#### **ORIGINAL ARTICLE**



# Numerical groundwater modeling and scenario analysis of Beijing plain: implications for sustainable groundwater management in a region with intense groundwater depletion

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Received: 23 April 2021 / Accepted: 26 July 2021 / Published online: 31 July 2021 © The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2021

### Abstract

Groundwater serves as one of the crucial natural resources in the safety and sustainable development of Beijing economy. Due to the fact that Beijing is one of the megacities with groundwater as the main water source, it abstracts two-thirds of the city's water supply from groundwater. Meanwhile, the groundwater aquifer storage depletion has been larger than  $1.04 \times 10^{10}$  m<sup>3</sup> during the past decades, which has brought serious eco-environmental problems to Beijing. The purpose of this study is to evaluate various abstraction schemes using a 3-D transient numerical groundwater flow model, to understand the present situation and future trend of groundwater resources in Beijing plain. The sustainable utilization of groundwater under these scenarios was comprehensively analyzed. The most reasonable scenario, which meets the appraisal restraint conditions, is the one that the groundwater abstraction rate of  $1.769 \times 10^9$  m<sup>3</sup>/year. Countermeasures that could be considered to improve sustainable groundwater management include: reducing groundwater abstraction directly; importing surface water from outside river basins; improving agricultural water use efficiency; and controlling the groundwater abstractions in the subsidence centers. The results of the modeling study could be used to inform policymakers and the government of Beijing.

**Keywords** Beijing plain  $\cdot$  Groundwater abstraction  $\cdot$  Numerical model  $\cdot$  Scenarios analysis  $\cdot$  Sustainable groundwater management

# Introduction

In the past few decades, groundwater has been increasingly utilized for urban water supply and for irrigated agriculture in many parts of the world (Zektser and Everett 2004; Wada et al. 2010; Qin et al. 2013). Consequently, over-abstraction of groundwater has become a major problem, which has been the focus of water debate for decades (Mitchell et al. 2012; Massuel and Riaux 2017). As an effect of unsustainable abstraction, the groundwater levels of major aquifers in some areas of the world are rapidly declining, such as in

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The resulting decline in groundwater levels may have a devastating impact on natural river flows, groundwater irrigated wetlands and related ecosystems (Wada et al. 2010). Besides, long-term and large-scale groundwater overabstraction may lead to significant ecological and environmental problems, such as groundwater level declines in aquitards and aquifers, land subsidence and salt water (Galloway and Burbey 2011; Xu et al. 2012; Budhu and Adiyaman 2013; Gharibi et al. 2017; Alfarrah and Walraevens 2018; Qin et al. 2018). Therefore, the sustainable management and utilization of groundwater in those regions that rely heavily on groundwater as their water supplies appear to be particularly important.

Beijing, as the capital of China, has been one of the cities facing serious water shortage problems (ranking the 5th most water-stressed city worldwide) in the past 40 years due to a rapidly increasing population, and the effects of urbanization and industrialization (McDonald et al. 2014; Chen et al. 2016; Oin et al. 2018). In the past 40 years, large-scale groundwater abstraction in Beijing has provided support for fast economic growth and the development of a large urban population (Guo et al. 2014). As per capita water consumption (300 m<sup>3</sup>/year) is far lower than the prescribed minimum value of the international society (1000 m<sup>3</sup>/year) (Yang et al. 2013), Beijing abstracts approximately two-thirds of its water supply from a groundwater aquifer (Qin et al. 2013; Hyndam et al. 2017). Meanwhile, Beijing has abstracted  $2.5 \times 10^9$  m<sup>3</sup> groundwater per year since the 1990s, resulting in an increase in the average depth of groundwater from 6.4 m below the surface in 1978 to 24.9 m in 2010 (Yang et al. 2013). Groundwater serves as one of the crucial natural resources that is necessary for the sustainable development of the Beijing economy. However, serious groundwater overexploitation has brought a whole string of environmental and ecological issues to Beijing. For example, the groundwater level in Beijing is declining continuously and the expansion of a cone of depression of the water table caused by groundwater abstraction is causing serious land subsidence problems in the area (Shi et al. 2014).

Numerical modeling has already been deemed as an effective and important tool for characterizing groundwater flow and for developing measures for its sustainable management (Bundschuh et al. 2010; Rao et al. 2013). Several historical studies have utilized numerical modeling for investigating the groundwater flow system of Beijing utilizing the finite-difference model MODFLOW (Wang et al. 2010; Sun et al. 2011; Yu 2012; Zhou et al. 2012; Guo et al. 2014; Wang 2014; Qin et al. 2018). Many of the models that were developed in these studies were either carried out at a local scale, or at a regional scale with a relative short simulation time of unsteady flow and a relative simple aquifer division. Therefore, it is impossible for these models to analyze the water exchange between the confined aquifers in different depths. The sustainable groundwater management analysis based on these models also needs more careful and further exposition and explanation.

Considering the serious water shortage in the North China Plain (NCP), especially in the Beijing and Tianjin areas, the Chinese government has already implemented the 4350 km South-to-North Water Diversion Project (SNWDP) since 2003 to divert  $4.48 \times 10^{10}$  m<sup>3</sup> water from southern China through three routes (the eastern, central and western routes) to satisfy the water requirement of the northern China (CCS-NWD 2008; Zhou et al. 2012). It is expected that once the water supply is diverted to Beijing, the amount of groundwater extraction will be reduced. Hence, the groundwater level decline rate and the related land subsidence increasing and expanding rates will also be reduced.

According to the hydrogeological situation of the Beijing plain and the analysis of long-term precipitation series and

dynamic change process of groundwater, the groundwater balance calculation result in 1995 shows that it is in a balanced state. Therefore, a three-dimensional steady-state (1995) and transient (1995-2014) groundwater numerical model has been established and calibrated using GMS version 9.2 to explore the present situation and development trend of groundwater resources in Beijing plain. Based on the calibrated model, the current groundwater balance was analyzed first to get a comprehensive understanding of the groundwater flow. Then, a total of four proposed groundwater abstraction scenarios were generated and simulated for the period 2015-2030 under the overall framework of comprehensive planning and development of water resources in Beijing plain. The future balance and sustainable utilization of groundwater under different scenarios were then comprehensively analyzed, and the most optimal groundwater abstraction scenario and implications for sustainable groundwater management were determined, providing scientific guidance and significant suggestions for policymakers and the government of Beijing.

The novelty of this paper lies in the following three aspects: first, a creative method is adopted in the simulation of groundwater flow and abstraction for the whole Beijing plain. Due to the large amount of groundwater monitoring data in Beijing, this method is feasible. Second, the GCM projection was adopted to generate future climate data for scenario modeling based on limited data. This approach takes into account the uncertainty of future climate, and to some extent, it can overcome the problem of insufficient data for large-scale groundwater modeling and prediction. Last but not the least, it proposes the implementation of a practical future groundwater abstraction scenario that allows both the sustainable economic growth and the sustainable groundwater abstraction.

# Study area descriptions

Beijing is a megacity with a total area of 16,410 km<sup>2</sup>. It is located in the transitional zone between the Mongolian Plateau and the North China Plain and composed of the northwest mountainous area and the southeast plain (Fig. 1). The study area is the plain area of Beijing with an area of 6400 km<sup>2</sup>. The climate type of Beijing is warm temperate and semi-humid continental monsoon, with a long-time (1955–2014) mean yearly precipitation of 590 mm and a long-time (1960–2012) average potential annual evaporation of 1772 mm. However, the inter-annual precipitation variability is large, while the largest evaporation occurs in April, May, and June. In addition, the seasonal precipitation of the study area is distributed unevenly within the whole year, with about 60–80% of the precipitation occurring in the



summer flood season from June to September. Since April, May, and June are the growth periods of most crops, the amount of groundwater extracted in these months is very large.

Groundwater abstraction for water supply in Beijing commenced in the 1960s. For the period 1961–1970, the average annual rate of groundwater abstraction was  $1.08 \times 10^9$  m<sup>3</sup>. In the 1970s, annual groundwater abstraction in the Beijing plain was  $1.38 \times 10^9$  and  $2.56 \times 10^9$  m<sup>3</sup> in 1971 and 1980, respectively. In the 1980s, due to the continuous dry years, the annual rate of groundwater extraction (average of  $2.62 \times 10^9$  m<sup>3</sup> in 1981–1984) was very large. In the 1990s, the groundwater abstraction in the Beijing plain was relative steady, with an average annual amount of  $2.50 \times 10^9$ – $2.70 \times 10^9$  m<sup>3</sup>. In 1995, the groundwater abstraction was  $2.55 \times 10^9$  m<sup>3</sup>, with a ratio of approximately 66% to total water supply in Beijing. From 1999 to 2011, Beijing had the longest continuous drought (except 2008), the surface water gradually decreased, and the groundwater recharge decreased. At the same time, Huairou, Pinggu, Machikou, and other emergency wells have been implemented successively, which increases the amount of groundwater extraction, leading to a large number of depletion of groundwater storage.

# Numerical model for Beijing plain

# Hydrogeological conceptual model and boundary conditions

In this study, GMS 9.2 is used to evaluate the groundwater flow of Quaternary loose sediments of Beijing plain. As the study area is large and the aquifer structure is complex, the conceptual model approach is adopted to develop the numerical model by analyzing the existing data and maps. General speaking, the aquifer thickness of the Beijing plain increases gradually from west to east and from north to south, and the



Fig. 2 GMS-solid geological section map of Beijing plain

geological conditions change from simple to complex. The aquifer system is divided into five aquifers separated by four aquitards according to the comprehensive analysis of the Quaternary hydrological situations and existing knowledge. Figure 2 shows a geologic section map of the Beijing plain showing these aquifer and aquitard layers. The spatial structure is divided into nine model layers, namely, five aquifer layers including 1st, 3rd, 5th, 7th, and 9th model layers, and four aquitard layers including 2nd, 4th, 6th, and 8th model layers. The five aquifer layers are: an unconfined water-table aquifer; a shallow confined aquifer; an intermediate confined aquifer; a deep confined aquifer; and aquifers at depths of greater than 300 m, respectively.

According to the hydrogeological conditions of the study area, the lateral boundary is divided into two types: one is the natural boundary between the western, northern, and eastern mountains and plains, which is set as a specified flux boundary; and second, the administrative boundary between the southern and eastern plain areas and Hebei province is set as a general head boundary. Recharge to the study area and the model domain from precipitation together with groundwater throughflow from the geographical watershed in front of the mountains. The supplement path is long with a range of several kilometers to more than 10 km. Due to the low permeability of the bedrock aquifer in the mountains, the infiltration of precipitation in this area commonly takes a few years to reach the plains, which makes the yearly fluctuation of the precipitation infiltration smaller. Therefore, the boundary between the plain and mountain areas serves as a specified flux boundary, and the yearly inflow is defined as a stationary value. The downstream boundary is the administrative boundary between the research region and Hebei province. Two possibilities of groundwater inflow and outflow exist in this region, belonging to the mixed boundary, which is generalized as a general head boundary.

The unconfined aquifer's free water surface serves as the top boundary to the model. There are several items that comprise the water fluxes across this boundary, including recharge from both the precipitation infiltration and the cropland irrigation return water, canal leakage supply, and evaporative emissions. The bottom boundary is the Quaternary aquifer's bottom, most of which are Tertiary strata, with poor water permeability, known as the impermeable boundary.

The aquifers in Beijing plain are heterogeneous and anisotropic from the regional point of view, and the major hydrogeological parameters are distributed by uniform zones according to the landform unit, formation lithology and aquifer's sedimentation type. According to the parameters obtained from pumping tests and estimates of aquifer parameters from lithological information and sedimentation type, the initial parameters of each zone were determined. Each model layer's vertical hydraulic conductivity was set as one-tenth of the horizontal hydraulic conductivity.

The recharge item includes precipitation infiltration, mountain side runoff, river infiltration, and irrigation return, while the discharge item includes abstraction, evapotranspiration, as well as lateral outflow. Precipitation recharge is the major source of recharge of the Quaternary aquifer, which is modeled through the Recharge Package in MODFLOW. The Well Package was selected to model the lateral mountain recharge. The River Package was selected to model the leakage from the main rivers and canals. The field irrigation infiltration was computed by the product of actual irrigation amount and irrigation regression coefficient. Groundwater abstraction is the main discharge from the aquifers and was simulated through the Well Package. The ET Package was used to simulate the evapotranspiration process, which was realized by soil capillary and plant transpiration. We have selected the observation well water levels with complete data and clear monitoring depths as the calibration objective. These wells are distributed in different aquifer layers. The well numbers in the five aquifer layers are 55, 46, 25, 12, and 12, respectively. There are various monitoring methods in these wells, some of which use automatic monitoring instruments. The frequency of monitoring varies from once a day to five times a day.

#### Mathematical groundwater flow model

According to the hydrogeological conceptual model, the groundwater aquifer system was conceptualized into a 3-D heterogeneous anisotropic transient groundwater flow system. The corresponding mathematical groundwater flow model is described by Eq. (1)

	$\int S_s \frac{\partial h}{\partial t} = \frac{\partial}{\partial x} (K_x \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y} (K_y \frac{\partial h}{\partial y}) + \frac{\partial}{\partial z} (K_z \frac{\partial h}{\partial z}) + W$	$x, y, z \in \Omega, t \ge 0$	
	$\mu \frac{\partial h}{\partial t} = K_x (\frac{\partial h}{\partial x})^2 + K_y (\frac{\partial h}{\partial y})^2 + K_z (\frac{\partial h}{\partial z})^2 + p$	$x,y,z\in \Gamma_0,t\geq 0$	
ł	$h(x, y, z, t) _{t=0} = h_0$	$x, y, z \in \Omega, t \ge 0$ ,	(1)
	$\frac{\partial h}{\partial n} _{\Gamma_1} = 0$	$x, y, z \in \Gamma_1, t \ge 0$	
	$K_n \frac{\partial h}{\partial n}  _{\Gamma_2} = q(x, y, z, t)$	$x, y, z \in \Gamma_2, t \ge 0$	

where  $\Omega$  is the flow domain; *h* is water-level elevation of the aquifer in m;  $K_x$ ,  $K_y$ , and  $K_z$  represent hydraulic conductivity in x-, y-, and z-direction in m/d, respectively;  $K_n$  is the hydraulic conductivity of the boundary surface's normal direction in m/d;  $S_s$  is the specific storage of the aquifer below the free water surface in 1/m;  $\mu$  is the gravitational specific yield of the unconfined aquifer on the phreatic water-table level; W is the source and sink terms of the confined aquifer in m/d; p is the evaporation and recharge of the phreatic water-table level in m/d;  $h_0$  is the initial water level of the aquifer in m;  $\Gamma_0$  is top boundary of the flow domain, namely, the free groundwater surface;  $\Gamma_1$  is the impermeable boundary of the flow domain;  $\Gamma_2$  is the flux boundary of the flow domain;  $\vec{n}$  is the normal direction of the boundary surface; q(x, y, z, t) is the flux per unit width of the second boundary condition of the aquifer in m<sup>3</sup>/d·m, with a positive value representing inflow, a negative value representing outflow, and zero representing the impermeable boundary.

The mathematical model is solved using the finite-difference method in MODFLOW. The study region was divided into 9 layers, 138 rows and 116 lines and the grid size is  $1 \times 1$  km. GMS can automatically define all grids within the study region boundary as valid grids, and the grids between the boundary and the grid framework as invalid grids, which do not display or calculate in the model. Totally, there are 57,930 valid cells in the model grid. The numerical groundwater model of Beijing plain was established using the digital concept modeling method. The digital concept model is established using professional software GMS and the groundwater flow was simulated by the MODFLOW model. Different modules are adopted to simulate the corresponding hydrogeological conditions in the numerical model (Table 1).

Table 1 The corresponding table of the conceptual model and numerical model

Hydrogeological condition	Digital concept model layer in GMS	MODFLOW module	
Piedmont boundary condition	Segmental arc flow boundary layer	WELL	
Administrative boundary between Beijing and Hebei	Segment of general head boundary layer	GHB	
Top/bottom elevation of aquifer and aquitard	Scatter interpolation	LPF	
Hydrogeological parameter	Hydrogeological parameter layer	LPF	
Planar recharge	Atmospheric precipitation infiltration and irrigation return flow layers	RECHARGE	
River and canal	River and canal layer	RIVER	
Evapotranspiration	Evapotranspiration layer	ET	
Groundwater abstraction	Exploitation well layer	WELL	
Groundwater observation	Observation well layer	WELL	

Table 2The calibration resultsof the steady-state flow model

Error item	First layer	Third layer	Fifth layer	Seventh layer	Ninth layer
ME (m)	- 1.65	1.066	0.682	- 1.123	1.734
RMSE (m)	4.014	5.014	3.391	4.682	6.039
$R^2$	0.9524	0.8644	0.8329	0.9414	0.9271

### Numerical model of groundwater flow

#### Steady-state flow model

The steady-state condition in 1995 with the recharge, discharge, and groundwater level observation data has been selected based on the strength of the analysis of the longterm precipitation and groundwater dynamic change processes for the purpose of model calibration using the trialand-error method. The calibration standards include ME (mean error) and  $R^2$  (determination coefficient), which can be calculated by Eq. (2)

$$\begin{cases}
\mathbf{ME} = \frac{1}{N} \sum_{i=1}^{N} (\mathrm{Obs}_i - \mathrm{Sim}_i) \\
R^2 = 1 - \frac{\sum_{i=1}^{N} (\mathrm{Obs}_i - \mathrm{Sim}_i)^2}{\sum_{i=1}^{N} (\mathrm{Obs}_i - \overline{\mathrm{Obs}})^2}, \\
\sum_{i=1}^{N} (\mathrm{Obs}_i - \overline{\mathrm{Obs}})^2
\end{cases}$$
(2)

where  $Obs_i$  and  $Sim_i$  are the observed and simulated groundwater levels of the *i*<sup>th</sup> well, respectively;  $\overline{Obs}$  represents the average observed groundwater level; *N* represents the groundwater level observation number.

Table 2 shows the error statistics for the calibration processes. It demonstrates that there are no systematic errors in this calibration process as the ME value is less than 5 m in general. Because the hydrogeological conditions of the ninth layer are not well understood due to the low number of observation wells in the deeper aquifers (only 12) and low rate of extraction, the simulation error of this layer is large. The measured and simulated groundwater levels are similar, and the determination coefficients are greater than 0.8 (Table 2); namely, more than 80% of the observed value changes can be explained by analog values.

The hydrogeological parameters ( $K_h$ ,  $K_v$ , and  $S_s$ ) of each model layer were estimated in the model calibration. The ranges of  $K_h$ ,  $K_v$ , and  $S_s$  of five aquifers were 10–300 m d<sup>-1</sup>, 0.8–30 m d<sup>-1</sup>, and  $2.5 \times 10^{-6}$ – $3 \times 10^{-3}$  m<sup>-1</sup>, respectively, while those of four aquifers are 0.003–102 m·d<sup>-1</sup>, 0.0003–10 m d<sup>-1</sup>, and  $1.5 \times 10^{-4}$ – $2.5 \times 10^{-6}$  m<sup>-1</sup>, respectively. The precipitation infiltration coefficient range was 0.0175–0.35.

Although the error appears to be large, it is difficult to rely on the method of repeated tests for calibration, as the spatial distribution of groundwater level varies greatly for the regional groundwater model. On the other hand, the distribution of monitoring network should be improved first to further improve the model. Considering that the purpose of the model is to propose countermeasures for water resource management, the accuracy of the model has reached the goal. Hence, the steady-state flow model can be used as the basis for developing a transient flow model.

#### **Transient flow model**

The transient flow model, with a simulation period of 1995–2014 and a 1 year stress period, was developed based on the calibrated steady-state flow model. The simulation period includes both the calibration stage (1995-2005) and the validation stage (2006–2014). The initial water levels used in the transient model were those simulated in the steady-state model. The precipitation recharge to the model was computed by the product of the measured precipitation from 1995 to 2014 and the local precipitation infiltration coefficient. According to the multi-year mean values of groundwater resources evaluation in Beijing, the river infiltration and lateral recharge in front of the mountain were determined. Based on the evaluation of groundwater resources in 1995 and 2000, the spatial distribution and types of groundwater exploitation were estimated. According to the statistical data of total groundwater exploitation and the spatial-temporal distribution ratio of groundwater exploitation in 1995 and 2000, the groundwater exploitations in other years were determined.

The trial-and-error method has been adopted to calibrate the transient flow model. First, a better correspondence between the simulated and observed water levels in the calibration period was obtained through the adjustment of the specific yield and storage coefficient values. Then, the model was validated through the comparison between the simulated and observed groundwater levels. The comparison curve of typical observation wells is shown in Fig. 3, demonstrating that the simulated groundwater levels generally reflect the variation trend of the observed one. By and large, the simulated groundwater levels match well with the observed ones, with  $R^2$  values of 0.84 and 0.73 for the calibration and validation periods, respectively. The calibration and verification results show that the model is applicable for Beijing plain and is available for the scenario forecast.

#### Groundwater balance analysis

Figure 4a, b lists the simulated groundwater recharge and discharge rates for 1995–2014. Precipitation and irrigation return flow make up a significant share (50%) of total recharge, followed by river and canal leakage and piedmont lateral recharge. The highest rate of annual groundwater recharge  $(2.9 \times 10^9 \text{ m}^3)$  occurred in 2012, and the lowest annual groundwater recharge rate  $(1.8 \times 10^9 \text{ m}^3)$  occurred in 1999. The reason for this is that the precipitation in 2012 and 1999 was 708 mm and 339 mm,



Fig. 3 Comparison between simulated and observed groundwater levels for typical observation wells

respectively. Abstraction makes up an extremely high share (over 90%) of the total discharge from the ground-water flow system. General speaking, groundwater discharge has been in the range of  $2.3 \times 10^9$ – $2.8 \times 10^9$  m<sup>3</sup>/ year in recent years.

The recharge rate decreased, while the discharge rate changed little during 1995–2014, illustrating that the groundwater aquifer storage is depleting. Figure 4c demonstrates that the aquifer system in 1995 was in balance, verifying the rationality of choosing 1995 to establish steady-state flow model. In 1996, 1998, 2008, and 2012, due to the normal precipitation in these years, the total reserves of groundwater increased. From 1995 to 2014, the groundwater recharge in 1999 was the smallest, resulting that the storage capacity consumption in that year was the largest  $(1.106 \times 10^9 \text{ m}^3)$ . Since 1999, due to the continuous years of drought and large-scale pumping in Beijing, groundwater recharge is generally less than discharge, resulting in the decline of water level and the depletion of groundwater reserves.

# Scenario analysis on groundwater abstraction

# **Scenarios design**

The model after calibration and validation was applied to simulate the future groundwater utilization under different abstraction scenarios that are designed taking into account the future water resource requirements stated in the 12th 5 year Plan of China.

The future precipitation data are generated on account of Global Circulation Models (GCM) projections under the A1B CO<sub>2</sub> emission scenario using the climate change scenario tool in MIKE SHE, which has built-in change factors for precipitation and reference ET according to the geographic location and the prediction year for various GCM projections and CO<sub>2</sub> emission scenarios (DHI 2012a; b). The climate data of 2015–2030 were obtained through applying the monthly delta change factors to the present climate (Anandhi et al. 2011). Change factors for 22 out of



Fig. 4 Groundwater balance of the Beijing plain for 1995–2014: a recharge items, b discharge items, and c total recharge, total discharge, and their difference

the 23 GCMs in the IPCC AR4 are available in the climate change scenario tool in MIKE SHE. We have selected three GCM projections with the wettest (UKMO\_HADCM3), the normal (CSIRO\_MK3), and the driest (CNRM\_CM3) change in precipitation. The normal GCM projection has been adopted in this study to represent the future climate condition of Beijing plain. During the forecast period, the precipitation infiltration zone and infiltration coefficient are consistent with the calibration model.

A total of seven zones, including week development zone (#1), Yudai zone (#2), Lixian zone (#3), Wangjing zone (#4), Baxiangzhuang zone (#5), Tianzhu zone (#6), and Wangsiying zone (#7), were adopted in the study region. These zones are divided according to the current land subsidence

degree map, the soil deformation characteristics, the Quaternary stratigraphic map, and the thickness contour map of compressible layer. Zones 5, 6, and 7 are the ones with the fastest land subsidence rates, while those in zones 1–4 have stabilized at a relatively small value. Hence, abstraction reductions in zones 5–7 are the major consideration to simulate the future groundwater level recovery. Meanwhile, this study has analyzed the impacts of the artificial recharge in the upstream reaches of Chaobai River on groundwater level recovery.

The main technical methods to achieve the groundwater sustainable development include reducing the groundwater abstraction amount, adjusting the distribution of groundwater abstraction, implementing groundwater artificial

oundwater ios for the	Name	Simple description	Abstractions (10 <sup>8</sup> m <sup>3</sup> /year)					
	BAU	Business as usual	21.67					
	AR	Artificial recharge in Chaobai river	20.82					
	GAR100	Groundwater abstraction reduction in zones 5-7 by 100%	17.00					
	GAR520	Groundwater abstraction reduction in zone 5–7 by 50%, 20%, and 100%, respectively	17.69					

Table 3Future grabstraction scenarBeijing plain

recharge, and undertaking the joint utilization of surface water and groundwater resources. Consequently, a total of four different scenarios were simulated to forecast groundwater level during 2015–2030. The data generated by GCM forecast were adopted as the precipitation of future forecast, and other input data and parameters are consistent with those of 2014. Table 3 is the summary of the scenarios, including business as usual scenario (BAU), an artificial recharge scenario (AR), a scenario with groundwater abstraction reduction in zones 5–7 by 100% (GAR100), and a scenario with groundwater abstraction software four scenarios range from 1.700 × 10<sup>9</sup> to 2.167 × 10<sup>9</sup> m<sup>3</sup>/year.

The scenario BAU is designed to appraise the groundwater utilization situation under the current development mode of Beijing. The surface water and groundwater joint regulation and storage project will be implemented after the SNWDP transfers water to Beijing. In the upper reaches of the Chaobai River, the effect of artificial groundwater recharge from the excess water of SNWDP on the recovery or maintenance of groundwater level in the main settlement areas such as Shunyi, Chaoyang, and Tongzhou in the lower reaches was carried out. The scenario AR is designed to evaluate this effect. For other scenarios (GAR100 and GAR520), our main consideration is to simulate and predict the groundwater level rise in the plain area of Beijing in the future by reducing groundwater abstraction in different degrees in zones 5–7.

The top of alluvial–proluvial fan in the Chaobai River serves as the proposed location for an artificial recharge scheme. The groundwater abstraction of Huairou emergency water supply plant decreased by 80% to  $2 \times 10^7$  m<sup>3</sup>/year, and the abstraction of other areas was consistent with that of BAU. For GAR100 and GAR520, the abstraction reductions



Fig. 5 Groundwater level changes of five aquifers under different scenarios

Table 4Average variation of<br/>groundwater level in Beijing<br/>plain under different scenarios<br/>(m/year)

Aquifer scenario	First layer (first aquifer)	Third layer (second aquifer)	Fifth layer (third aquifer)	Seventh layer (fourth aquifer)	Ninth layer (fifth aquifer)	
BAU	- 0.26	- 0.26	- 0.25	- 0.25	- 0.25	
AR	-0.08	- 0.07	- 0.07	- 0.07	-0.07	
GAR100	0.80	0.90	1.27	1.57	1.56	
GAR520	0.68	0.76	1.03	1.31	1.33	

Table 5 Groundwater balance for the four scenarios during 2015–2030, where TR, TD, and SC represent total recharge, total discharge, and storage change, respectively (unit: 10<sup>8</sup> m<sup>3</sup>)

Scenario (year)	BAU		AR		GAR100			GAR520				
	TR	TD	SC	TR	TD	SC	TR	TD	SC	TR	TD	SC
2015	19.49	22.57	- 3.08	20.99	21.71	- 0.72	19.49	17.90	1.60	19.49	18.59	0.91
2016	21.42	22.65	- 1.23	22.92	21.79	1.13	21.42	17.96	3.46	21.42	18.65	2.77
2017	21.34	22.64	- 1.29	22.84	21.78	1.06	21.34	17.96	3.38	21.34	18.65	2.69
2018	23.64	22.68	0.96	25.14	21.82	3.32	23.64	18.00	5.64	23.64	18.69	4.95
2019	21.74	22.59	- 0.85	23.24	21.73	1.51	21.74	17.92	3.83	21.74	18.61	3.14
2020	18.27	22.51	- 4.24	19.77	21.65	- 1.88	18.27	17.83	0.45	18.27	18.52	- 0.24
2021	16.66	22.49	- 5.84	16.66	22.49	- 5.84	16.66	17.82	- 1.16	16.66	18.51	- 1.85
2022	25.79	22.63	3.16	25.79	22.63	3.16	25.79	17.96	7.83	25.79	18.64	7.14
2023	23.24	22.64	0.61	23.24	22.64	0.61	23.24	17.96	5.28	23.24	18.65	4.60
2024	21.59	22.64	- 1.05	21.59	22.64	- 1.05	21.59	17.95	3.64	21.59	18.64	2.95
2025	19.76	22.54	- 2.79	19.76	22.54	- 2.79	19.76	17.87	1.89	19.76	18.56	1.20
2026	21.55	22.55	- 1.00	21.55	22.55	- 1.00	21.55	17.88	3.67	21.55	18.56	2.99
2027	21.57	22.59	- 1.02	21.57	22.59	- 1.02	21.57	17.92	3.65	21.57	18.61	2.96
2028	23.92	22.68	1.24	23.92	22.68	1.24	23.92	17.99	5.93	23.92	18.68	5.24
2029	21.48	22.59	- 1.11	21.48	22.59	- 1.11	21.48	17.92	3.56	21.48	18.60	2.87
2030	21.49	22.57	- 1.08	21.49	22.57	- 1.08	21.49	17.90	3.60	21.49	18.59	2.91

of zones 5–7 were just for household and industrial use, while the agricultural use was consistent with that of BAU.

# Scenarios simulation and analysis

Figure 5 shows the groundwater level changes of the different aquifers under different scenarios. It can be seen that the groundwater levels in all the five aquifers show a downward trend of about 0.25 m/year under the BAU scenario (Table 4). If the artificial recharge scenario is adopted by Beijing, the groundwater level also shows a downward trend of about 0.07 m/year (Table 4). However, if the groundwater abstraction reduction scenarios are adopted by Beijing, the groundwater levels show upward trends with ranges of 0.80-1.57 m/year (scenario GAR100) and 0.68-1.33 m/year (scenario GAR520), respectively (Table 4). The groundwater levels can be recovered in scenarios GAR100 and GAR520, and the degree of recovery is positively related to the degree of groundwater abstraction reduction. That is, the greater the reduction in abstraction is, the more the groundwater levels would recover. Although scenario GAR100 can recover



Fig. 6 Average and maximum groundwater storage changes for different scenarios

groundwater level to a large extent, it is not acceptable for Beijing plain to completely stop groundwater abstraction; scenario GAR520 can not only effectively recover groundwater level, but also ensure the social and economic development of Beijing plain.



Fig. 7 The proportion of groundwater storage change to total recharge for different scenarios

Table 5 shows the groundwater balances under all scenarios for 2015-2030. The negative water balances in most years in BAU indicate the continuous depletion of the aquifer storage. A positive water balance in AR during the recharge period implies an increase in aquifer storage, while the aquifer storage is exhausted after the recharge period. Due to the decrease of groundwater extraction in the other two cases, the aquifer storage increases in most years. On average, the aquifer storages dried up at a rate of  $1.2 \times 10^8$  and  $2.8 \times 10^7$  m<sup>3</sup>/year in BAU and AR, respectively; while the aquifer storages recover by  $3.5 \times 10^8$  and  $2.8 \times 10^8$  m<sup>3</sup>/year in GAR100 and GAR520, respectively (Fig. 6). The largest aquifer storage depletions are  $5.84 \times 10^8$  and  $5.84 \times 10^8$  m<sup>3</sup>/ year in BAU and AR, respectively, while the largest aquifer storage recoveries are  $7.8 \times 10^8$  and  $7.1 \times 10^8$  m<sup>3</sup>/year in GAR100 and GAR520, respectively (Fig. 6). There are different recoveries of aquifer storage in different scenarios, but all of them have achieved the goal of preventing the depletion of aquifer storage.

Figure 7 shows a comparative analysis diagram of the proportion of groundwater storage change to total recharge under different scenarios. It can be seen that this proportions under the four scenarios are consistent with the precipitation change trend in the predicted period. This proportion in GAR100 is the largest among all scenarios, indicating that stopping groundwater abstraction can have an immediate effect on the recovery of groundwater aquifer storage, followed by GAR520. This analysis is consistent with the above analysis on the groundwater balance. Therefore, GAR100 and GAR520 are better than BAU and AR from the perspective of whether the groundwater system can reach a stable state.

Based on the analysis of the four scenarios aforementioned, scenario GAR520 is considered to be the optimal groundwater abstraction one for Beijing plain in the future. Under this scenario, the abstraction reductions in zones 5–7 would be  $2.55 \times 10^7$  m<sup>3</sup>/year (50% reduction),  $1.2 \times 10^7$  m<sup>3</sup>/ year (20% reduction), and  $3.52 \times 10^8$  m<sup>3</sup>/year (100% reduced), respectively. The total abstraction reduction would be  $3.895 \times 10^8$  m<sup>3</sup>/year and the total abstraction would be  $1.769 \times 10^9$  m<sup>3</sup>/year.

# Discussion

# Implications for sustainable groundwater management

Intensive and large-scale groundwater abstraction has not only supported the rapid economic growth and urban population but also caused a continuous groundwater level decline in Beijing over recent decades. Since 2000, the Beijing municipal government has shut down all privately drilled wells in the city and strengthened the management of underground wells in suburban counties, which has significant effect on the recovery of groundwater level and aquifer storage. Measures, including strict control of project construction drainage, artificial recharge of groundwater, and rainwater harvesting, shall be taken to effectively control aquifer storage depletion (Qin et al. 2018). By 2014, the annual rate of groundwater abstraction has been progressively reduced to approximately  $2.1 \times 10^9$  m<sup>3</sup>.

The most direct and effective way to improve the sustainability of groundwater management in Beijing is to reduce groundwater abstraction. Compared to the other scenarios with no reduction in abstraction, the scenario with a reduction in abstraction leads to a recovery in groundwater storage in aquifers in the area. This is a part of sustainable groundwater management. However, the reduction in groundwater abstraction should be adopted under the condition that the economic development of the study area cannot be deteriorated or ignored. Only the guarantee of both sustainable groundwater management and economic development can be acceptable for such an economically developed and densely populated megacity like Beijing.

Importing surface water from outside river basins, such as SNWDP, is one potential method of protecting groundwater in Beijing. The water diversion from SNWDP not only increases the water supply but also reduces the groundwater abstraction in Beijing. Therefore, the groundwater aquifer storage has recovered a lot. On the other hand, the surplus diverted water from SNWDP could be used as a source of artificial recharge in the top of alluvial–proluvial fan in the Chaobai River, which would raise the groundwater level. In conclusion, additional water allocated from SNWDP would help to alleviate the water deficit problems and hence achieving sustainable groundwater management in Beijing (Qin et al. 2013). However, these sorts of measures may cause problems in areas where the water is being diverted from. Transporting water long distances is also costly due to the costs involved with the construction and maintenance of pipelines and pumping costs. Relevant regions need to evaluate whether to adopt such measures according to the actual situation.

As agriculture is an important water consumer in the Beijing plain, another possibility is to reduce evapotranspiration (ET), which could directly reduce the discharge from the groundwater system. There are two potential measures that could be used to reduce ET from agricultural land use. These include: altering the plant rotation pattern; and employing water conservation methods to reduce evapotranspiration. Therefore, improving the efficiency of agricultural water use is the primary focus of water conservation attempts. Several water conservation irrigation technologies, including border irrigation, low-pressure pipe irrigation, and sprinkler irrigation (Blanke et al. 2007), are the most effective measures to replace the flood irrigation widely used in Beijing plain.

Meanwhile, as the magnitude of groundwater depletion in the subsidence centers is the largest in the study area, the strictest sustainable groundwater management countermeasures should be adopted in these areas to greatly decrease the rate of abstraction from the deep confined aquifer. If the SNWDP starts to supply water to Beijing, the distribution of water from the SNWDP should be optimized in case that the effect of SNWDP in mitigating groundwater depletion can be fully achieved.

# Model limitations and improvements

Although the nonstationary flow model of groundwater developed for Beijing plain has its own advantages, such as conceptualizing the aquifer system into five aquifers separated by four aquitards, generating the future precipitation data using GCM projections of the A1B  $CO_2$  emission scenario, and considering the use of artificial recharge in the top of alluvial–proluvial fan in the Chaobai River, the model has several limitations.

First, the methods used for grid discretization, time division, and hydrogeological parameter division in this model were greatly simplified due to the large area and complex hydrogeological conditions in the study area. To improve the modeling speed and running efficiency of the model, the grid size used in the model was  $1 \times 1$  km, the time stress period was 1 year, and the hydrogeological parameter division was relatively simple. This kind of model construction may result in the failure to accurately capture and characterize the flow field and head distribution of the region where the land subsidence seriously exceeds the standard. These two aspects can be improved by adopting a refined grid size and hydrogeological parameter division in future work of this model.

Second, there are insufficient monitoring wells in the deep confined aquifer and, consequently, there are insufficient monitoring data from this aquifer for effectively calibrating the model. This may cause uncertainties in the model calibration and validation processes. There are only 12 wells in both the seventh and ninth model layers. This aspect can be improved by constructing additional multilevel monitoring wells and other measures that can increase the number of monitoring wells in the deep confined aquifer.

Third, the land subsidence is mainly caused by the exploitation of deep groundwater. The compressed water release of aquifer is the main source of the exploitation amount of deep groundwater. At the same time, the reduction of water storage coefficient and permeability coefficient is caused by the reduction of the ratio of compressed deformation porosity, which has an impact on the inelastic water release and overflow supply amount of the weak permeable layer. The nonlinear variation of hydrogeological parameters in the process of land subsidence and the feedback effect on the confined aquifer system have also become frontier issues in the field of hydrogeology. However, due to the data availability, the effect of land subsidence on the aquifer parameters is not considered in this model. This effect could be considered in future research work.

Finally, the only groundwater management scenarios that were considered in this study were the reduction of groundwater abstraction and the use of artificial recharge in the top of alluvial–proluvial fan in the Chaobai River due to the limited availability of data for the model simulation. There are other situations that can be considered in the scenarios design, such as artificial recharge in other locations, the combination of groundwater abstraction reduction and artificial recharge, and so on. This aspect can be improved once the data required by the model are available in future time.

# Conclusions

A 3-D numerical transient groundwater flow model has been established for the Beijing plain to accurately capture and characterize the groundwater flow field. Then, the sustainable groundwater abstraction management in Beijing plain was simulated and analyzed using the scenario analysis method. The following conclusions can be drawn from this study:

(1) The principal sources of groundwater recharge on the Beijing plain are precipitation infiltration, piedmont lateral seepage recharge, irrigation return recharge, and river leakage recharge; the main sources for discharge from the groundwater flow system are abstraction for water supply and evapotranspiration. The aquifer system can be divided into five aquifers and four aquifers, which can more accurately capture and characterize the groundwater flow field in Beijing plain, and the model could be further used in groundwater pollution transport and land subsidence modeling. (2) On average for the prediction period, the groundwater storage depletions of scenarios BAU and AR are  $1.2 \times 10^8$  m<sup>3</sup>/year and  $2.8 \times 10^7$  m<sup>3</sup>/year, while the groundwater storage recoveries of scenarios GAR100 and GAR520 are  $3.5 \times 10^8$  m<sup>3</sup>/year and  $2.8 \times 10^8$  m<sup>3</sup>/year, respectively. The maximum storage depletions of scenarios BAU and AR are  $5.84 \times 10^8$  m<sup>3</sup>/year and  $5.84 \times 10^8$  m<sup>3</sup>/year, respectively while the maximum storage recoveries of scenarios GAR100 and GAR520 are  $7.8 \times 10^8$  m<sup>3</sup>/year and  $7.1 \times 10^8$  m<sup>3</sup>/year, respectively.

(3) Based on the comprehensive analysis on all the scenarios, the scenario GAR520, which has a total groundwater abstraction reduction of  $3.895 \times 10^8$  m<sup>3</sup>/year and a total groundwater abstraction of  $1.769 \times 10^9$  m<sup>3</sup>/year, is a reasonable abstraction scenario that not only sustains the groundwater management but also ensures sustainable economic development in Beijing. This scenario should be adopted in Beijing plain in the future.

(4) The results of the modeling study have implications for sustainable groundwater management in the region. Measures that could be considered to improve the sustainability of groundwater management in the region include reducing the rate of groundwater abstraction, importing surface water from outside river basins, improving agricultural water use efficiency by adopting water-saving irrigation techniques, controlling the groundwater abstractions in the subsidence centers, and so on, are suggested to the policymakers of the government. Only the measures adopted and implemented comprehensively that the sustainable groundwater management and economic development in Beijing can be achieved finally.

Acknowledgements The authors would like to thank Chunmiao Zheng at Southern University of Science and Technology, Jie Liu at Peking University, and Fang Tian and Yong Luo at Beijing Institute of Hydrogeology and Engineering Geology for their help on the modeling work and preparation of this manuscript. Additional supports during the process of preparing the paper come from my wife, Liyuan Zhu. I would like to express my deeply and everlasting love to her.

**Funding** This work was supported by National Natural Science Foundation of China (Grant No 41807179) and Doctoral Start-Up Fund of the East China University of Technology (Grant No DHBK2016104).

Data availability Not applicable.

#### Declarations

Conflict of interest The authors declare no conflict of interest.

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