

# Restoration of Groundwater Over-Exploitation Area Based on MODFLOW in North Weifang, Shandong Province, China



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**Abstract** With rapid socio-economic developments, significant exploitation of groundwater has emerged as a serious environmental concern. In order to alleviate groundwater over-exploitation and determine a reasonable mining layout, a groundwater numerical simulation model was used in this study for the years 2014 to 2023. Simulations were conducted for various scenarios, including current conditions, agricultural water saving, groundwater replacement, and a comprehensive scenario. The results showed that under the current mining scenario, the groundwater level in the entire area decreased with a water budget of  $-0.45 \times 10^8 \text{ m}^3/\text{a}$ . Agricultural water saving can raise the groundwater level in most areas and groundwater replacement can efficiently control the drawdown funnels. However, the effect of a single measure is not comprehensive. Therefore, a utilisation coefficient of irrigation water at 0.7 and a 100% replacement of groundwater sources was established as a comprehensive scenario which resulted in groundwater level recovery and the disappearance of drawdown funnels by the end of 2023. Additionally, the groundwater flow returned to its natural direction from south to north and the northern water level was simulated to be higher than 0 m which would effectively prevent seawater intrusion. The conclusion can provide a reasonable reference for other areas facing similar challenges.

**Keywords** Groundwater over-exploitation · Numerical simulation · Restoration of groundwater · South to north water transfer project · Visual MODFLOW

## 1 Introduction

Groundwater resources play an important role in determining social and economic growth in many countries (Zektser et al. 2005; Konikow and Kendy 2005). However, with ever increasing water demands and limited surface water resources,

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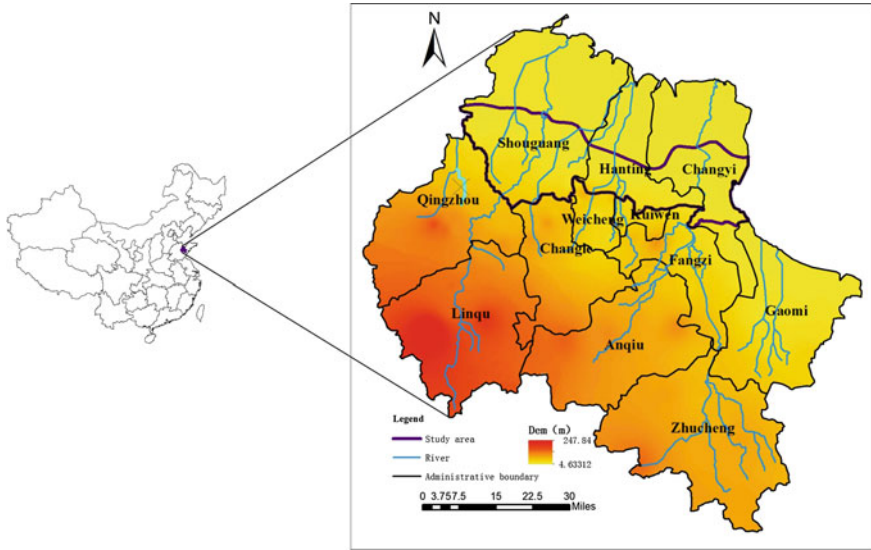
massive groundwater resources are exploited. Groundwater over-exploitation areas are formed when the exploitation of groundwater over the years is greater than the recharge (Bromley et al. 2001; Camp et al. 2010). Such over-exploitation not only lowers the groundwater level but also results in ecological and environmental problems such as seawater intrusion and land subsidence (Pei 2018). Therefore, it is important to control groundwater over-exploitation areas (Huo et al. 2007; Lin et al. 2015).

In the past decades, much attention has been paid to restoration of groundwater system to alleviate groundwater over-exploitation and assist in the recovery of groundwater levels (Hu et al. 2010; Nam and Ooka 2010; Seo et al. 2014). The exploitation of groundwater mainly results from operation of pump wells and, therefore, closing such wells is a direct way for restoring groundwater level. In China's Zhangye Oasis, the degree of groundwater level recovery varies according to the reduction of exploitation; a decrement of up to 30% of the current conditions will result in a maximum groundwater level rise of 10 m after 10 years (Chen et al. 2016). Additionally, as for confined aquifer, since the early 1960s, artificial injection of groundwater has been proposed as an important measure for restoring confined aquifers and this method has been successfully adopted in numerous locations (Donovan et al. 2002; Han 2003; Phien-Wej et al. 1998; Tu et al. 2011). A study in Jordan (Abdulla 2010) compared different artificial recharge options (low, moderate, and high) with no recharge scenario for a period of 27 years. The results show that groundwater level in different areas ranged from 1.5 to 20 m under a high recharge scenario, indicating the need for management of groundwater resources in arid and semi-arid areas.

Although a simple reduction in the extraction of groundwater can raise the groundwater levels, it cannot fundamentally address the water supply and demand contradiction. The artificial recharge of groundwater can effectively conserve the groundwater system. However, several factors, such as water quality and economic feasibility, need to be considered. Presently, in the context of sustainable development, conservation of groundwater and its resources is an inevitable choice and groundwater replacement is an optimal scheme to alleviate over-exploitation of such resources. Several studies have indicated groundwater replacement to be an effective method for addressing the problem of over-exploitation of groundwater resources (García Gil et al. 2015; Mossmark et al. 2008).

In order to determine the dynamic changes to groundwater levels under different schemes, numerical models have been established using several software programs such as MODFLOW (McDonald and Harbaugh 1988), FEFLOW (DierschHJG 2005), and GMS (Group 2006). Additionally, Visual MODFLOW has been developed by integrating PEST and MT3D and has been utilised in several studies to analyse groundwater levels and water budgets (Zume and Tarhule 2008; Ayvaz 2009; Xu et al. 2012; Mohtashami et al. 2017; Iwasaki et al. 2014; Jang et al. 2016).

In this study, north Weifang in China, which exhibits the typical features of most groundwater over-exploitation areas, such as groundwater level decline and seawater intrusion, was selected as the study area. Moreover, it is also a water receiving area which makes it further suitable for conducting this study. To address the over-exploitation of ground water and determine the optimal groundwater restoration lay-



**Fig. 1** Overview of the study area

out, Visual MODFLOW software was utilised to predict the groundwater flow after 10 years and the water budget under different scenarios were compared and analysed. Finally, make sure that the combination of agricultural water saving and replacement of groundwater sources as the proper restore scenario, which will provide a scientific reference in other over-exploitation area.

## 2 Methods and Data

### 2.1 Study Area

Over-exploitation of groundwater is mainly concentrated in three areas in north of Weifang, i.e. Shouguang, Hanting, and Changyi. These regions cover a total area of 2101.96 km<sup>2</sup>. As shown in Fig. 1. According to the water resources bulletin statistics, the groundwater exploitation in 2013 was  $2.51 \times 10^8$  m<sup>3</sup> which accounted for 58% of the total water supply. The consumption for agricultural activities and daily water usage by the residents were  $1.43 \times 10^8$  m<sup>3</sup> and  $0.51 \times 10^8$  m<sup>3</sup>, accounting for 57 and 20% of the total groundwater consumption, respectively.

Based on the data from 17 boreholes, two hydrogeological profiles were drawn for the study area. As shown in Fig. 2. The aquifer system in the study area was divided into two parts, the southern piedmont alluvial plain which is a part of the

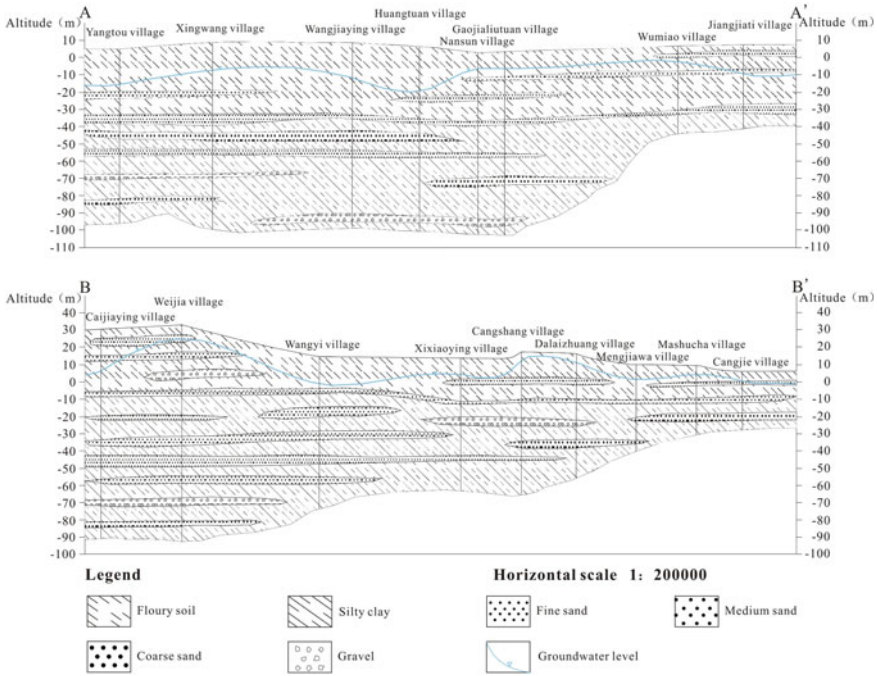


Fig. 2 Hydrogeological profiles of sections A and B

single-layer phreatic aquifer, the other part is the multi-layer complex aquifer in the northern flood plain which is complex in lithology.

### 2.2 Method

According to the hydrogeological conditions of the study area, a two-dimensional groundwater numerical simulation model was established by using Visual MODFLOW software. Its horizontal direction was defined as a two-dimensional grid structure while its vertical direction was defined as a phreatic aquifer. Based on the conceptual model, the mathematical model is established as follows:

$$\begin{cases} \frac{\partial}{\partial x} \left[ k_x (h - b) \frac{\partial h}{\partial x} \right] + \frac{\partial}{\partial y} \left[ k_y (h - b) \frac{\partial h}{\partial y} \right] + \frac{\partial}{\partial z} \left[ k_z (h - b) \frac{\partial h}{\partial z} \right] + \varepsilon = \mu \frac{\partial h}{\partial t}, (x, y, z) \in \Omega \\ h(x, y, z, t)|_{t=0} = h_0(x, y, z), (x, y, z) \in \Omega \\ h(x, y, z, t)|_{\Gamma_1} = h_1(x, y, z), (x, y, z) \in \Gamma_1 \\ k_n \frac{\partial h}{\partial n} |_{\Gamma_2} = q(x, y, z, t), (x, y, z, t) \in \Gamma_2 \end{cases} \quad (1)$$

Where  $\Omega$  is the domain of the simulated scope,  $\Gamma_1$  and  $\Gamma_2$  are the boundaries of the first boundary and the second boundary,  $n$  is the direction of the outer normal line of the second boundary,  $\mu$  is the specific yield,  $h_0(x, y, z)$  represents the initial conditions, i.e. the initial head distribution (m),  $h_1(x, y, z)$  indicates the first type boundary conditions (m),  $q(x, y, z)$  represents the second type boundary conditions with inflow being negative and outflow being positive (m<sup>3</sup>/day),  $h$  is the groundwater level (m),  $b$  is the elevation of phreatic aquifer baseboard (m),  $k$  is the permeation coefficient of the aquifer (m/day), and  $\varepsilon$  denotes the source/sink factors of groundwater, i.e. the intensities of vertical water pumping and of percolation recharge per unit area (m/day).

A series of statistical indexes, such as the root mean square error (RMSE), the relative error (RE), the error at the end of the year (E), and the correlation coefficient (R<sup>2</sup>) Were used to judge the simulation precision of the model. R<sup>2</sup> measures the degree to which two variables are linearly related. RMSE and RE provide different types of information about the predictive capabilities of the model. E represents the deflected degree at the simulated period. RMSE, RE, E, and R<sup>2</sup> are defined as follows:

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^n (S_i - O_i)^2} \tag{2}$$

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

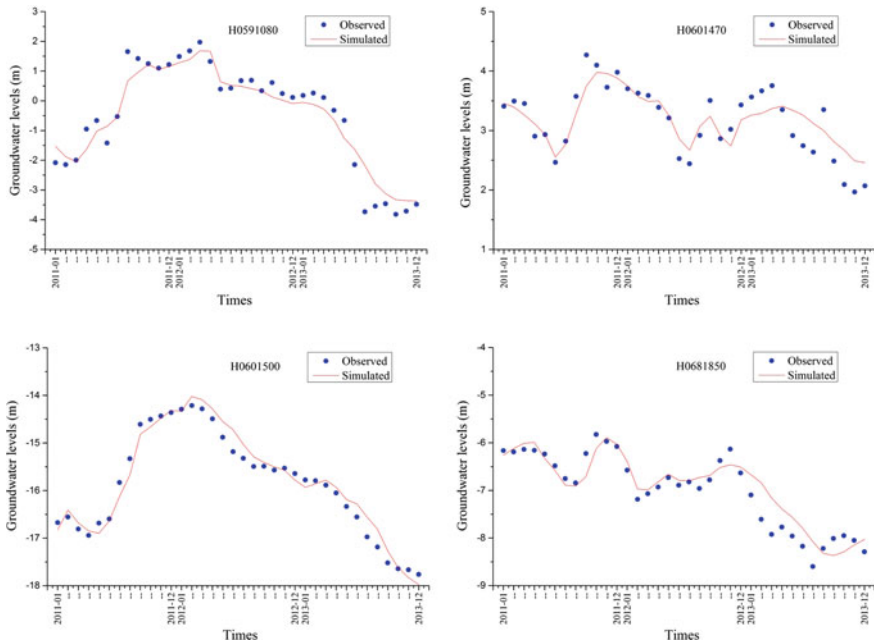
$$E = |S_i - O_i| \tag{4}$$

$$R^2 = \frac{\left[ \sum_1^N (S_i - \bar{S})(O_i - \bar{O}) \right]^2}{\sum_{i=1}^N (S_i - \bar{S})^2 \sum_1^N (O_i - \bar{O})^2} \tag{5}$$

where N is the number of observations,  $O_i$  and  $S_i$  are the i-th values of observed and simulated data, respectively,  $\bar{S}$  and  $\bar{O}$  are the averages of the data arrays of  $S_i$  and  $O_i$ , respectively.

### 3 Results and Discussion

In order to improve the reliability of the model simulation results, it is necessary to simulate the transient flow. To estimate transient flow, data from the 36 observation wells were also used for model calibration (2011–2012) and validation (2013). Each month was a stress period and each stress period was divided into six time-steps. The hydrogeological and the boundary conditions were assigned according to the



**Fig. 3** Comparison of simulated and observed groundwater levels for four monitoring wells from 2011 to 2013

actual conditions. Figure 3 indicates a comparison between the measured levels and the simulated levels for four observation wells.

It is believed that when the RMSE of the model is less than 1 m, a correlation coefficient greater than 0.9 conforms to the requirement of model accuracy. The results for model precision are presented in Table 1. The model calibration (2011–2012) index values are as follows: RMSE = 0.17–0.56 m, RE = 4.84–20.63%, E = 0.14–0.73 m, and  $R^2 = 0.99$ , while those for model variation (2013) are the following: RMSE = 0.22–0.87 m, RE = 5.45–30.38%, E = 0.19–1.25 m, and  $R^2 = 0.98$ . The accuracy of the validation period was slightly lower than the calibration period and could be attributed to the lack of actual data for groundwater exploitation in some areas.

In this study, three basic scenarios, i.e. water saving, groundwater replacement, and the comprehensive scheme were considered. The current condition represents the basic scheme to compare groundwater remediation under different scenarios (Table 2).

**Table 1** Statistical indexes for model calibration and validation

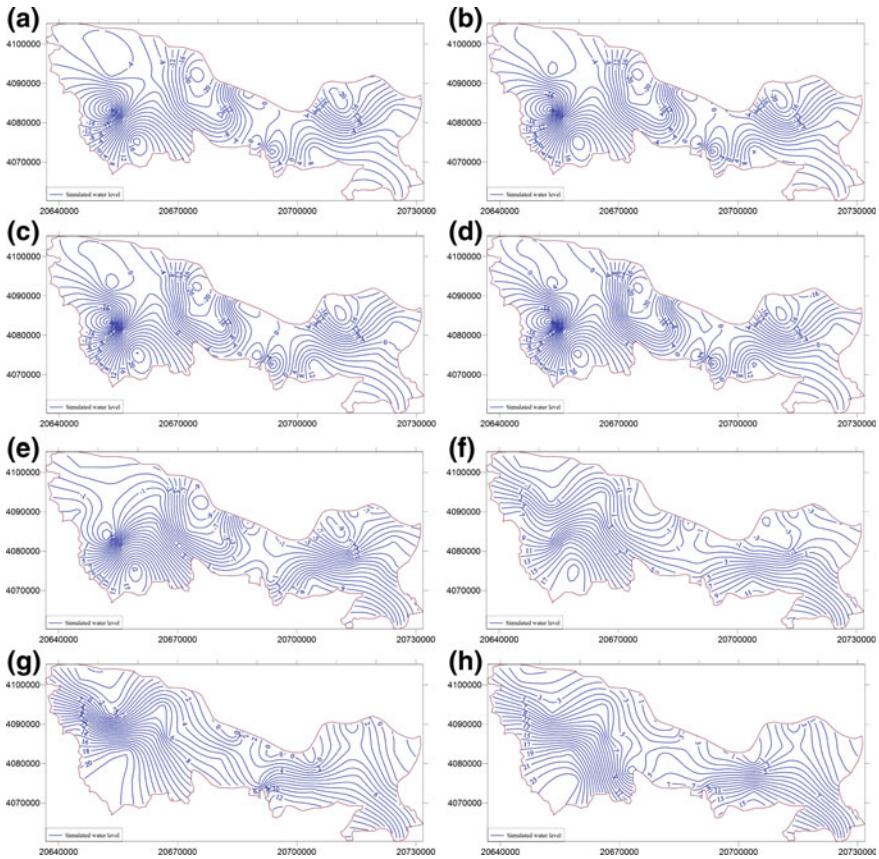
Observation well	Calibration (2011–2012)			Validation (2013)		
	RMSE	RE (%)	E	RMSE	RE (%)	E
H0591020	0.33	20.63	0.42	0.61	26.95	0.74
H0591030	0.42	15.79	0.21	0.39	14.83	0.18
H0591080	0.37	4.99	0.29	0.61	8.69	0.50
H0601440	0.56	26.41	0.63	0.87	30.38	1.25
H0601470	0.20	6.99	0.16	0.41	17.10	0.39
H0601500	0.20	4.84	0.17	0.22	5.45	0.19
H0681840	0.22	7.53	0.38	0.35	9.33	0.51
H0681850	0.17	5.52	0.14	0.44	15.26	0.40
H0681880	0.49	19.37	0.73	0.58	21.52	0.92
H0681940	0.27	10.24	0.25	0.48	15.27	0.37

**Table 2** Simulation scenarios of groundwater in over-exploitation area of north Weifang

Simulation scenarios	Description
Scenario A	Current condition
Scenario B1	Improving effective water utilisation coefficient to 0.6
Scenario B2	Improving effective water utilisation coefficient to 0.7
Scenario B3	Improving effective water utilisation coefficient to 0.8
Scenario C1	Using external transfer water to replace groundwater sources to 50% of the current condition
Scenario C2	Using external transfer water to replace groundwater sources to 75% of the current condition
Scenario C3	Using external transfer water to replace groundwater sources to 100% of the current condition
Scenario D	Improving effective water utilisation coefficient to 0.7 and using external transfer water to replace groundwater sources to 100% of the current condition

### 3.1 Current Conditions

Figure 4a shows the groundwater contour map for 2023. The results indicate that the groundwater flow field was largely consistent with the previous results of steady flow. Additionally, the groundwater level showed a significant downward trend due to excessive exploitation. In particular, for most areas, groundwater exploitation was entered evenly in the model, therefore, no apparent drawdown funnel was observed. The groundwater level was found to decline at a rate of 0.3–0.4 m/a. However, in the groundwater source areas, the groundwater level is likely to decline at a rate of 0.6–1 m/a due to concentrated mining of the wells. The maximum groundwater depth in the centre of the funnel is likely to reach 50 m.



**Fig. 4** Groundwater contour map under different scenarios after 10 years

According to the water budget, the average groundwater budget was  $-0.494 \times 10^8 \text{ m}^3/\text{a}$  which was slightly higher than the previous results. Therefore, it is urgent to definite reasonable groundwater exploitation mitigation measures for the study area.

### 3.2 Scenarios B1–3: Different Utilisation Coefficients

As indicated in Fig. 4b, c, d, in comparison to scenario A, groundwater level in most areas will rise. Shouguang, an agriculturally developed area, uses  $1.37 \times 10^8 \text{ m}^3/\text{a}$  as irrigation water, of which groundwater contributes  $1.16 \times 10^8 \text{ m}^3/\text{a}$ . With continuous improvement of the utilisation coefficient, compared to the other two regions, the groundwater level was shown to increase and the largest water level increase was to



8 m. The rise of the groundwater level in Hanting was estimated between 2 and 4 m, while in most areas of Changyi, the trend of groundwater level showed an initial rise followed by a decline. This trend could be attributed to surface water irrigation in Changyi where only a small volume of groundwater is used for irrigation. Therefore, the increase in the coefficient resulted in a decrease in groundwater exploitation, and consequent a rise in the groundwater level. However, with continuous improvement of the coefficient resulted in is almost no irrigation return recharge. Moreover, the decrease of groundwater exploitation was less than the return recharge, therefore, the groundwater level was shown to drop. In the vicinity of several groundwater sources, regardless of the utilisation coefficient changes, the variation of the groundwater level was always small and a drawdown funnel was obvious. Therefore, although agricultural irrigation was the main consumer of water in the study area, it was not the direct cause of the drawdown funnel.

As shown in Fig. 4, the groundwater budgets under the scenarios B1-3 were  $-0.334 \times 10^8 \text{ m}^3/\text{a}$ ,  $-0.265 \times 10^8 \text{ m}^3/\text{a}$ , and  $-0.269 \times 10^8 \text{ m}^3/\text{a}$ , respectively. In general, agricultural water savings were beneficial to groundwater safety. However, because the study area is not dependent only on groundwater irrigation, there are several areas where surface water is used for irrigation and the rise of utilisation coefficient will affect the volume of return recharge. For example, the utilisation coefficient of scenario B2 is 0.7 and groundwater budget is  $-0.265 \times 10^8 \text{ m}^3$  when the utilisation coefficient is increased to 0.8, the budget is  $-0.269 \times 10^8 \text{ m}^3$  which is less than that observed for a utilisation coefficient of 0.7.

### ***3.3 Scenarios C1–3: Different Replacement of Groundwater Source***

In order to govern the groundwater drawdown funnel, three scenarios were designed in accordance with the South to North Water Diversion Project. As shown in Fig. 4e, f, g, compared to scenario A, groundwater level in the drawdown funnel area is likely to increase significantly through replacement of groundwater and the greater the replacement, the more the rising of the groundwater level. The maximum rise of the water level in the funnel centre was 35 m and the area of the drawdown funnel was shown to obviously reduce. When the replacement water reached 100%, as indicated in Fig. 4g, there was almost no drawdown funnel in the study area and the groundwater flow returned to the natural state from south to north. But in most areas, the trend of groundwater level decline in most areas is still not solved. In summary, the concentrated exploitation of groundwater was found to be the main reason for the drawdown funnel and agricultural irrigation was the main reason for the decline in groundwater levels across large areas.

Water budget shows that when the replacement of water sources comes to 75% of current exploitation, the total water budget of the groundwater system achieves balance. However, it is evident from the flow field that there is still a small part of the

drawdown funnel in the study area considering the external transfer water was  $0.6 \times 10^8 \text{ m}^3$  and could not be completely replaced. Therefore, with regards to repairing the drawdown funnel, the optimal replacement proportion was estimated to be 100%.

### **3.4 Scenario D: Comprehensive Scheme**

In order to achieve the comprehensive management of the entire over-exploitation area, the optimal utilisation coefficient is 0.7 and the optimal replacement of water is 100%. It is evident from Fig. 4h that there is no drawdown funnel in the study area and the groundwater level in the north is higher than the sea level. Additionally, the flow of water is from south to north and eventually into the Laizhou Bay. Under such scenario, the problem of overexploitation of groundwater can be alleviated and the invasion of sea water will be effectively controlled.

## **4 Conclusion**

In this study, Visual MODFLOW was used to simulate the dynamic changes of groundwater. After calibration and validation, the model was used to predict dynamic changes of groundwater from 2014 to 2023 in the over-exploitation area of Weifang.

Under the current mining scenarios, the groundwater level showed different degrees of decline. In particular, the decline in most areas was estimated at a rate of 0.3–0.4 m/a and the decrease in groundwater sources ranged from 0.6–1 m/a. The maximum water depth was calculated to reach 50 m, therefore, it is important to alleviate the over-exploitation of groundwater resources. In order to restore the groundwater system, first agricultural water savings were simulated. However, from the simulation results, the utilisation coefficient of B2 was found to be less than the utilisation coefficient of B3, while the water budget of B2 was more than the water budget of B3. Therefore, a higher utilisation coefficient is not always more conducive to the restoration of groundwater system. The second simulation was based on groundwater replacement. The results indicate that the groundwater system realises balance when the replacement is 75% of the current water sources and the more the replacement water is, the better the drawdown funnel repair effect. Thus, the combination of B2 and C3 is suggested as a comprehensive plan to effectively control the over-exploitation area. These results not only provide a scientific basis for groundwater restoration in study area but also for other similar areas.

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