levels will rise to 1,310 m and the groundwater depth will be approximately 10 m by 2020.

Overall, the groundwater budgets will change from -2.574×10^8 m³ to -0.781×10^8 m³ at Minqin oasis with an increase of surface water from 1.45×10^8 m³ to 3.4×10^8 m³. Water-diversion projects can contribute to groundwater renewal, especially in the Huqu sub-area, which can improve ecological environment at the oasis. So, water resources in the Shiyang river basin should be

**Fig. 7** Changes of groundwater levels in the Huqu area of Minqin oasis under water-diversion projects from outer regions

managed effectively and ensure enough water flow downstream into Minqin oasis.

Table 4 Groundwater budget in the study area and two sub-areas under water-diversion projects ($10^8 \text{ m}^3/\text{year}$)

Annual inflow into the reservoir ($10^8 \text{ m}^3/\text{year}$)	Scenarios	The study area	Quanba area	Huqu area
1.45	Lateral recharge	0.479	0.391	0.042
	Lateral discharge	0.016	0.089	0.015
	Vertical recharge	0.339	0.140	0.190
	Vertical discharge	3.376	2.764	0.547
	Total	-2.574	-2.322	-0.331
2.51	Lateral recharge	0.481	0.357	0.035
	Lateral discharge	0.016	0.094	0.017
	Vertical recharge	0.671	0.277	0.375
	Vertical discharge	2.810	2.391	0.366
	Total	-1.674	-1.852	0.028
2.93	Lateral recharge	0.488	0.334	0.028
	Lateral discharge	0.016	0.097	0.018
	Vertical recharge	0.825	0.277	0.533
	Vertical discharge	2.270	2.013	0.217
	Total	-0.973	-1.499	0.326
3.4	Lateral recharge	0.490	0.335	0.025
	Lateral discharge	0.016	0.097	0.021
	Vertical recharge	1.036	0.277	0.727
	Vertical discharge	2.291	2.038	0.212
	Total	-0.781	-1.522	0.519

Scenarios 8–11: integrative water resources management measures

Usually, several measures are used to more effectively manage local water resources and protect ecological environments. In this study, different water-diversion projects were combined with water-saving irrigation reducing irrigation area as four integrative water resources management scenarios. The simulated results of groundwater level changes and groundwater budgets are presented in Fig. 8 and Table 5. Under the scenario with surface water of $1.45 \times 10^8 \text{ m}^3$, water-saving irrigation, and reducing irrigation area, groundwater in the Huqu sub-area will decline by 0.5 m every year in the Quanba sub-area. When the surface water is increased to $2.51 \times 10^8 \text{ m}^3$, groundwater levels will rise by 0.6 m every year in the Huqu sub-area and drop 0.14 m every year in the Quanba sub-area. Meanwhile, the groundwater budget is $0.303 \times 10^8 \text{ m}^3$ in the Huqu sub-area and only $-0.019 \times 10^8 \text{ m}^3$ in the Minqin oasis. This indicates that the groundwater budget is near to equilibrium if inflow of the reservoir is $2.51 \times 10^8 \text{ m}^3$, crops were irrigated with water saving technology, and the irrigation area was reduced to $3.75 \times 10^4 \text{ hm}^2$. Furthermore, when surface water is enhanced to $2.93 \times 10^8 \text{ m}^3$, groundwater in the Minqin oasis has a significant rising trend. It is noted that annual groundwater budget will be

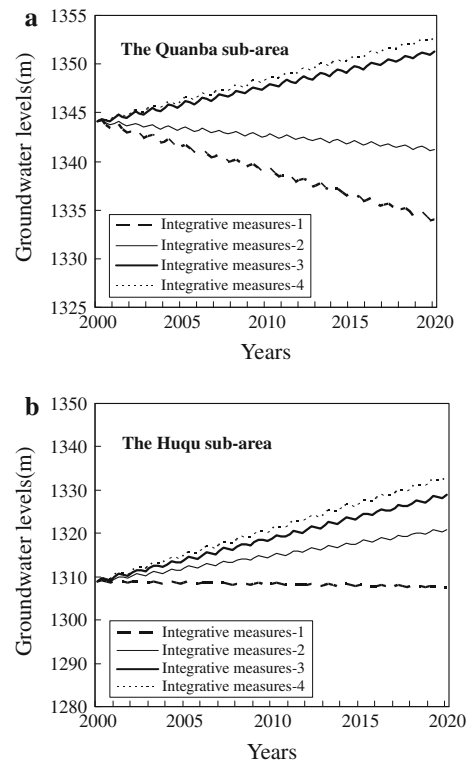


Fig. 8 Changes of groundwater levels in Huqu area of Minqin oasis under different integrative measures

Table 5 Groundwater budget in the study area and two sub-areas under different integrative measures

Annual inflow into the reservoir ($10^8 \text{ m}^3/\text{year}$)	The study area	Quanba area	Huqu area
1.45	-1.311	-1.309	-0.018
2.51	-0.019	-0.331	0.303
2.93	1.082	0.522	0.475
3.40	1.337	0.624	0.498

$1.337 \times 10^8 \text{ m}^3$ at Minqin oasis and groundwater levels will rise by 0.43 and 1.2 m every year, respectively, in the Quanba and Huqu sub-areas under the scenario with surface water of $3.40 \times 10^8 \text{ m}^3$. Groundwater fillers will vanish by 2015 and groundwater depth will decrease to 5–10 m by 2020 in the Huqu sub-area. At the same time, the groundwater depths will also decrease to 10–15 m. Simulated results indicate that the integrative water resources management measures are more effective for sustainable use of groundwater and for protecting the ecological environment than the single measures.

Conclusions

A groundwater numerical model for Minqin oasis, an arid area of northwest China, was developed using FEFLOW software to simulate regional groundwater changes under transient conditions. Vertical recharge and discharge (source/sink terms) for the groundwater models were determined from land-use data and irrigation systems for the different crops in the different sub-areas. The results from calibration of the model show reasonable agreement between observed and calculated water for the observation wells.

The calibrated model was used to predict changes for the period from 2000 to 2020 under 11 different water resources management scenarios. Under current water resources management conditions, groundwater levels in the Minqin oasis are in a continuous drawdown trend. It is necessary to take measures to reduce groundwater exploitation to protect the ecological environment. Saving water irrigation and reducing the irrigation area are two effective measures for sustainable groundwater management, and the latter is more effective at reducing groundwater decline at Minqin oasis. Moreover, water-diversion projects can also reduce the trend of groundwater drop at Minqin oasis, and the groundwater budget in the Huqu sub-area will be in zero equilibrium when annual inflow into the oasis is enhanced to $2.51 \times 10^8 \text{ m}^3$. Integrative water resources management measures including water-diversion projects, water-saving irrigation, and reducing irrigation area are the most effective measures for solving groundwater problems

at Minqin oasis. For sustainable utilization and development of water resources, further study is necessary to determine reasonable exploitation volume of groundwater and the suitable range of groundwater level in the oasis. It must be pointed out that the boundary conditions were not varied within the groundwater simulation period although the simulation results of different scenarios can be compared to understand the relative benefits of different resources management measures. In a future study a groundwater numerical model with changed boundary conditions will be developed to investigate the response of groundwater levels and budgets to different water resources management scenarios.

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