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ORIGINAL ARTICLE

Groundwater simulation for efficient water resources management in Zhangye Oasis, Northwest China

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Abstract Human activities, especially groundwater exploitation for agricultural production, have resulted in an excessive decline of the groundwater level and posed a serious threat of aquifer overdraft in the arid and semi-arid region of northwest China. For the purpose of managing water resources effectively, this study applied the Visual MODFLOW package to simulate the aquifer changes under various agricultural scenarios from 2009 to 2018 in Zhangye Oasis, the middle reaches of the Heihe River Basin, Northwest China. In addition to current conditions, limited irrigation and channel leakage prevention, which represent the essential trend of today's irrigation, were set as future water-saving agricultural scenarios. As the results show, under current water resource management conditions, groundwater levels fall at an alarming rate of 1 m/year in irrigation areas and 0.2 m/year in non-irrigation areas; moreover, the annual groundwater budget in the oasis will be -7.64×10^8 m^3. In addition, taking agricultural water saving measures can alleviate the groundwater problems efficiently, and the most promising water resource management for the Zhangye oasis could be decreasing the irrigation quota and the leakage coefficient of the canal system to 80 % of the current level and 0.3, respectively. Contrast of the two optimal scenarios indicates that limited irrigation is more effective than channel leakage prevention for groundwater protection in the Zhangye Oasis.

Keywords Groundwater simulation · Visual MODFLOW · Water resources management · Water-saving agriculture · Zhangye Oasis

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Introduction

Water scarcity has become an increasingly serious issue, and this scarcity relates to water for food production (Rijsberman 2006). Irrigated agriculture accounts for more than 90 % of the total global consumptive water use (FAO 2010; Shiklomanov 2000). According to a report made by UNESCO (United Nations Educational, Scientific and Cultural Organization 2006), the lack of sustainable methods for water resource management accounts for this water scarcity. In arid and semi-arid areas, water scarcity is a main factor restricting local economic development (de Vries and Simmers 2002; Alvarez et al. 2012) and influencing the ecological environment balance (Scanlon et al. 2007). In these areas, groundwater is of fundamental importance to meet the needs of economic development. However, in recent years, groundwater depletion has been reported for many semi-arid and arid regions worldwide, and can be attributed to agricultural withdrawals (Siebert et al. 2010; Ahmed and Umar 2009; Konikow and Kendy 2005; Rodell et al. 2009) that result in a series of ecological problems, such as water quality deterioration, vegetation degradation, soil salinization and land desertification (Wada et al. 2010; Ding and Zhang 2002; Ji et al. 2006; Zhu et al. 2004; Kong et al. 2005). It is therefore of great importance for arid and semi-arid areas to have scientific groundwater management in the face of increasing water

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scarcity and growing conflicts over water use (Postel 1996; Frederick 1993).

Understanding and quantifying the impact of irrigated agriculture on groundwater will provide a basic guidance for regional water resource management. In the last few years, much attention has been paid to the interactions between local surface water and groundwater (Harvey and Bencala 1993; Morrice et al. 1997; Negrel et al. 2003; Grasby et al. 1999; Wu et al. 2004). Most of these studies adopted isotope technology and the tracer method to quantify the current exchange capacity. It is not enough to simulate the response of regional groundwater dynamics to human activities and thereby to assess different water managements, although groundwater flow numerical models can be appropriate tools for these problems. As a result, many models have been widely developed and applied, including MODFLOW (McDonald and Harbaugh 1988), FEFLOW (Diersch 1998) and GMS (Anon 2000). Of them, MODFLOW is the most commonly used numerical model to simulate regional groundwater dynamics (Furman 2008; Barlow and Harbaugh 2006). On the basis of MODFLOW, the Visual MODFLOW system was developed by integrating MT3D and PEST, followed by applying modern visualization technology that has been used worldwide because of its easy accessibility, user-friendliness and versatility (Kashaigili et al. 2003). In the past several years, many researchers have applied these numerical models, but few have predicted groundwater evolution under different agricultural activities (Pisinaras et al. 2007; Xu et al. 2011; Feng et al. 2011).

In this paper, the Zhangye Oasis was selected as the study area as it is located in the middle reaches of the Heihe River, which has the most developed area of agriculture and is the area where the groundwater-surface water interact most frequently in the whole basin. For the purpose of managing water resources effectively, the model Visual MODFLOW is applied to simulate the dynamic groundwater response to agricultural activities. With the aid of the Geographic Information System, information about terrain, geology, land use, landform, vegetation, soil, water system and irrigation schedule is input into the model. Calibrating and validating the hydrogeological parameters, we can use the model to simulate and predict groundwater flow. Given the trend of agricultural water use in the Zhangye Oasis, groundwater resources affected by water-saving irrigation and limited irrigation are simulated for the period 2009–2018. Compared with current conditions, the optimal water-saving scenario is accessible from a groundwater protection perspective. Additionally, the output of this study can be combined with the study on water use efficiency (WUE) at field level or regional level to manage water resources more comprehensively.

Overview of study area

The Heihe River Basin, located in the middle of the Hexi corridor and ranging from 37°43′–42°42′N, 97°24′–101°30′E, is the second largest inland river basin, Northwest China. The middle reaches that contain the Zhangye Basin and Jiuquan Basin refers to the corridor plain located between the Qilian Mountain and Heli Mountain and controlled by the Yingluo Gorge and Zhengyi Gorge. As shown in Fig. 1, the Zhangye oasis discussed in this paper refers specifically to the agricultural region of Gaotai County, Linze County and Ganzhou District. In this area, the annual precipitation is 117 mm, whereas the annual potential evaporation is 2390 mm. There are 17 rivers in the oasis, with an annual mountainous runoff volume of 23.81×10^8 m^3 altogether. Except for the Liyuan River, water in other rivers flows at a low flux and there is no water flowing into Heihe River.

In its gravel and pebble layer, the water permeability is extremely good and the porosity is high. Additionally, there are also impervious or weak permeable terrane distributed in the basement. Therefore, the Zhangye Basin forms a natural reservoir storing plentiful groundwater. According to the structure, the aquifer system is divided into two classifications:a single-layer phreatic aquifer in the alluvial plain in front of the mountain in the southern basin and a multi-layered aquifer in the river valley fine-soil plain in the north-central basin. The former consists of single heavy-thickness gravels and pebbles as well as rich in fresh water, whereas the latter mainly consists of gravels and pebbles, then clay, clay loam, sand, etc.

Zhangye Oasis, the most developed area of agriculture and industry in the Heihe River Basin, is the region with maximal water resource consumption of the whole basin. According to statistics, there was 17.62×10^8 m^3 water supplied to the three counties and districts in 2011, approximately 89 % of which was used for agricultural irrigation. As to its source, in addition to 13.53×10^8 m^3 surface water, there was also 4.08×10^8 m^3 groundwater, which accounts for 23 % of the total. In the oasis, a predominant proportion of agriculture is the cultivation of wheat, barley, corn and corn for seed. Owing to the large water requirement quantities, the agricultural region is be studded with numerous canals and wells. Additionally, a total 5900 km of canals were lined for decreasing the loss of irrigation water. However, the regional groundwater level continually declined due to the overexploitation of groundwater at the same time. From the data monitored by two typical observation wells that were located in different places (Fig. 2), we can see that the levels practically decreased year by year, and the drawdown in the typical well (No. 11) from 1985 to 2010 has even reached 14 m.

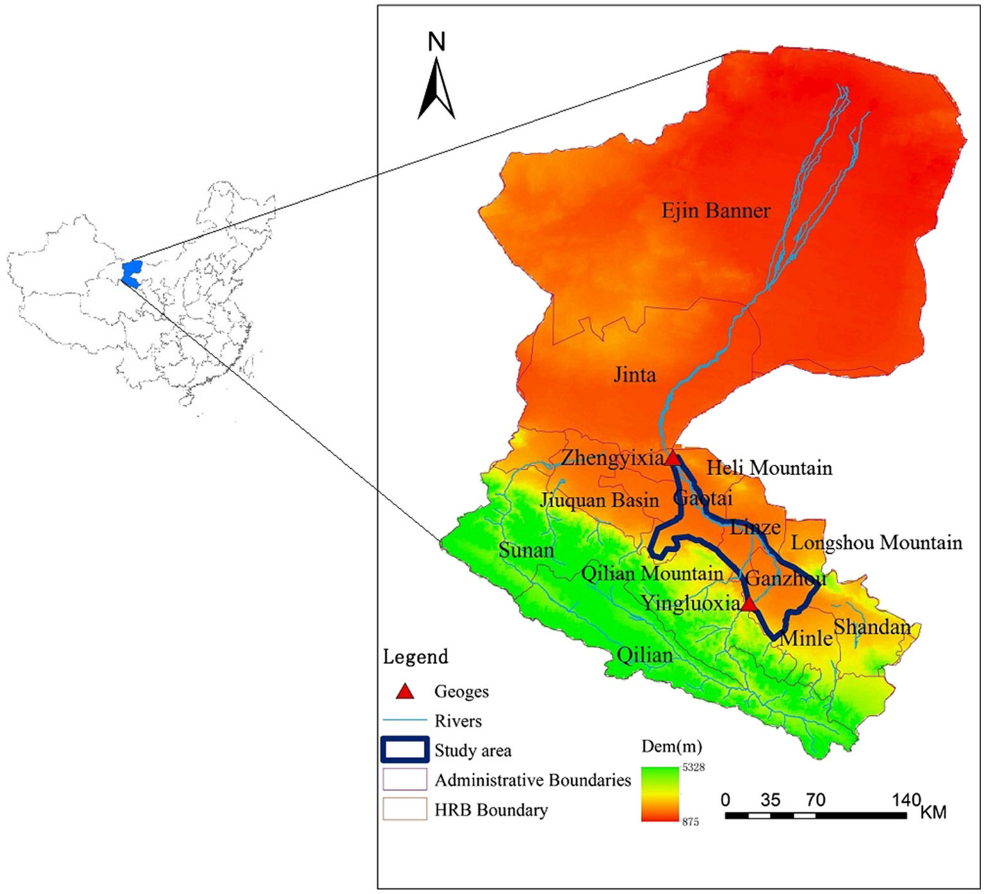

Fig. 1 Location of the study area

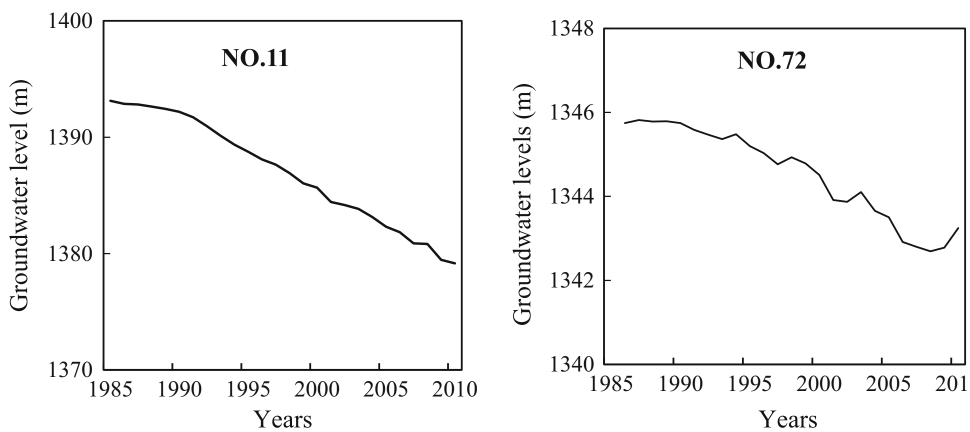

Fig. 2 Change of groundwater levels from 1985 to 2010 at two typical observation well

Groundwater model

Conceptual model

In the fine-soil plain, there is a plentiful absence of clay aquiclude and no stable impermeable layer between aquifers in different periods of the Quaternary. Furthermore, the aquifers are pierced by widely distributed wells. Therefore, the various aquifers of Zhangye Basin that are hydraulically well connected constitute a continuous and unified aquifer system. According to the causes for aquifer lithological structure and the results of the pumping test (Wu et al. 2010), the study area is divided into 30 hydraulic parameter zones (Fig. 3); in each zone, the aquifer is homogeneous and the hydraulic parameters are basically same. In general, the groundwater flow system was simplified as two-dimensional with transient flow

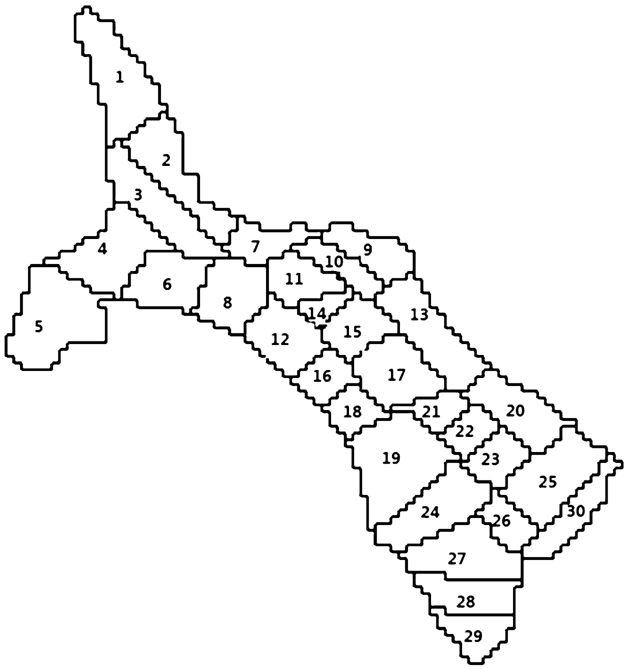

Fig. 3 The layout of hydraulic parameter partition

in the homogeneous anisotropic medium of a single phreatic aquifer.

Mathematical model

The two-dimensional plane was defined on the basis of the spatial discretization of a 5000 km^2 area. A grid was set up using 100 rows and 100 columns, which added up to a total of 10,000 cells. Cells outside the study area were defined as inactivity. The time step is 1 day. On the basis of the hydrogeology conceptual model, the flow can be expressed mathematically by the following governing equations (Bear 1977):

$$\begin{cases} \frac{\partial}{\partial x}\left[K_x \frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial y}\left[K_y \frac{\partial h}{\partial y}\right] + W = \mu_s \frac{\partial h}{\partial t} \\ H(x, y, t)|_{t=0} = H_0(x, y), (x, y) \in \Omega \\ K \frac{\partial h}{\partial n}|_{\Gamma_2} = q(x, y, t), (x, y) \in \Gamma_2 \end{cases} \tag{1}$$

where Ω is the study domain; Γ_2 the second type boundary, i.e., the Neumann boundary; h the hydraulic head (m); K_x and K_y are, respectively, the hydraulic conductivity in x, y directions (m/d); W the source/sink factors of groundwater (m/d), μ_s the specific yield; H_0 (x, y) the initial hydraulic head (m); and $q(x, y, z)$ is the recharge per unit width (m/d) under the second type boundary conditions. The solution for the system of governing equations is performed by the finite difference method using Visual MODFLOW 4.2 software.

Boundary conditions

The lateral boundaries of the groundwater model depend on the natural conditions and hydraulic characteristics in the study area. The eastern inflow boundary connecting the Zhangye Oasis with Shandan County and Minle County, as well as the northwestern outflow boundary including the stream outlet, can be defined as a flux boundary whose fluxes are calculated by Darcy law and the hydraulic gradients are determined by groundwater contour. Other boundaries were taken as impermeable boundaries: the north boundary is in Heli Mountain where the hydraulic conductivity in the hard rock is significantly smaller than that of the basin sediments; the west boundary is near a down-warped basin where there is scarcely a hydraulic connection between either side; on the south, the Zhangye Basin exchanges water with Qilian Mountain mainly through rivers, and the exchanged volume is so limited that the boundary can be considered as a no-flow boundary. It should be especially noted that the recharge from alpine streamflow was treated as a line source regardless of the lateral recharge.

The mudstone and the sandy mudstone of the Jurassic or the Tertiary, located below the Quaternary strata, had extremely low water content and were regarded as the impervious floor of the study area. The unsaturated zone between the air–soil interface and groundwater level connects atmospheric precipitation, surface water and the groundwater. In this paper, the unsaturated zone and the saturated zone were considered to be a unified system, and the air–soil interface is the top boundary of the system.

Source-sink terms of groundwater

The source-sink terms of the groundwater model represent the recharge and discharge in the vertical direction. In this area, scarce precipitation is far less than other terms and can be neglected. Groundwater recharge from the return flow of irrigation water, canal seepage and river leakage, together with discharge from groundwater exploitation, the base flow to rivers, spring overflow and groundwater evaporation, were considered in this study.

There are more than 3000 wells and 5000 km of canals. It is impossible to collect all of the groundwater pumping and canal flow data. In this case, groundwater pumping and canal seepage flux were treated as an average value for every irrigation district in the present groundwater model. The recharge from deep percolation of field irrigation I_r and canal seepage C_r during the crop growth period were estimated, respectively, as:

$$I_r = \alpha \times I \tag{2}$$

$$C_r = (1 - \beta)(1 - \gamma)Q_c \tag{3}$$

where I is the irrigation volume, α the infiltration coefficient of irrigation which is shown in Table 1. Q_c the water transferring from rivers to canals, β the utilization ratio of canal system, and γ the consumption coefficient in vadose zone. For the fine-soil plain, γ is approximately 0.1, whereas for the alluvial plain in front of the mountain, γ ranges from 0.2 to 0.3. The parameters α and β entered in the model were supplied by the Gansu Hydrogeology Team 2. Of all the existing data, only the data in Linze County are complete. For Ganzhou District and Gaotai County, the detailed water distribution data are estimated by allocating the full-year data to various irrigation rounds according to the proportion in each round of the Liyuanhe irrigation area, which is the biggest one in Linze County.

As shown in Fig. 4, in the reach between Yingluo Gorge and Heihe Bridge of the Heihe River (AB), together with Liyuan River (CD), the river recharges groundwater. However, the groundwater discharges to the river in the reach between Heihe Bridge and Zhengyi Gorge (BE). Additionally, the discharges from springs around AB empty into the Heihe River directly, showing that it is feasible to incorporate the springs into BE. So, AB and CD were simplified as line sources, while BE was simplified as a line sink. In the three lines, the mean annual groundwater exchange capacities are 2.32×10^8, 0.86×10^8 and 13.06×10^8 m^3, respectively (Wang 2007).

The discharge to river in five points of reach BE can be known according to the data of monitoring stations in 2001. Reach BE was divided into four parts, and the discharge of each part was calculated by the mean value of two terminals. Naturally, the percentage of the discharge in each part among the total discharge in BE can be easily realized, and then the annual discharge in BE was allocated to each part

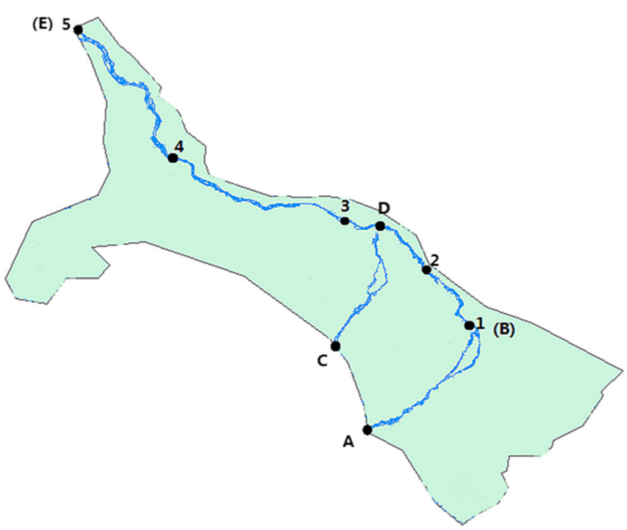

Fig. 4 The distribution of the main rivers in Zhangye basin

Table 1 The infiltration coefficients of the field irrigation at different groundwater depths

	Groundwater depth			
	<1 m	1–3 m	3–5 m	5–10 m
Infiltration coefficient (%)	28.1	34.9	28.4	18.5

proportionately to obtain the annual data of each part. The calculated results are presented in Table 2.

Model calibration and validation method

The hydrogeological parameters containing the permeability coefficient K and specific yield μ_s were calibrated according to the groundwater level observed in 2008. Then, using the data in 2007, we validated the verified groundwater model. Some statistical indices, such as the root mean square error RMSE, the relative error RE, the correlation coefficient R^2 and the error at the end of the year E_{12} were used to quantitatively evaluate the performance of the groundwater model. RMSE and RE reflect the predictive precision in different ways, and a lower value indicates higher precision. R^2 was used to evaluate the linear relationship between the two variables. E_{12} represents the deflected degree at the end of the simulated period.

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(P_i - O_i)^2} \quad (4)$$

$$\text{RE} = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{|P_i - Q_i|}{\max(O_i) - \min(O_i)}\right) \times 100\,\% \quad (5)$$

$$R^2 = \frac{\left(\sum_{i=1}^{N}\left(P_i - \overline{P}\right)\left(O_i - \overline{O}\right)\right)^2}{\sum_{i=1}^{N}\left(P_i - \overline{P}\right)^2\sum_{i=1}^{N}\left(O_i - \overline{O}\right)^2} \quad (6)$$

$$E_{12} = |P_{12} - O_{12}| \quad (7)$$

where N is the total number of groundwater observations; P_i and O_i are the ith simulated and observed groundwater level, respectively; $\bar{P}$ and $\bar{Q}$ are the averages of P_i and O_i; P_{12} and Q_{12} are the 12th value.

Results and discussion

Calibration and validation results of groundwater model

Based on the method of trial and error, the values of K and μ in each partition were modified to make the simulated

Table 2 The volume of groundwater discharging to surface water in each reach

	1–2	2–3	3–4	4–5	Total
Groundwater discharge in 2001 (m^3)	0.501	0.633	0.2	0.03	1.364
Ratio (%)	36.7	46.4	14.6	2.3	100
Annual average groundwater discharge (10^8 m^3)	4.793	6.060	1.907	0.330	13.060

Table 3 The permeability coefficient K and specific yield μ of the calibrated model

Partition number	K (m/d)	μ	Partition number	K (m/d)	μ
1	4	0.15	16	15	0.05
2	10	0.23	17	3.5	0.1
3	0.5	0.35	18	6	0.1
4	2	0.23	19	10	0.1
5	1.5	0.23	20	0.1	0.35
6	2	0.23	21	20	0.15
7	10	0.2	22	20	0.35
8	1	0.1	23	5	0.1
9	30	0.35	24	10	0.1
10	10	0.24	25	1	0.2
11	5	0.35	26	20	0.1
12	1.5	0.1	27	1	0.25
13	25	0.3	28	1	0.23
14	2.5	0.25	29	20	0.23
15	8	0.35	30	10	0.23

value fit with the observed value as well as possible. At last, the hydrogeological parameters were fixed (Table 3) after calibration, and then we validated the model to guarantee its suitability and reliability.

For the calibration and validation period, the simulated levels fit well with the observed levels (Figs. 5, 6). As for the precision of the model, results are presented in Fig. 7 and Table 4. In 2008, the statistical indices show a reasonable matching degree between the two types of levels (RMSE = 0.22–0.84 m, RE = 15–48.2 %, E_{12} = 0.02–0.89 m, $R^2 = 0.9992$). The precision in 2007 (RMSE = 0.20–0.87 m, RE = 22.44–46.20 %, E_{12} = 0.11–1.05 m, $R^2 = 0.9990$) is lower than that of 2008, which can be attributed to the lack of partial irrigation data in 2007. For deep groundwater areas, the precision is high enough and the model is capable to predict a dynamic groundwater response to agricultural activities.

Groundwater simulation under various agricultural water management scenarios

The calibrated and validated model can be an appropriate tool for water resource management. Improving irrigation efficiencies is becoming an essential trend in today's irrigation; additionally, it is of great importance under water scarcity conditions because high efficiencies would represent more beneficial uses of the water (NRC 1996; Pereira et al. 2002; Fang et al. 2010). In the north and northwestern part of China, this includes: (1) water-saving irrigation, including channel leakage prevention, spray irrigation, micro irrigation and low pressure pipe transport of water; (2) limited irrigation; and (3) dryland cultivation (Deng et al. 2006). At the regional level, considering the widespread use, we set strengthening channel leakage prevention and limited irrigation as the future water-saving scenarios. In these scenarios, land use, irrigation area and canal water transferred from rivers remain unchanged, whereas groundwater extraction volume reduces with the decrease of leakage coefficients of canal system or irrigation quota until the canal water arriving at field can satisfy the irrigation demand. For the purpose of analysis on the impact of water-saving measures, the current conditions was set as a control scenario. The detailed scenarios set in this paper are listed in Table 5, and the corresponding groundwater dynamics were simulated for the period 2009–2018.

Scenario A: current conditions

Figure 8 shows the predicted groundwater levels in 2018 under current conditions. Groundwater levels will generally decline at a rate of 1 m/year in irrigation areas and 0.2 m/year in non-irrigation areas; as a result, the annual groundwater budget in the oasis will be -7.64×10^8 m^3 (Fig. 9). In

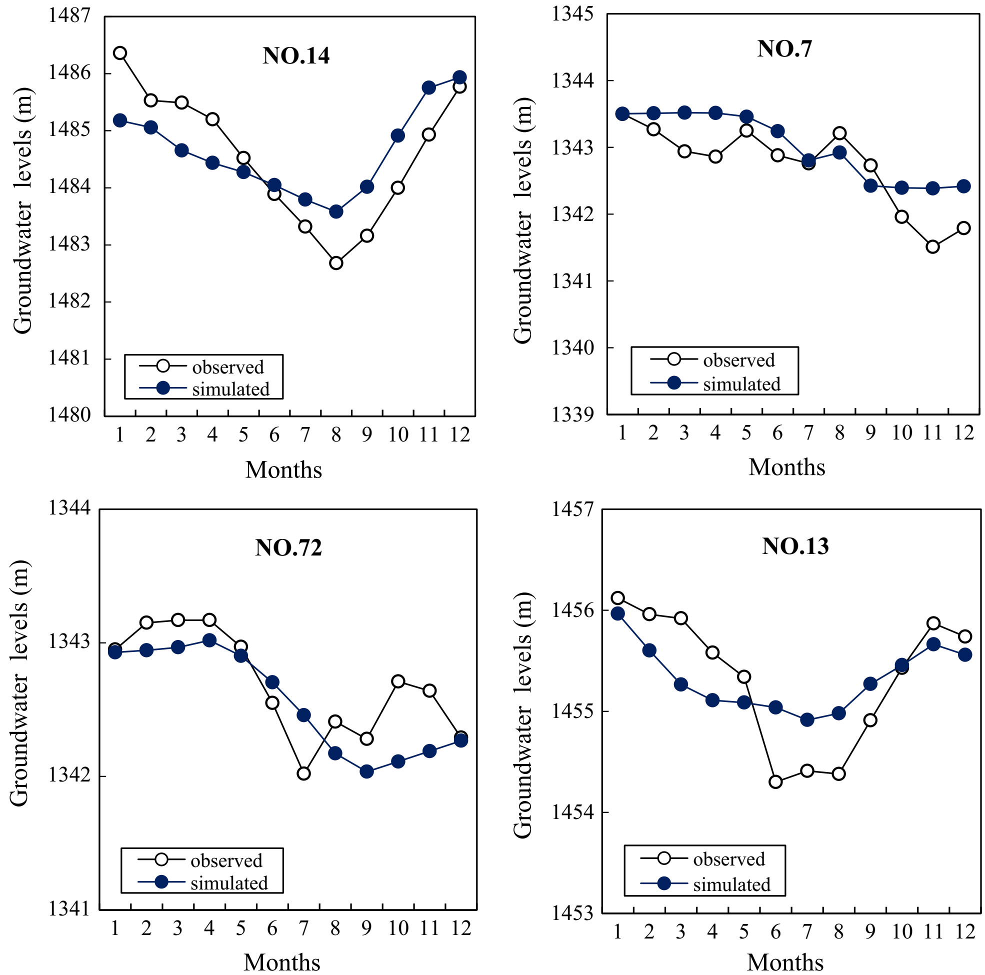

Fig. 5 Comparison of simulated and observed groundwater levels for four monitoring wells in 2008

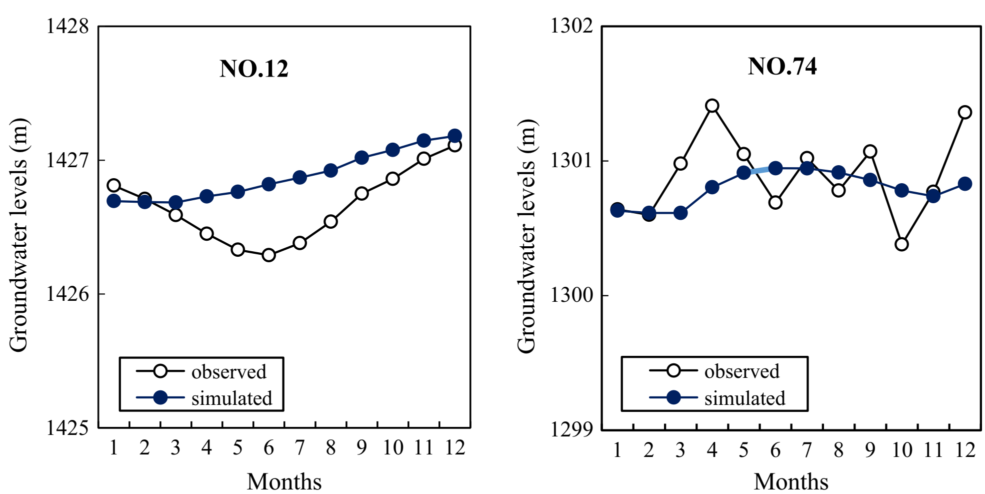

Fig. 6 Comparison of simulated and observed groundwater levels for two monitoring wells in 2007

particular, the groundwater recharge from field irrigation and canal system are 3.43×10^8 and 3.66×10^8 m^3, respectively, and the volume of groundwater extraction is 3.54×10^8 m^3. From this it can be seen that the groundwater decline has been a serious problem, which can be largely ascribed to its overexploitation. Groundwater mining is

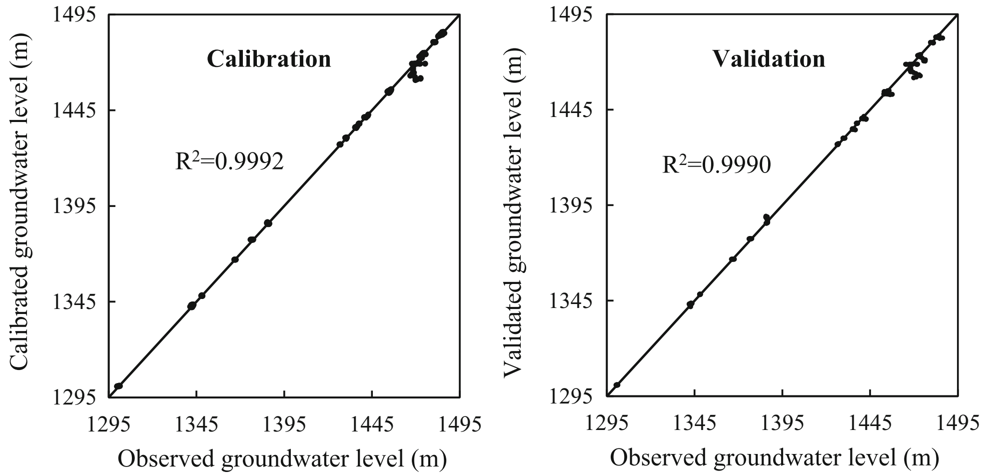

Fig. 7 1:1 plot and linear regression between observed and calculated groundwater levels at 20 sites for the period of calibration and validation

Table 4 Statistical indices of the model calibration in 2008 and validation in 2007 (partly)

Station	Calibration (2008)			Validation (2007)		
	RMSE (m)	RE (%)	E_{12} (m)	RMSE (m)	RE (%)	E_{12} (m)
74	0.44	18.9	0.15	0.30	22.44	0.53
7	0.46	19.4	0.63	0.58	27.10	0.11
2–3	0.37	19.6	0.27	0.73	46.20	0.97
72	0.29	20.3	0.02	0.44	36.54	1.05
13	0.43	20.6	0.18	0.87	26.56	0.93
32	0.27	30.2	0.35	0.20	30.44	0.15
12	0.24	32.4	0.15	0.30	30.86	0.23
87–1	0.31	44.3	0.33	0.35	24.34	0.75
68	0.22	48.2	0.22	0.24	22.68	0.65

Table 5 Simulation scenarios sets for efficient water resources management in water-saving agriculture: water-saving irrigation and limited irrigation in Zhangye Oasis

Simulation scenarios	Description
Scenario A	Current conditions
Simulation B	Without land use, irrigation area, canal water transferring from rivers and canal leakage coefficients changed, cutting down irrigation quota. Groundwater extraction volume depends on irrigation volume and the volume of canal water arriving at fields
Scenario B1	Cutting down irrigation quota to 90 % of the current
Scenario B2	Cutting down irrigation quota to 80 % of the current
Scenario B3	Cutting down irrigation quota to 70 % of the current
Simulation C	Without land use, irrigation area, canal water transferring from rivers and irrigation quota changed, advancing the quality of canal system. Groundwater extraction volume depends on irrigation volume and the volume of canal water arriving at fields
Scenario C1	The leakage coefficients of canal system is reduced to 0.3
Scenario C2	The leakage coefficients of canal system is reduced to 0.25
Scenario C3	The leakage coefficients of canal system is reduced to 0.2
Scenario C4	The leakage coefficients of canal system is reduced to 0.15
Scenario C5	The leakage coefficients of canal system is reduced to 0.1

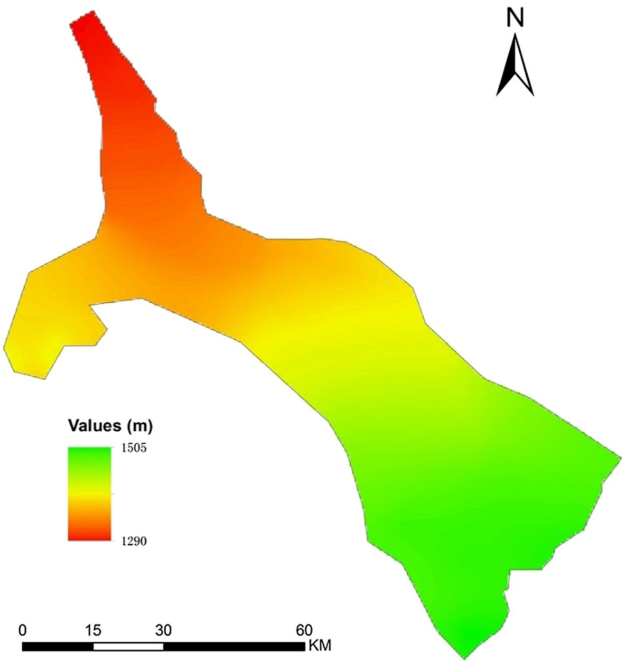

Fig. 8 The groundwater level under current conditions in 2018

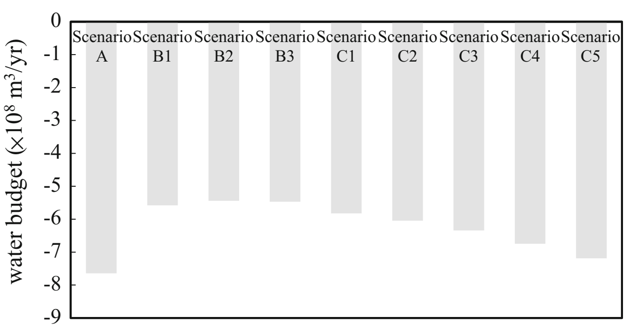

Fig. 9 Simulated water budget in different agricultural water management scenarios

treated as area in the model, so there is no cone of groundwater depression in the oasis.

Scenarios B1–3: different irrigation quotas

Compared to the current conditions, groundwater levels with the three irrigation quotas will rise in most of the study area (Fig. 10). Furthermore, the most obvious rising will occur in the middle part of Ganzhou District and Gaotai County, and the maximal rise is approximately 10 m. Only in a small part of the northeast, northwest and southwest do the groundwater levels decline slightly with <2 m of change. Through crosswise comparison of the three scenarios, there are several zone levels varying visibly. Specifically, in the middle part of Gaotai County, as the irrigation quota decreases, the groundwater levels rise; however, levels decrease in the southwest of Gaotai County and south of Ganzhou District. In the middle part of Ganzhou District, the levels almost remain unchanged when the irrigation quota is reduced from 90 to 80 %; however, if the quota continuously decreases to 70 %, there appears to be a downward trend on the groundwater levels. In other zones, no matter how the irrigation quota changes, the change is not very noticeable.

According to the equilibrium calculation (Fig. 9), the groundwater recharge from field irrigation will decrease to 3.06, 2.72 and 2.38 $\times$ 10^8 m^3 per year in Scenarios B1–3, respectively, while the exploitation yield of groundwater will be reduced to 1.11, 0.64 and 0.32 $\times$ 10^8 m^3 per year, respectively. In Scenario B1, the surface water can satisfy the irrigation demand in most irrigation areas, which will result in the sudden drop of groundwater extraction relative to Scenario A. In general, water budgets in all three scenarios increase to a certain extent. However, the water budget of -5.44×10^8 m^3/year when the irrigation quota is cut down to 80 % of the current conditions, is even higher than that of 90 %, with a value of -5.47×10^8 m^3/year. When the irrigation quota is 70 %, or at a lowest level of water-saving agricultural irrigation, the water budget of -5.58×10^8 m^3/year is the lowest value of the three. Therefore, there is not a positive correlation between the water-saving force and the aquifer storage. In the limited irrigation practice, there is an irrigation quota threshold for groundwater protection, and the value is approximately 80 % of the current.

Scenarios C1–5: different leakage coefficients of canal system

Under current conditions, the average leakage coefficient of the canal system in the Zhangye Oasis is approximately 0.35. In Scenarios C1–5, the leakage coefficients are reduced to 0.3, 0.25, 0.2, 0.15 and 0.1, respectively. Figure 11 indicates that improving canal quality on the basis of current conditions can be attributed to groundwater protection at the regional scale, especially when the leakage coefficient is reduced to 0.3. Additionally, the zones where groundwater levels rise or decrease in these scenarios are the same as the Scenarios B1–3. With the decrease of the leakage coefficient, there will be less leaking water from canals to recharge the groundwater. At the same time, more canal water will arrive at the field and less groundwater needs to be exploited for irrigation. When the leakage coefficient is reduced from 0.35 (current conditions) to 0.3, in most areas, the reduction of groundwater recharge from canal leakage is more than the reduction of groundwater extraction and groundwater levels will rise; however, the opposite occurs when the leakage coefficient continues to decrease.

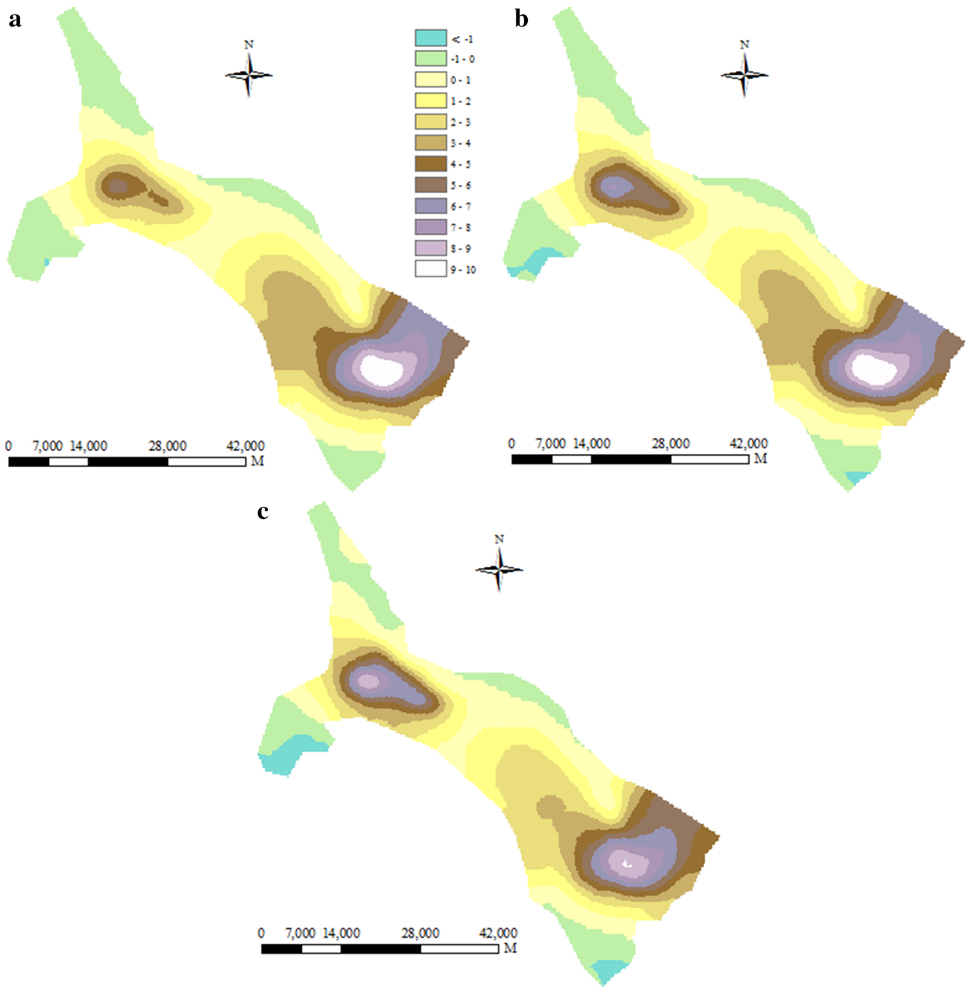

Fig. 10 The groundwater level difference with 90 % (**a**), 80 % (**b**), 70 % (**c**) of the present irrigation quota compared to current conditions in 2018, respectively

In total, compared to current conditions, groundwater recharge from canal leakage in Scenarios C1–5 will decrease to 3.33, 2.87, 2.30, 1.73 and 1.15 × 10^8 m^3/year, respectively, and the corresponding exploitation yield of groundwater will be reduced to 1.44, 1.16, 0.89, 0.71 and 0.58 × 10^8 m^3/year. As shown in Fig. 9, when the leakage coefficient is reduced to 0.3, water budget reaches its maximum and the optimal groundwater management can be achieved.

In particular, the groundwater extraction volume used in this model under current conditions is the actual data gathered by water resources department. While under other conditions (Scenarios B1–3 and Scenarios C1–5), groundwater extraction volume input into the model was calculated by subtracting canal water arriving at the field from irrigation need. To test its accuracy, we also calculated the groundwater extraction volume under current conditions and compared it with the measured extraction. The results show that the calculated values are basically the same as the measured values in Linze County and Gaotai County; meanwhile, the calculated value is far less than the measured value in Ganzhou District, which may be due to the statistical deviation of canal water utilization ratio. Ganzhou District is also an area lacking detailed water distribution and canal system data, so the error cannot be avoided. Because of the statistical deviation of the canal water utilization ratio, groundwater extraction drops suddenly in Scenario C1 compared to Scenario A, which should be a smaller margin in actuality. However, for Scenario B, diverted water volume from rivers to canals and leakage coefficient of canals remain unchanged, so the canal water arriving at the field is equal to the volume in Scenario A and can be known according to irrigation and groundwater extraction data. In this way, the calculation of groundwater volume entered into Scenario B does not require the canal water utilization ratio, so the error caused by its statistical deviation can be avoided. Comparing the two optimal scenarios, the water budget in Scenario B2 was

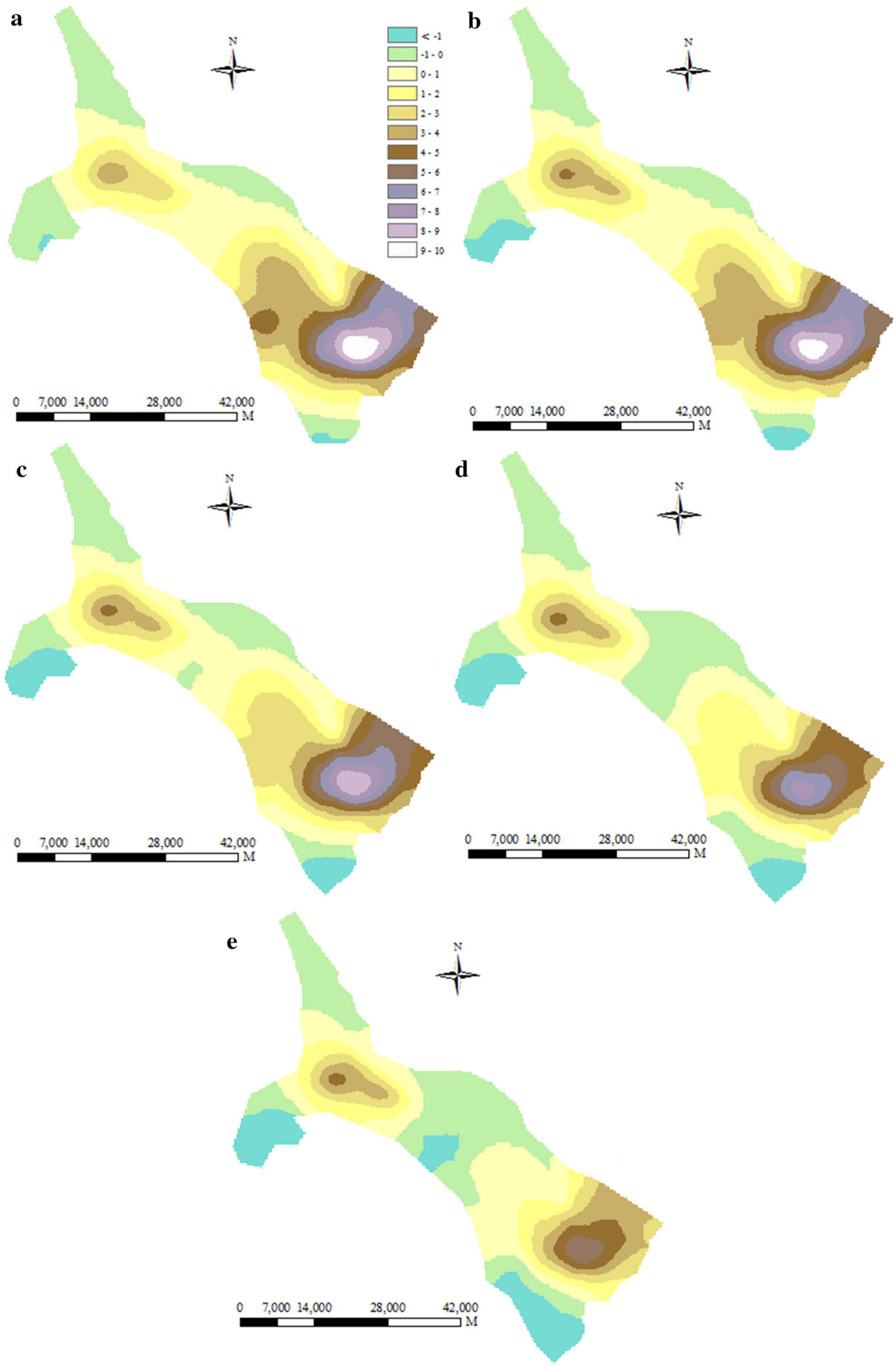

Fig. 11 The groundwater level difference with 0.3 (**a**), 0.25 (**b**), 0.2 (**c**), 0.15 (**d**), 0.1 (**e**) leakage coefficient of canal system compared to current conditions in 2018, respectively

even bigger than in Scenario C1. Thus, when the statistical deviation of the canal leakage coefficient is taken into account, cutting down the irrigation quota is more effective than improving the quality of canal linings for groundwater protection.

Conclusions

Groundwater is seriously threatened by overexploitation in the Zhangye Oasis, a region of northwest China. In this study, the model Visual MODFLOW was applied to simulate the dynamic groundwater response to agricultural activities. The study area was generalized to a conceptual hydrologic model: a two-dimensional model under transient conditions and an aquifer considered as a single heterogeneous and isotropic phreatic aquifer. After calibrated and validated, the groundwater model was used to simulate the groundwater dynamics of the Zhangye Oasis from 2009 to 2018 under different agricultural water management scenarios. Under current conditions, the annual groundwater budget in the oasis will be -7.64×10^8 m^3. This shows that it is necessary and urgent to take measures to resolve water scarcity and protect the fragile ecological environment in the Zhangye Oasis. According to the trend of agricultural water use in this situation, two approaches that include limited irrigation (reducing irrigation quota) and strengthening channel leakage prevention (advancing the quality of canal linings) are proposed. For each approach, several scenarios were simulated to obtain the optimal scheme. The results indicate that the descending rate can be reduced to some extent, although the downward trend in groundwater levels cannot be reversed by the two water resource management approaches mentioned above. Additionally, when irrigation quota is cut down to 80 % of the present conditions and the leakage coefficient of the canal system is decreased to 0.3, water budgets reach the maximum, with values of -5.58×10^8 and -5.82×108 m^3/year, respectively. Thus, the two scenarios B2 and C1 are relatively effective agricultural water resource management measures. Taking the statistical deviation of the canal leakage coefficient into account, minimizing the irrigation quota is more effective than improving the quality of canal linings in protecting groundwater. In future research, groundwater recharge processes from the return flow of irrigation water and canal seepage will be studied far more accurately in the model. For higher precision groundwater level simulation, more detailed parameters of soil water movement, crop growth and canal linings will be required in the future groundwater model.

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