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Research papers

Towards sustainable groundwater development with effective measures under future climate change in Beijing Plain, China

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ABSTRACT

To cope with the groundwater depletion problem and achieve sustainable groundwater development, groundwater conservation measures and managed aquifer recharge (MAR) have been implemented worldwide. However, knowledge gaps exit how does the aquifer system respond to these interventions differently and if these interventions are adequate to lead to long-term sustainable groundwater development under future climate change. In Beijing Plain, two measures have been implemented: reduction of groundwater abstraction by substituting groundwater abstraction with transferred surface water and implementation of managed aquifer recharge (MAR) in two major rivers. This study aims to assess how do the shallow and deep aquifers respond to these measures and if these measures can lead to long-term sustainable groundwater development in Beijing Plain under future climate change. A 3-D transient groundwater flow model was calibrated and used to simulate groundwater level and budget changes from 2021 to 2050. The monthly groundwater recharge was estimated using the projected monthly precipitation from three downscaled regional climate models under two scenarios (RCP4.5 and RCP8.5). The results show that declines in groundwater head and storage can be reversed with the combined two measures, thereby contributing to achieve sustainable groundwater development. The reduction of abstractions is a deciding measure to reverse the trend of groundwater depletion, especially in the deep confined aquifers, while large scale MAR schemes can restore the cones of depressions in shallow aquifers and maintain the groundwater abstraction. Climate variation has large impacts on groundwater resources, especially, consecutive dry years can cause rapid groundwater storage depletion. The projected monthly precipitation from 2021 to 2050 is not significantly different from the past. Therefore, the projected future precipitation has minor impacts on groundwater resources in the next 30 years. The findings from the study will support the Beijing municipality to maintain the tight control on groundwater abstraction and to implement large-scale MAR schemes in two rivers. This successful example will encourage managers of other heavily exploited aquifers to take similar measures to achieve sustainable groundwater development.

1. Introduction

Ever since 20th century, groundwater exploitation has been booming due to the flourishing of socio-economic development and population growth globally (van der Gun, 2012). Especially in arid and semi-arid regions, groundwater is a reliable water supply source that is more resilient to climatic variability, especially during drought periods (Cuthbert et al., 2019; Edmunds, 2003). Groundwater withdrawal increased 15% per decade globally between 1960 and 2010 to meet the demand for all kinds of anthropogenic activities (Wada and Bierkens, 2014). Consequently, the abstraction rate has exceeded the groundwater renewal rate. The estimate of global groundwater depletion ranges between 100 and 200 km3/year, constituting approximately 15 to 25% of the world's total groundwater withdrawals (UN-water, 2022). Particularly, regions such as Central Asia, USA, North China and Middle East, face the most severe groundwater depletion issues (Ashraf et al., 2021; Konikow and Kendy, 2005; Wada, 2016; Zhao et al., 2019).

Researchers and policymakers have recognized the urgent need to develop effective strategies for remediating and restoring depleted aquifers (Liu et al., 2001; Liu et al., 2022a). One crucial aspect of aquifer

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management involves reducing groundwater abstraction to minimize the stress on aquifers (Deines et al., 2019; Van et al., 2023). By enhancing the efficiency of water usage and implementing strict regulations to limit groundwater extraction, a sustainable development can be achieved. However, limiting groundwater use alone may not be sufficient to fully restore depleted aquifers. This is where MAR techniques come into play (Bouwer, 2002; Dillon et al., 2009). MAR involves artificially recharging aquifers by diverting excess surface water or treated wastewater to infiltration basins, injection wells, or other engineered structures. MAR has been applied globally at different operation scales (IGRAC, 2007). The combined efforts of optimizing the water supply structure and implementing MAR techniques hold significant potential for addressing the challenges of over-exploited aquifers. These approaches not only provide immediate relief by mitigating extraction pressure on aquifers but also contribute to the long-term sustainability of groundwater resources (UNESCO, 2021). Numerical modelling is a powerful tool to evaluate the effectiveness of mitigation measures (Konikow and Kendy, 2005; Maliva et al., 2009; Ringleb et al., 2016). Numerical modelling provides a quantitative approach to assess and analyse the recovery of groundwater storage and groundwater levels with the implementation of MARs and groundwater conservation policies (Valley et al., 2005; Vandenbohede et al., 2008; Xanke et al., 2016).

Apart from the impact of human activities on the groundwater system, the influence of climate change has also been recognized and emphasized in recent years (IAH, 2016). A common method to investigate the potential impact of climate change on groundwater is coupling downscaled General Circulation Model (GCM) climate projections with the hydrological models (Epting et al., 2022; 2023; Gemitzi et al., 2017; Green, 2016; Pulido-Velazquez et al., 2015). The downscaling of the GCM output can be achieved by two approaches: dynamic downscaling and statistical downscaling. Dynamic downscaling reproduces the Regional Climate model (RCM) by taking GCM data as boundary conditions and employs some physical principles considering the interactions of atmosphere, land water and social economics (Xu et al., 2019). Statistical downscaling, on the other hand, corrects the RCM or GCM data by applying statistical analysis of the historical climate data and the RCM/GCM model data. Amanambu et al. (2020) summarized a generalized conceptual framework of modelling the future impacts of climate change on groundwater. Typically, downscaled GCM/RCM data were used as inputs to hydrological models to future predictions. Many studies have been conducted using this methodology in different types of climatic zones, which has expanded our understanding of the interplay between climate and groundwater systems. Most of the modelling scales fall between small (10^2-10^3 km^2) to medium (10^3-10^4 km^2). Although the uncertainty in prediction is still a major challenge, research results show deviated future trends in groundwater recharge, groundwater storage and groundwater levels in different climate regions. For instance, studies have reported a decrease in groundwater recharge and storage in humid tropical regions (Alam et al., 2019; Klaas et al., 2020; Patil et al., 2020) as well as semi-arid and arid tropical regions (Ghazavi and Ebrahimi, 2019; Goodarzi et al., 2016; Herrera-Pantoja and Hiscock, 2015). Predictions in temperate zones show more uncertainty, with the majority of studies concluding in a decrease in groundwater recharge and storage, but some research has also reported an increase of recharge and storage (Niraula et al., 2017; Ou et al., 2018; Rasmussen et al., 2023; Tillman et al., 2016).

The climate change and groundwater over-exploitation create challenges for sustainable groundwater management, particularly in regions with severely depleted aquifers. In the Indus basin, achieving sustainable development requires a focus on reducing water consumption, which can be accomplished through the improvement of irrigation techniques and the optimization of cropping patterns (Muzammil et al., 2023). Similarly, in California's Central Valley, groundwater is heavily over-exploited due to huge groundwater pumping for irrigation during consecutive droughts over two decades (Konikow, 2015; Liu et al., 2022a). To combat the threat of groundwater depletion and other related hazards, the Sustainable Groundwater Management Act (SGMA) was enacted, dedicating to manage the groundwater use at a sustainable level by implementing a better water allocation scheme (Alam et al., 2019). Similarly, in the U.S. Central High Plains aquifer, to stop the trend of groundwater level decline, with a bottom-up approach, farmers were empowered to work together with the local officials to make future water conservation plans. Assessment of these measures found that the water use in Kansas state decreased 31% over the first five-year period (Deines et al., 2019). In the North China Plain, the depletion rate of groundwater has been quantified and mapped (Cao et al., 2013). Several measures have been considered, including the implementation of MAR, increasing water use efficiency, and implementing inter-basin water transfer schemes. These global examples highlight the strong commitment of scientists, governments, and local communities to ensure the sustainability of groundwater for future generations.

However, knowledge gap exits if the present groundwater conservation measures and MAR could lead to long-term sustainable groundwater development under future climate change. Little is known how do the shallow and deep aquifers respond to these interventions differently. There are few studies dealing with joint assessment of groundwater conservation polices and future climate change on the long-term groundwater sustainability.

Beijing is one of the few successful cases that is moving rapidly towards sustainable groundwater development. Two drastic measures have been planned and implemented. The first measure is substituting a large amount of groundwater abstraction with transferred surface water from the South-to-North transfer scheme (Liu and Zheng, 2002). The second measure is enhancing groundwater recharge by implementing MAR in two major rivers (Zhou et al., 2012). Observed groundwater levels have shown that the declining trend of groundwater levels in the last two decades has been reversed and an increase in groundwater levels has been observed in shallow aquifers (Long et al., 2020). Are these two measures sufficient to achieve sustainable groundwater development? Will future climate change compromise these measures? This study aims to assess the sustainability of groundwater development in Beijing Plain under the implementation of these two measures under future climate change. The specific objectives are: 1) to develop a 3-D transient groundwater flow simulation model using MODFLOW model including pilot MARs in two rivers from 1995 to 2020; 2) to calibrate and validate three downscaled climate models for monthly precipitation projections; 3) to develop a groundwater prediction model including operational MARs from two rivers and updated recharge with the biased correction of the projected monthly rainfall from 2021 to 2050; 4) to predict changes of groundwater level and storage under three climate models and to assess sustainability of future groundwater development.

2. Materials and Methods

2.1. Study area

Beijing City (39°28́N − 41°05́N, 115°25́E −117°30́E), the capital of China, functions as the political, cultural, diplomatic, and educational centre of the nation. The total area of the municipality is 16,410 km^2 with 38 % of plain area and 62 % of mountainous area (Fig. 1). The plain area of Beijing gently decreases from 100 m above mean sea level at the foot of the mountains in the north and west to 20 m in the southeast. Beijing has a continental type of climate with hot, humid summers and cold and dry winters. The average monthly temperature varies from −2.9℃ (in January) to 26.9℃ (in July). The average annual precipitation from 1959 to 2020 is 573 mm. With uneven temporal precipitation distribution, 75 % of the rainfall occurs during the rainy season (June-August). The annual precipitation from 1959 to 2020 is shown in Fig. 2. In general, the annual rainfall shows a decreasing trend in the last 60 years.

In the last several decades, Beijing has become a mega city with rapid urban development. In 2020, the total population in Beijing reached

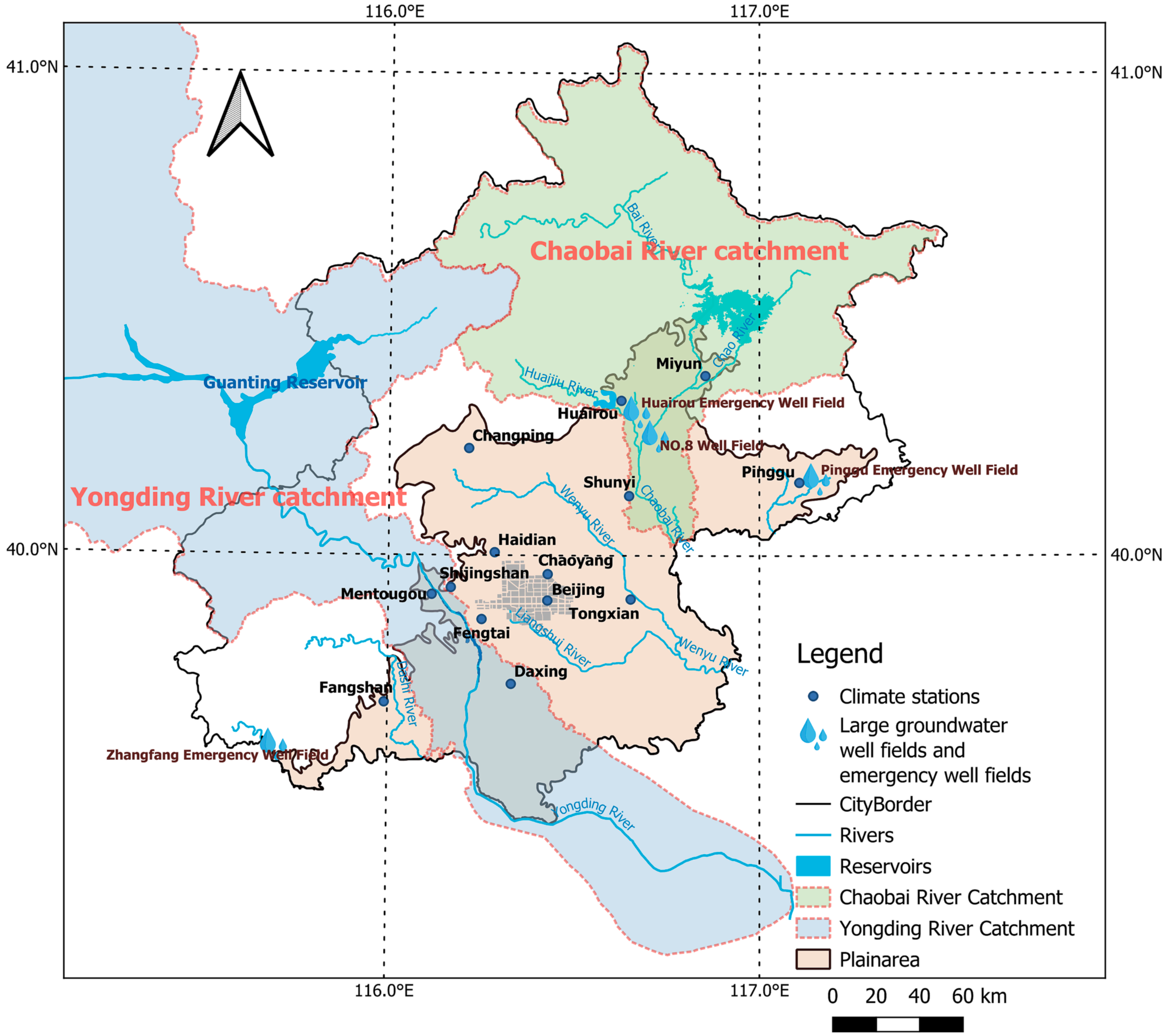


Fig. 1. Map of Beijing City, Beijing Plain, main groundwater well fields and two main river catchments.

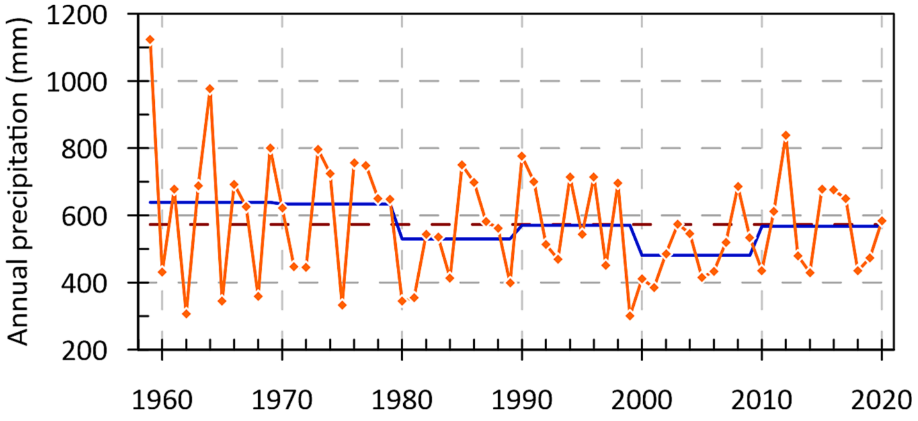


Fig. 2. Historical annual precipitation data from 1959 to 2020 in Beijing, blue line indicates the step changes of annual precipitation, red dashed line plots the average annual precipitation from 14 stations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

21.9 million. However, the water shortage problem largely restrained the city's sustainable development. The city's average per capita water resource was only 118 m^3 in 2020 (Beijing Water Authority, 2021), which is far below the international water shortage limit standard (1000 m^3 per capita) (WWAP, 2012). Fig. 3 shows the water supply sources of Beijing from 1999 to 2020. Before the large-scale use of reclaimed water and the implementation of the South-to-North (S2N) water transfer project, groundwater accounted for more than 60 % of the urban water supply. Since 1999, the city experienced a continuous 10-year drought period with an average of only 480 mm/year of precipitation. The decrease in rainfall and surface runoff resulted in the drying up of the main rivers and less water supply from the surface reservoirs. To meet the huge water demand, emergency well fields were put into operation to increase groundwater supply. Consequently, the groundwater was heavily over-exploited, and the groundwater storage was depleted. Moreover, groundwater depletion also brought other environmental problems to the region including water quality deterioration, riverine ecosystem deterioration, and land subsidence (Hu et al., 2019; Li et al., 2015).

2.2. *Effective measures to achieve sustainability*

To cope with the water scarcity problem, the Central Route of the South to North (S2N) Water Transfer project was initiated in 2003. The Central Route diverts Yangzte River water to Beijing and other neighbouring provinces along a 1267 km constructed canal. The Central Route S2N Water transfer became operational in 2015. Beijing receives approximately 1.0 billion m^3 of transferred water annually. The transferred water has become a new alternative water source for the urban water supply and alleviated the water shortage problem in the city. Thus, groundwater abstraction has been reduced from more than 2 billion m^3 per year to 1.5 billion m^3 per year in Beijing since 2015. The operation of emergency well fields was suspended. Pumping wells for industrial water supply from deep confined aquifers were shut down. Moreover, some of the transferred water was used for recharging the aquifer. The MAR project was piloted in 2015 in the Chaobai River and found to be feasible. Due to the over-abstraction at the No.8 Well Field and the Huairou Emergency Well Field (Fig. 1) during the drought period from 1999 to 2009, a large cone of depression was formed near the Chaobai River, which provided adequate underground space for recharging and storing the transferred water from the S2N Water Transfer Project. A large-scale MAR is planned to convert the 12 km river channel into 9 terraced infiltration basins for artificial recharge (Fig. 4, right). Details of the design can be found in Liu et al. (2022b). The estimated annual recharge capacity is about 290 million m^3 for the large-scale MAR operation.

To cope with the degraded surface water bodies and the degraded riverine ecosystem, an environmental flow release (EFR) project was also implemented in the Yongding River Catchment. In 2009, Beijing Water Authority initiated the “Yongding River Green Ecological Corridor” project, aiming to restore the environmental flow and improve the ecosystem. The original Yongding River channel was constructed with several lakes and wetlands. Water diverted from the Yellow River Diversion Project was released from the upstream reservoirs before the flood season to both mitigate the flood risk and maintain the environmental flow in the Yongding River (Fig. 4). Due to the high permeability of the riverbed and surrounding aquifer, the released water also enhances the groundwater recharge through the river leakage. The pilot project was launched in 2019 and 2020. The results show that the released water is able to sustain the river flow and also restore the groundwater storage in this region (Liu et al., 2023).

In general, with extra water resources from the regional water transfer projects, the water supply structure of the city is in a transition. The percentage of groundwater use for the urban water supply reduced significantly from 52 % in 2014 to 33 % in 2020 (Fig. 3). Together with the implementation of the MAR in Chaobai River and EWR in Yongding River, the groundwater depletion caused by the over-exploitation in the past is expected to be gradually recovered and sustainable groundwater development may be achieved in the future.

2.3. *Evaluating the impact of future climate change on the groundwater system*

- **Selection of the RCM models and scenarios.**

The infiltration from rainfall and the lateral inflow from the mountain are the major sources for recharging the shallow aquifer in Beijing Plain. The lateral inflow consists of two components. The first one is subsurface inflow from hard rock aquifer in the mountainous areas into the alluvial plains. The second one is the infiltration of runoff from hillslopes during the rains. Natural recharge from two rivers is limited. The Chaobai River is dry since the Miyun Reservoir upstream stores surface water and is one of the main sources of surface water supply for Beijing City. The Yongding river is also regulated by reservoirs upstream. Leakage from EFR provides artificial groundwater recharge. The spatial and temporal variability in precipitation patterns directly affect the distribution and volume of groundwater recharge. Thus, to predict the future groundwater level and storage change in Beijing Plain, the

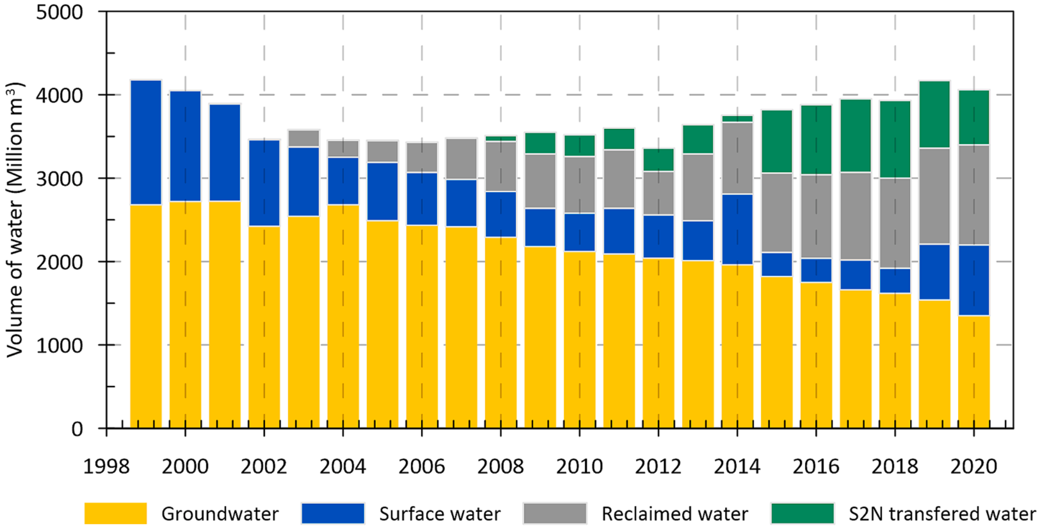


Fig. 3. Water supply sources in Beijing from 1999 – 2020.

Fig. 4. Locations of MAR project in Chaobai River (right) and EFR project in Yongding River (left).

groundwater recharge estimated from the projection of the future precipitation is essential.

This study used the projected future precipitation generated by Regional Climate Models (RCMs) from the Coordinated Regional Climate Downscaling Experiment (CORDEX) project (Remedio et al., 2019). The CORDEX project was initiated by the World Climate Research Program (WCRP) to coordinate the downscaling of Coupled Model Intercomparison Project (CMIP5) simulation results produced in support of Intergovernmental Panel on Climate Change (IPCC) assessments, which contain more than twenty RCMs. In total 13 domains are defined in the CORDEX project including the East Asia domain. Selection of the climate model is crucial in conducting impact studies as large differences and uncertainties have been observed among various RCMs and their driving models (the GCM model behind the RCM model). In this study, four RCMs have been initially selected for analysis (Hereafter referred to as M1, M2, M3 and M4). Details of these four RCMs can be found in Table 1. All selected RCMs could provide monthly precipitation data at a resolution of 0.44° (~50 km) for the historical period from 1951 to 2006, and for the future period under different Representative Concentration Pathway (RCP) scenarios. In this study, RCP 4.5 and RCP 8.5 scenarios are selected. RCP 4.5 scenario is a moderate estimation, which assumes the greenhouse gas emission will reach the peak in the mid-21st century and then decline. While RCP 8.5 assumes continuous increase of greenhouse gas emissions throughout the century. These RCP scenarios provide the potential impacts of different greenhouse gas emission pathways on the future precipitation patterns, which indirectly influence the groundwater recharge from the precipitation infiltration.

- **Bias correction of the projected precipitation data.**

Table 1
Information of the selected RCM models.

Model ID	M1	M2	M3	M4
RCM model	CCLM5-0–2	CCLM5-0–2	CCLM5-0–2	HIRHAM5
Institute	Helmholtz-Zentrum Geesthacht	Helmholtz-Zentrum Geesthacht	Helmholtz-Zentrum Geesthacht	Danish Meteorological Institute
Driven GCM model	MPI-M−MPI−ESM−LR	ICHEC-EC-EARTH	CNRM-CERFACS-CNRM-CM5	ICHEC-EC-EARTH
Spatial resolution	0.44°			
Temporal resolution	Daily/Monthly			
Driving GCM scenarios	Historical, RCP 4.5, and RCP 8.5			
Model Ensemble	r1i1p1	r12i1p1	r1i1p1	r3i1p1
Application	(Awad et al., 2021; Chen et al., 2020; Voldoire et al., 2013; Zhuo et al., 2022)			

Although RCMs provide dynamically downscaled outputs that consider atmospheric processes and heterogenous land topography at the regional level, there are still systematic biases against observational data. To evaluate the performance of the four RCM models, the observed precipitation data from 14 meteorological stations were compared with the model projections. The comparison results for three stations are presented in Fig. 5, and results for the other stations can be found in Supplementary material S1. M4 model produced consistently extremely low monthly precipitations comparing to measured precipitations in Beijing plain in the validation period from 1950 to 2006 (Fig. 5d). Therefore, M4 model was discarded from further analysis. For the other three RCM models, large discrepancies were also detected between the observations and projections, particularly during the wet period of the year, with rainfall in summer months being highly underestimated. To address this issue, bias correction methods were applied to the monthly precipitation output of the RCMs before conducting further study. The correction assumed that the discrepancy between the model output and observed data is constant over time, and it was formulated as:

$$P'_{cor} = T_{BC}(P'_{M}) \tag{1}$$

where P'_{cor} is the corrected precipitation for the future period, and P'_{M} is the projected precipitation from the RCM model for the corresponding future period. T_{BC} is the statistical transformation function that compensates for the discrepancy between the projected and observed data.

In the calibration phase, 30 years of data (1961–1990) comprised of observed monthly precipitation and RCM monthly precipitation outputs were used to derive the statistical transformation function. The validation phase consisted of 15 years of data (1991–2005). In this study, we tested both the mean-based and variance-based transformation methods, which are calculated as:

$$P_{cor} = P_M \frac{\mu_O}{\mu_M} (\mathrm{Mean-based\,Transformation}) \tag{3}$$

$$P_{cor} = \frac{P_M - \mu_M}{\sigma_M} \times \sigma_O + \mu_O (\mathrm{Variance-based\,Transformation}) \tag{3}$$

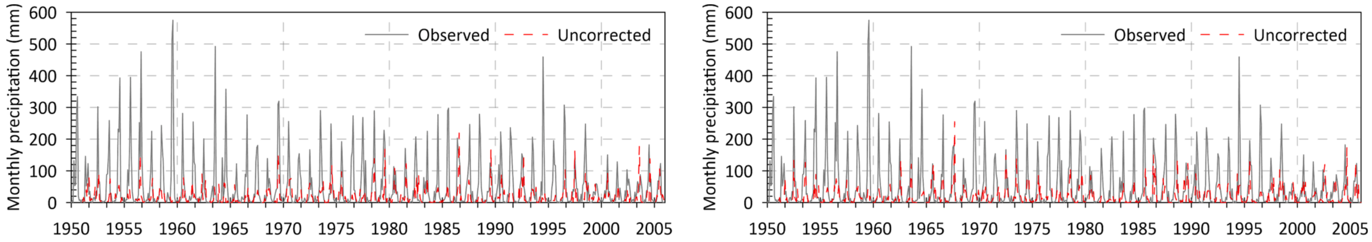
Where P_{cor} and P_M are the corrected precipitation and projected precipitation from the RCM model for the calibration and validation period. μ_O and μ_M are the monthly average of the observed and projected precipitation of the calibration and validation period. σ_O and σ_M are the monthly standard deviation of the observed and projected precipitation of the calibration and validation period. The corrected precipitation data of the validation period were compared with the observations to select an optimal method for the bias-correction of the future period.

The average of the bias-corrected precipitation data of the 14 stations from the three RCMs were used to estimate the groundwater recharge to 2050 for both RCP 4.5 and RCP 8.5 scenarios. These data were then utilized as precipitation infiltration in groundwater models. To accomplish this, the Beijing Plain area was divided into 74 recharge zones using polygons. Infiltration coefficients were assigned to each polygon based on hydrogeological settings of the plain and lithology of the unsaturated zone in the particular area. The infiltration coefficients range from 0.15 to 0.35 and to avoid unrealistically high infiltration rates, a threshold of 6 mm/day was set based on the maximum infiltration capacity of the top layer soil. Further information can be found in Supplementary Materials S2.

2.4. Construction of the transient groundwater flow model

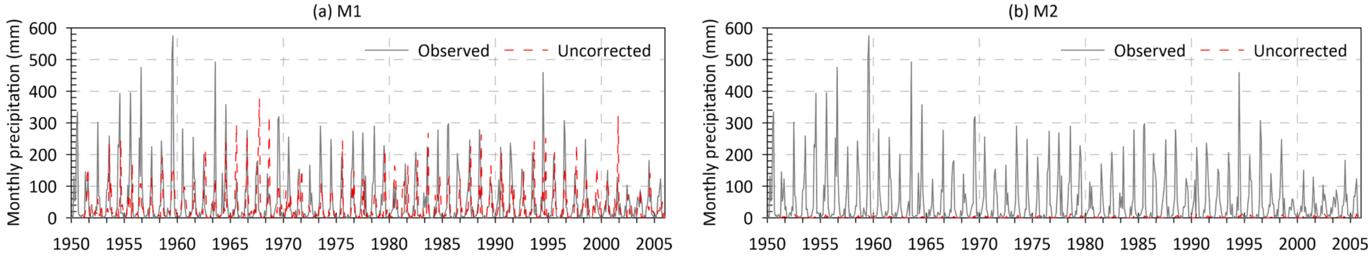
In this study, the transient groundwater flow model was constructed with the MODFLOW 2005 program. Transient groundwater flow models developed by Liu et al. (2022b) and Liu et al. (2023) were combined to form a transient simulation model for this study. This new model was checked with monthly groundwater level measurements from 1995 to 2020. The performance of the new model is comparable with the model calibration of Liu et al. (2022b, 2023). A brief summary of the model structure is given here. The model comprises nine model layers including five aquifers and four aquitards with a grid resolution of 1000 m. The extent and elevation of each model layer are determined by the interpolated geological borehole data. Lateral flow from the mountain is simulated as inflow boundary represented by injection wells using the Well (WEL) package at the western and northern model boundaries. The administrative border at the eastern and southern model boundaries are set as head-dependent flow boundaries by the General Head Boundary (GHB) package. The conductance value was estimated with the aquifer thickness and hydraulic conductivity values. The model includes six types of sources and sinks. Precipitation infiltration, irrigation return flow and pipeline leakage were simulated using the Recharge (RCH) package. Evapotranspiration (EVT) package was used to simulate groundwater evaporation. Groundwater abstraction for agriculture, domestic and township water supply and industry was simulated using the WEL package. The pilot MAR in Chaobai River and EFR in Yongding River were simulated with the River (RIV) package. The model was run monthly from 1995 to 2020 to compute groundwater levels and water budget components. The computed groundwater levels were compared with the measured groundwater heads at observation wells.

The prediction model covers a time period from 2021 to 2050 with a monthly stress period. The initial condition was inputted from the



(a) M1

(b) M2



(c) M3

(d) M4

Fig. 5. Raw precipitation data predicted by four RCM models (a)-(d) against the observed historical precipitation data for Beijing station.

computed groundwater heads in December 2020 from the simulation model. For the GHB package, reference heads at the boundary were kept the same as the computed heads in December 2020 across the future prediction period (2021–2050). The historical monthly mean evapotranspiration rates were used in the EVT package for the prediction model. Groundwater abstraction for the year 2020 was held 1.57 billion m^3/year constantly for the future periods. The implementation of the large-scale MAR (Fig. 4) in the Chaobai River and the EFR in the Yongding River were also included in the simulation, which were simulated using the RIV package. The river stages for the nine infiltration ponds in the Chaobai River were computed based on the elevation of pond bottom and designed water depth for the prediction model (Liu et al., 2022b). For the Yongding River, the computed river stages in 19 polygons according to the water release in 2019 were used for the prediction model(Liu et al., 2023). Recharge from precipitation and lateral inflow from the mountain were adapted from the projected precipitation.

Three prediction models were constructed: a model using the average monthly precipitation (hereafter referred to as Pav), one using the projected precipitation from the RCP4.5 scenarios (hereafter referred to as Prcp45) and one using the projected precipitation from with RCP8.5 scenarios (hereafter referred to as Prcp85). The groundwater recharge from the precipitation was derived from the monthly precipitation and the projected monthly precipitation of both climate scenarios. Apart from the groundwater recharge from the precipitation, lateral inflow from the mountains to the Beijing Plain will also be influenced by the future climate change since it is dependent on the precipitation. Thus, the variation of the lateral inflow was also considered in the prediction model.

3. Results

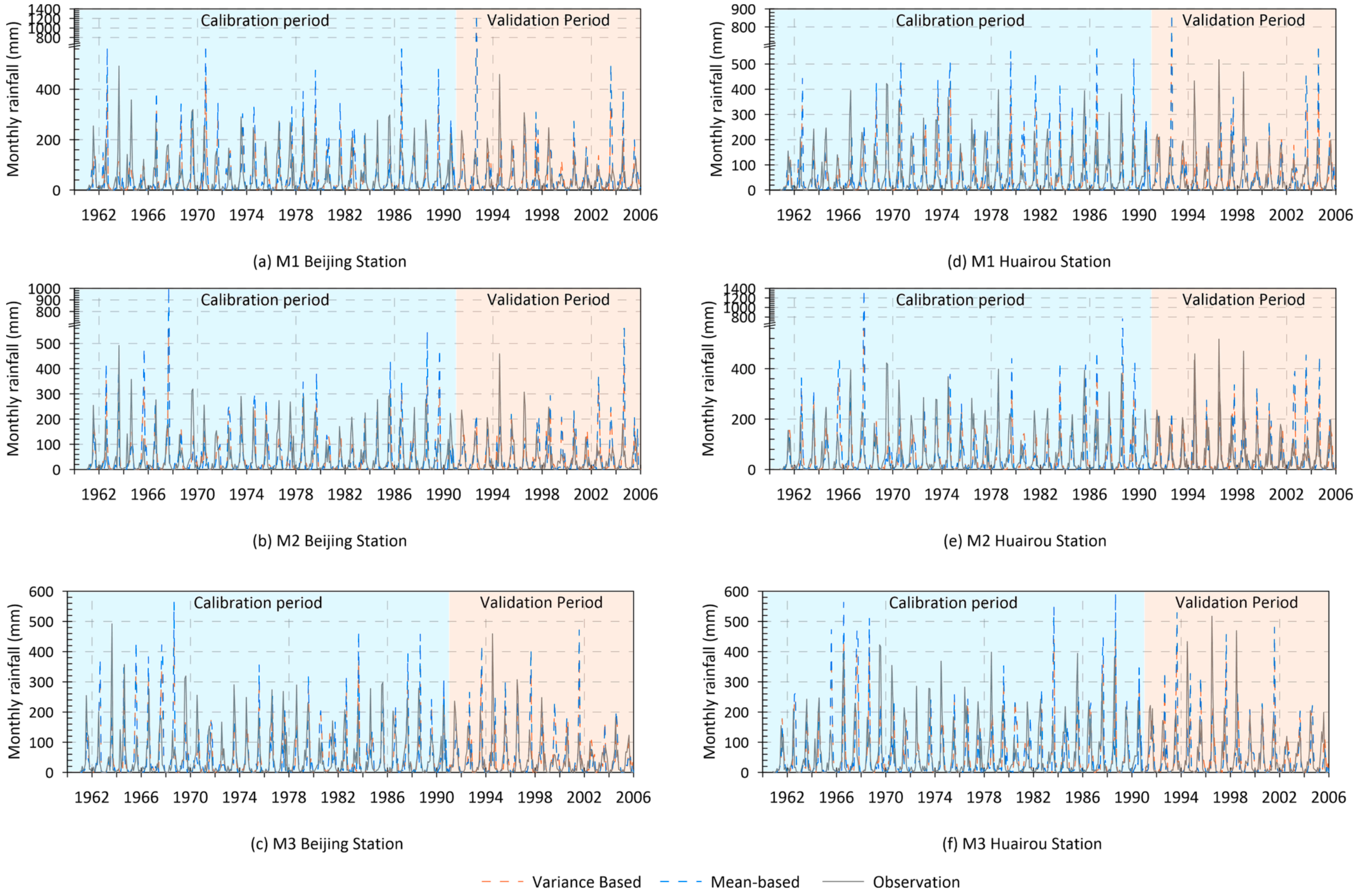
3.1. Calibration and validation of the projected precipitation series

The projected precipitation series from the RCM data were bias corrected by mean and variance-based correction methods. Fig. 6 illustrates the corrected precipitation data from the three RCMs for Beijing and Huairou stations, while additional data for the remaining stations can be found in Supplementary Material S3. The data accuracy was significantly improved after performing the bias-correction by both methods.

Statistics of the difference between the bias-corrected and observed monthly precipitations was shown in Table 2 using the Beijing station as an example. In general, the standard deviations of residuals from variance-based bias correction were found to be smaller in all stations. As a result, the variance-based bias correction method was chosen to predict and correct the monthly precipitation from 2006 to 2050, for

Table 2
Statistics of the differences between the observed and bias-corrected monthly precipitation for Beijing station from the period of 1961–2005.

	Mean-based corrected precipitation (mm/month)		Variance-based corrected precipitation (mm/month)	
	Calibration	Validation	Calibration	Validation
Mean	0.47	3.20	0.52	4.08
Median	1.28	1.06	1.51	2.47
Standard Deviation	53.24	64.33	46.74	54.75
Kurtosis	16.12	17.79	16.30	14.33
Skewness	−1.23	0.70	−1.72	−0.17



(a) M1 Beijing Station
(d) M1 Huairou Station
(b) M2 Beijing Station
(e) M2 Huairou Station
(c) M3 Beijing Station
(f) M3 Huairou Station

Fig. 6. Comparison of the variance based and mean based bias-corrected precipitation data with the observations.

RCP 4.5 and RCP 8.5 scenarios.

Fig. 7 shows the predicted precipitation data by averaging the three RCMs for Beijing station and Huairou Station. Information for other stations can be found in Supplementary Material S3. Compared to the historical period, more extreme rainfall during the summer months is predicted expecially in RCP 8.5 scenarios. However, the average annual precipitation for all 14 stations is 512 mm and 544 mm for RCP 4.5 and RCP 8.5 scenarios, respectively, which is 12 % and 6.5 % lower than the historical precipitation (Table 3). Student *t*-test has been performed to detect if there is significant difference between the historical and future precipitation. However, there is no significant trend of decrease in precipitation for both scenarios. Nevertheless, it is noted that RCP 4.5 scenarios predict several consecutive wet and dry years. After 2038, there are a few years with precipitation larger than the long-term average value. While wet and dry years are distributed more evenly in the RCP 8.5 scenarios.

Table 3
Comparison of the historical annual precipitation with the projection.

Station	Historical annual precipitation (mm/year)	RCP 4.5 projected precipitation (mm/year)	RCP 8.5 projected precipitation (mm/year)
Beijing	597	486	523
Changping	537	471	493
Chaoyang	579	507	530
Daxing	537	470	507
Fangshan	557	496	542
Fengtai	569	496	537
Haidian	566	522	555
Huairou	649	572	601
Mentougou	600	517	561
Miyun	638	567	586
Pinggu	627	549	572
Shijingshan	541	514	551
Shunyi	592	516	541
Tongzhou	555	487	521
Average	**582**	**512**	**544**

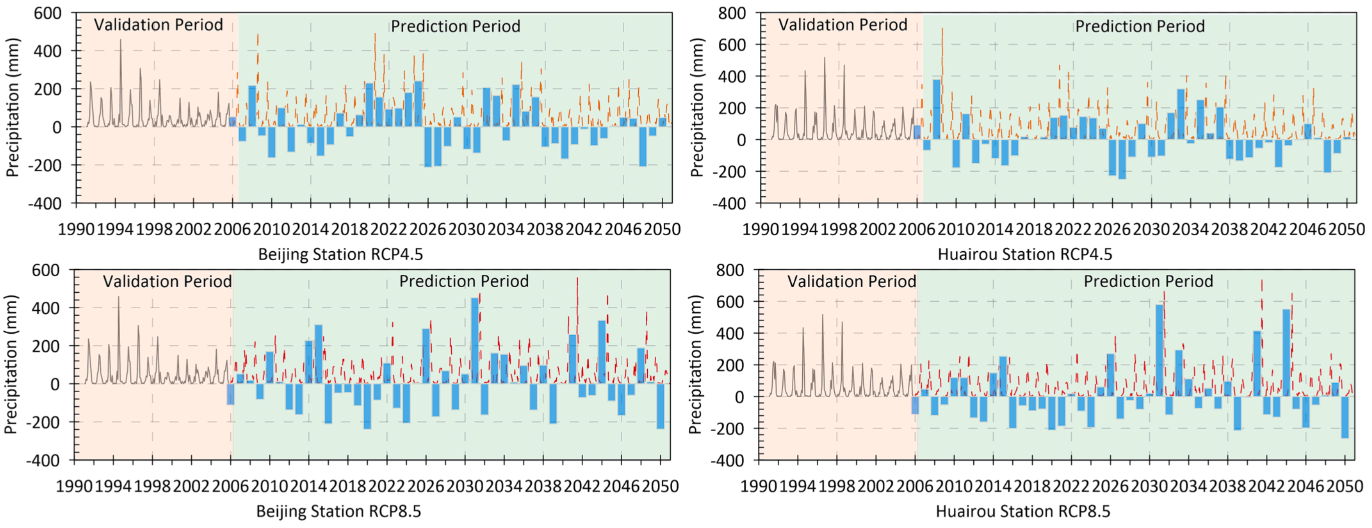
3.2. *Effects of three future climate scenarios*

The spatial and temporal distribution of groundwater heads and groundwater budgets of the three scenario models were compared to analyze the aquifer response to future climate change and human activities. The Pav model used the historical mean monthly precipitation as input and Prcp45/Prcp85 models applied the projected monthly precipitation as inputs.

Fig. 8 compares the groundwater level contour map in year 2021 and 2050 for the shallow unconfined aquifer (model layer 1) and the deep confined aquifer (model layer 5) for the Prcp45 model. Results in Prcp85 and Pav models are not shown here due to the high resemblance of the contour map results of the three models. Details can be found in Supplementary Material S4. Fig. 9 plots predicted groundwater level series from five selected areas. It can be seen that the cone of the depression in the shallow unconfined aquifer in the Chaobai River area (northeast) will be recovered completely by 2050 with MAR in the Chaobai River (Fig. 8b). The increase of groundwater level is significant from below 0 m to 24 m in 15 years and gradually reach a new equilibrium state (Fig. 9, *H*01). In Yongding River area, groundwater levels in the shallow aquifer are also increased with the EFR implementation in the Yongding River. The predicted groundwater levels at H02 and H04 will increase by 6 to 10 m. However, the cone of depression in the deep confined aquifer remains by 2050 (Fig. 8d). The predicted groundwater heads in the middle confined aquifer (H03_m) and the deep confined aquifer (H03_d) in the Tongzhou area will increase with a slower pace. In this area, multi-aquifers are separated by the clay and silty confining layers. These deep aquifers were over-exploited for industrial water supply over decades. The reduction of deep aquifer abstraction since 2015 results in slow recovery of groundwater levels. However, the only source water to recover the depleted storage is the vertical leakage from the shallow aquifer. Due to the existence of the low permeable layers, the renewal rate of the groundwater in deep aquifer is much slower than the unconfined aquifer. Thus, without other measures implemented, the recovery of the deep aquifer depletion may take much longer time.

In general, the Prcp45 model predicts lower groundwater level increase comparing to the Prcp85 model for all locations. Especially, the Prcp45 model predicts a decrease of groundwater levels after 2038. This is caused because the RCP 4.5 scenario predicts lower precipitation after 2038 (Fig. 7), therefore, results in less recharge after 2038 (Fig. 10a).

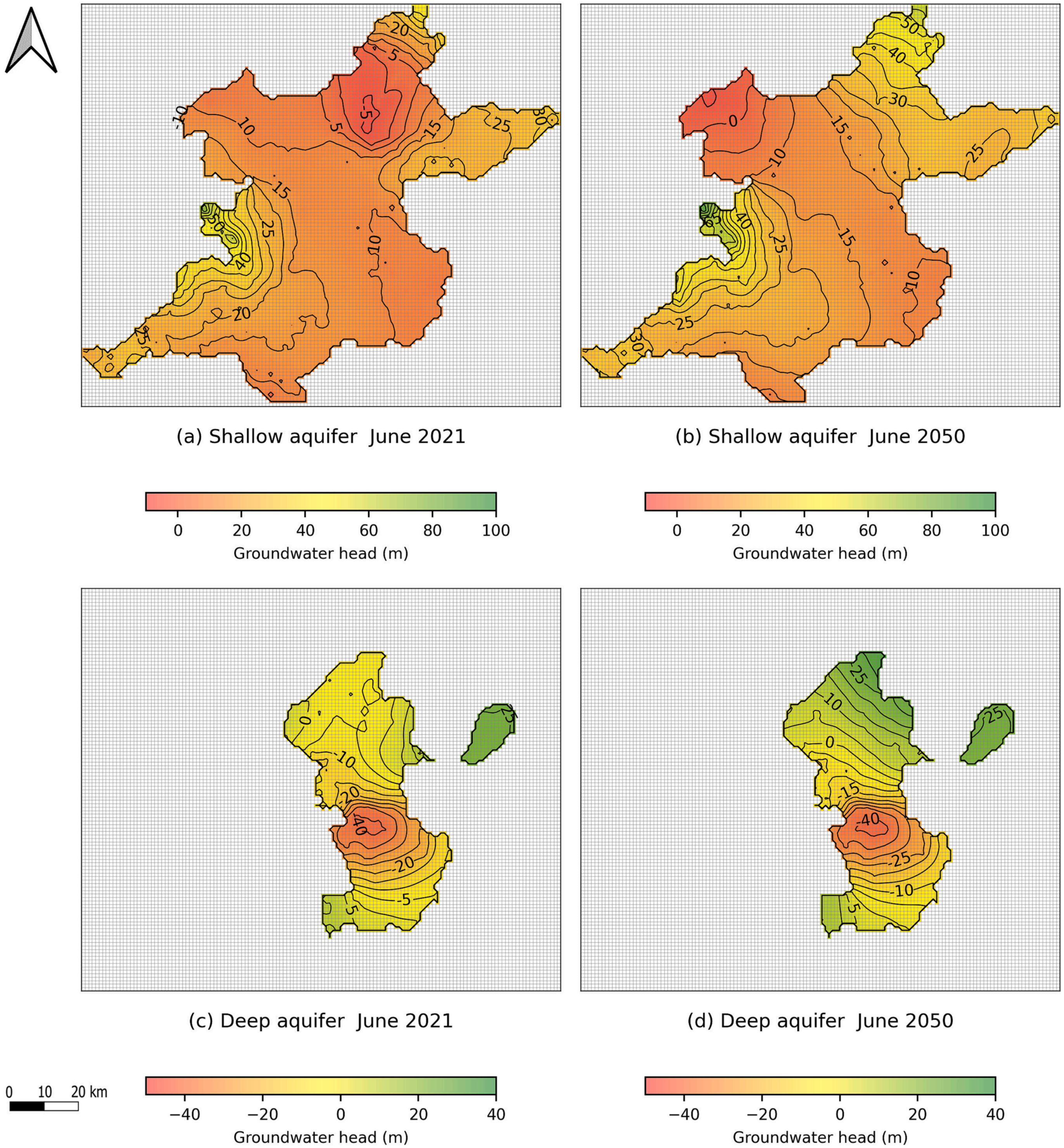
Groundwater balance analysis provides a quantitative assessment of groundwater resources in Beijing Plain for the future. Fig. 10a shows the projected annual groundwater recharge from the natural precipitation infiltration, which is the major recharge component. In general, the Prcp45 model predicted lower groundwater recharge comparing to the Prcp85 model. Especially, the predicted groundwater recharge by the Prcp45 model is lower than the historical average (Pav) after 2038. In



(a)

(b)

Fig. 7. Projected precipitation data from the bias-corrected precipitation from the three RCMs for (a) Beijing Station (b) Huairou Station. Line plots are the monthly projected precipitation, and the bar chart depicts the difference between the annual precipitation and the average precipitation from 2006 to 2050.



(a) Shallow aquifer June 2021

(b) Shallow aquifer June 2050

(c) Deep aquifer June 2021

(d) Deep aquifer June 2050

Fig. 8. Groundwater level contour maps of the shallow aquifer (a-b) and deep aquifer (c-d) at the beginning and end of the simulation period predicted by Prcp45 model.

the Prcp45 model, the average annual precipitation infiltration in the next 30 years is 1.09 billion m^3. The minimum and maximum recharge will be 6.74 million m^3 and 1.57 billion m^3 in 2027 and 2033 respectively. In the Prcp85 model, the average annual precipitation infiltration in the next 30 years is 1.18 billion m^3. The minimum and maximum recharge will be 6.84 million m^3 and 2.21 billion m^3 in 2050 and 2031, respectively. It can be concluded that under the RCP 8.5 scenario, there will be an average of 8 % more precipitation infiltration compared with the RCP 4.5 scenario and extreme dry and wet years are likely to occur more frequently in the RCP 8.5 scenario.

Other water balance components of the Prcp45 and Prcp85 models are compared in Fig. 10b. The lateral inflow from the mountains is also an important source of groundwater recharge. Average lateral inflow from the mountains in the Prcp45 model will be only 286 million m^3/year, which will be lower than the Pav model all the time from 2020 to 2050. In the Prcp85 model, average annual lateral inflow is 294 million m^3/year, which is 3 % higher than the Prcp45 model.

Table 4 lists the average amount and percentage of all flow

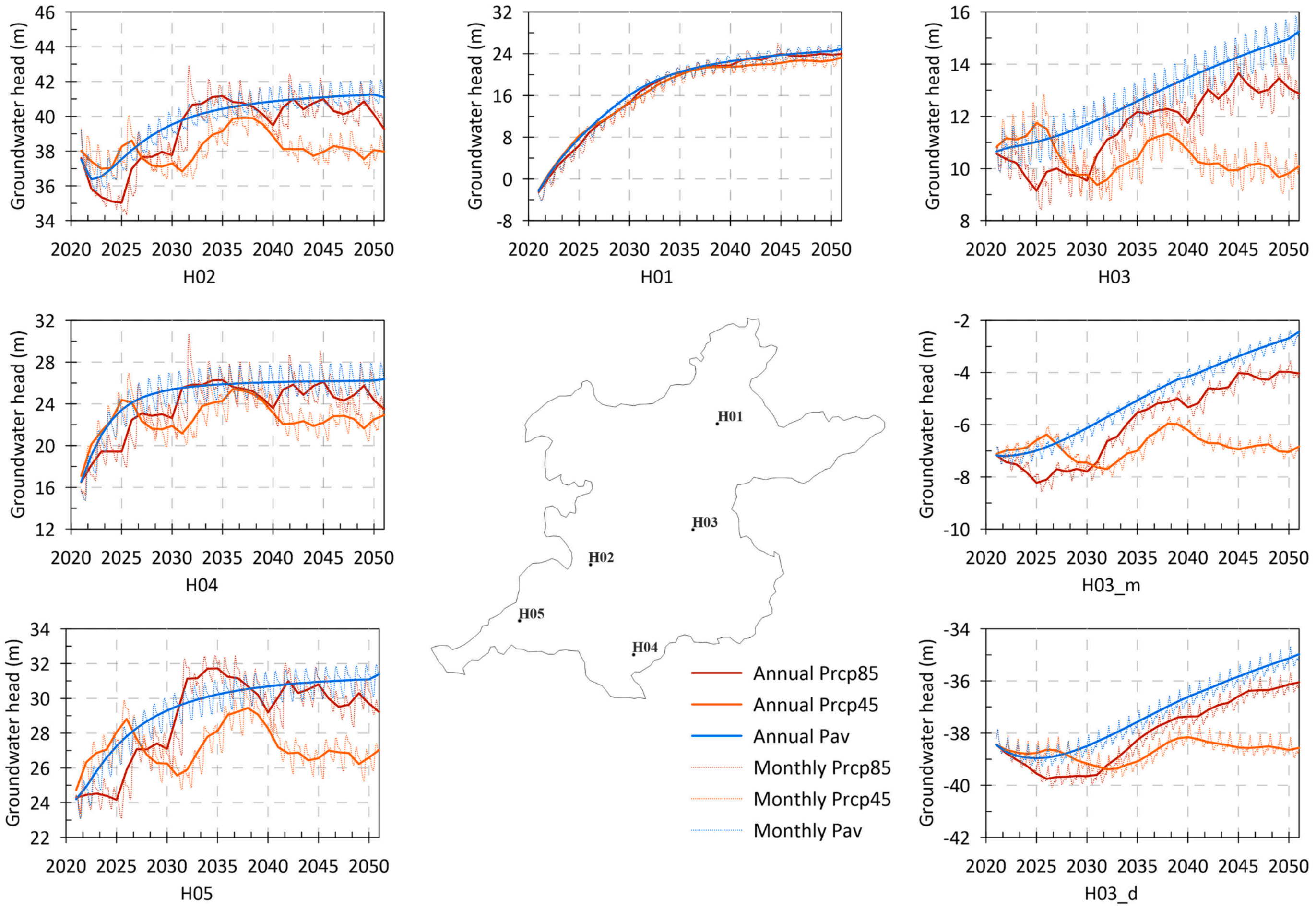


Fig. 9. Predicted groundwater level at different locations and aquifers from 2020 to 2050 by the three prediction models. Solid lines stand for the annual average groundwater levels. Dashed lines show the monthly fluctuations.

components for each scenario. As can be seen, groundwater abstraction is the major discharge component that accounts for more than 90 % of the total outflow. Historically, the annual groundwater abstraction in Beijing Plain has declined from 2.4 billion m^3 in 2004 to 1.5 billion m^3 in the recent years, which is still the dominant groundwater discharge component. Natural recharge from precipitation accounts for about 60 %, lateral inflow from the mountain accounts for about 14 %, and artificial recharge from the MAR and EFR accounts for about 17 %. The total average annual groundwater recharge summing up from the precipitation infiltration and lateral inflow from the mountains will be 1.38 and 1.47 billion m^3 predicted by the Prcp45 and Prcp85 models. The natural groundwater recharge alone cannot meet the 1.5 billion m^3 annual groundwater abstraction. Therefore, MAR is necessary. With a combined artificial recharge of 0.34 billion m^3 from two major rivers, the total groundwater recharge exceeds the total abstraction, so groundwater storage gradually increases and sustainable development can be achieved.

3.3. *Effects of the managed aquifer recharge*

The amount of artificial groundwater recharge from the MAR implementation in Chaobai River and the EFR project in Yongding River was calculated for the Prcp45 and Prcp85 models (Fig. 11). The average annual artificial groundwater recharge simulated by the Prcp45 model is 350 million m^3, which is 11 million m^3 higher than the Prcp85 model (339 million m^3). This difference is caused by the computed higher groundwater level from the Prcp85 model near the Chaobai and Yongding River channels (Fig. 9: *H*01 and H02). Higher groundwater levels reduce the hydraulic gradient between the surface water and groundwater, resulting in less recharge through the river leakage, which also explains the decrease of total recharge from MAR and EFR with the increase of groundwater levels in the next 30 years. In 2021, both models predict more than 420 million m^3 total artificial recharge. The artificial recharge declines to 317 million m^3 and 311 million m^3 in 2040 for the Prcp45 and Prcp85 models and remain relatively stable as they reach a new equilibrium state. The recharge from the MAR and EFR accounts for 62 % and 38 % of the total artificial recharge, respectively. Fig. 8 shows that the cone of depression in the Chaobai River area (Fig. 8a) is effectively recovered with the MAR operation (Fig. 8b). Similar effects occur in the Yongding River area with the EFR operation.

3.4. *The recovery of the groundwater storage in the near future*

The changes in groundwater storage for the Prcp45 and Prcp85 models are also calculated and depicted in Fig. 12a. Storage change indicates the storage recovery when it is positive and storage depletion when it is negative. The impact of future climate change on the groundwater system can be clearly seen by comparing the two climate scenario models with the Pav model, which uses the average historical precipitation. Larger variations are found in the Prcp85 model. In the next 30 years simulation, there are 15 years and 18 years with positive groundwater storage change. Strong correlations are found between the year with groundwater storage recovery and the wet year predicted by the future climate scenarios. The average annual storage changes of the Prcp45 and Prcp85 models are 137 million and 186 million m^3, respectively. From the cumulative storage change plotted in Fig. 12b, we

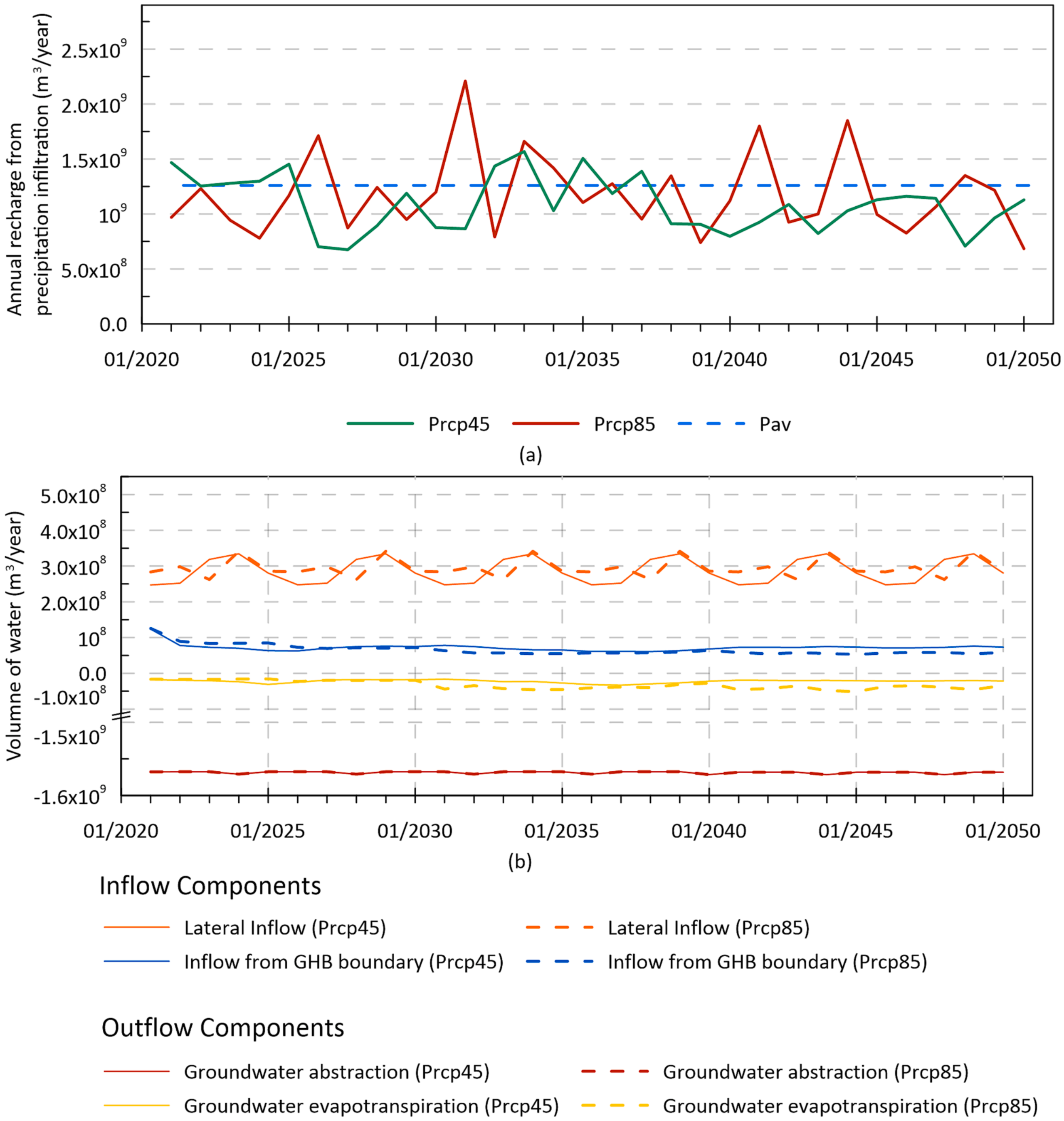


Fig. 10. Annual groundwater recharge from (a) precipitation infiltration and (b) lateral inflow from the mountain from 2021 to 2050 predicted by the three prediction models.

clearly see that the groundwater storage will recover significantly in the first 15 years of simulation and then gradually approaches stationary values. This is a clear indication that the groundwater system is approaching a new equilibrium so that groundwater development becomes sustainable. The predicted total groundwater recovery until 2050 will be 4.14 and 5.58 billion under the RCP 4.5 and RCP 8.5 scenarios, respectively. However, it is noted the storage recovery will mostly occur in the shallow aquifer. In the deep confined aquifer, only a very limited amount of storage can be recovered after 2035.

4. Discussion

4.1. Climate and human impacts on groundwater sustainability in Beijing Plain

The impacts of future climate change on the groundwater system, particularly groundwater recharge have been widely recognized, and many modelling studies investigated this aspect in recent years (Chang et al., 2015; Crosbie et al., 2013; Goderniaux et al., 2009; Jackson et al., 2011; Zhou et al., 2020). Based on our simulation results, future climate change has minor impacts on groundwater resources in Beijing Plain. The variation of the wet and dry years predicted by the RCP8.5 scenario only results in inter-annual groundwater storage change with limited effect. Nevertheless, the model results from the RCP 4.5 scenario show

Table 4
Average amount and percentage of each flow component for each prediction model.

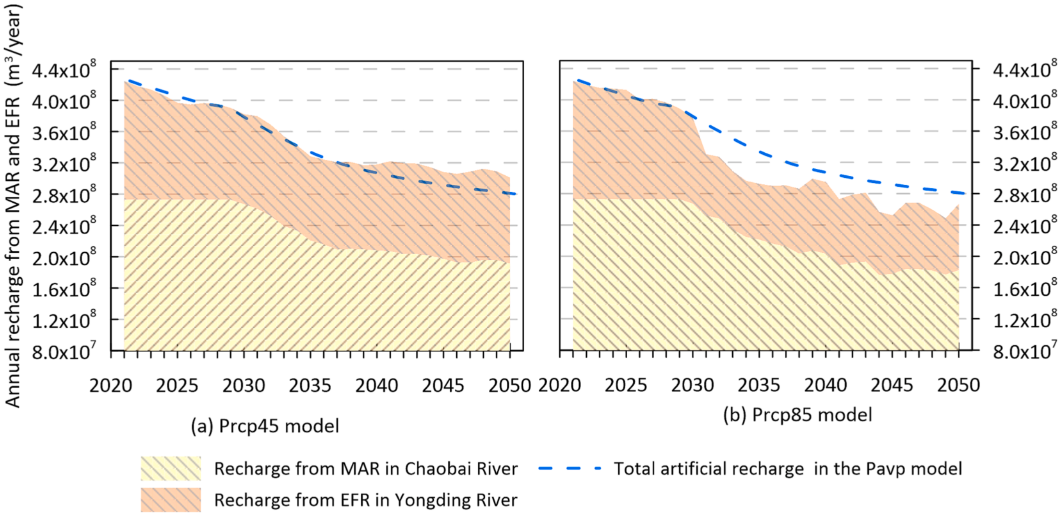
Flow components	Pavp model		Prcp45 model		Prcp85 model	
	Amount(m^3/year) and percentage					
Natural groundwater recharge	1.26×10^9	63.4 %	1.04×10^9	57.6 %	1.14×10^9	60.7 %
Lateral inflow from the mountains	326×10^6	14.4 %	292×10^6	16.2 %	299×10^6	16.0 %
Infiltration from MAR and EFR	286×10^6	17.2 %	308×10^6	17.1 %	285×10^6	15.2 %
Head dependent inflow	50.6×10^6	2.5 %	73.2×10^6	4.1 %	56.4×10^6	3 %
Groundwater abstraction	1.57×10^9	91.9 %	1.57×10^9	94.4 %	1.57×10^9	92.7 %
Groundwater discharge to surface water	56.9×10^6	3.3 %	42.7×10^6	2.6 %	57.6×10^6	3.4 %
Groundwater evapotranspiration	57.6×10^6	3.4 %	20.8×10^6	1.3 %	41.3×10^6	2.4 %
Head dependent outflow	72.8×10^6	4.3 %	40.3×10^6	2.4 %	52.1×10^6	3.6 %
Change of storage	166×10^6		38.0×10^6		52.1×10^6	

continues groundwater storage depletion (Fig. 12, Prcp45) during seven consecutive dry years after 2038 (Fig. 7b). Other climate change models need to be investigated to ascertain the results of the impact.

Measures undertaken by Beijing municipality have addressed various key factors to guide the city towards groundwater sustainability.

The most important measure was the reduction of groundwater abstraction by substituting groundwater supply with the transferred surface water (about 1.0 billion m^3/year), which is a deciding measure to reverse the trend of groundwater depletion in Beijing Plain. Especially in deep confined aquifers, shutdown of pumping wells for industrial water supply effectively stopped rapid groundwater level decline. However, the recovery of groundwater level and storage in the deep confined aquifers will still take a longer time because leakage from shallow aquifers is the only recharge and limited.

Additionally, large-scale MARs in two major rivers are very effective to close the gap of groundwater balance and contribute to sustainable development. These two measures combined can effectively restore the depleted groundwater storage and gradually contribute to a sustainable development by 2050. Furthermore, artificial recharge from MAR operations can restore the cone of the depression and become the main source of water for maintaining groundwater abstraction in the Chaobai



(a) Prcp45 model

(b) Prcp85 model

Fig. 11. Artificial recharge from the MAR and EFR project in Chaobai and Yongding River predicted by the Prcp45 and Prcp85 model.

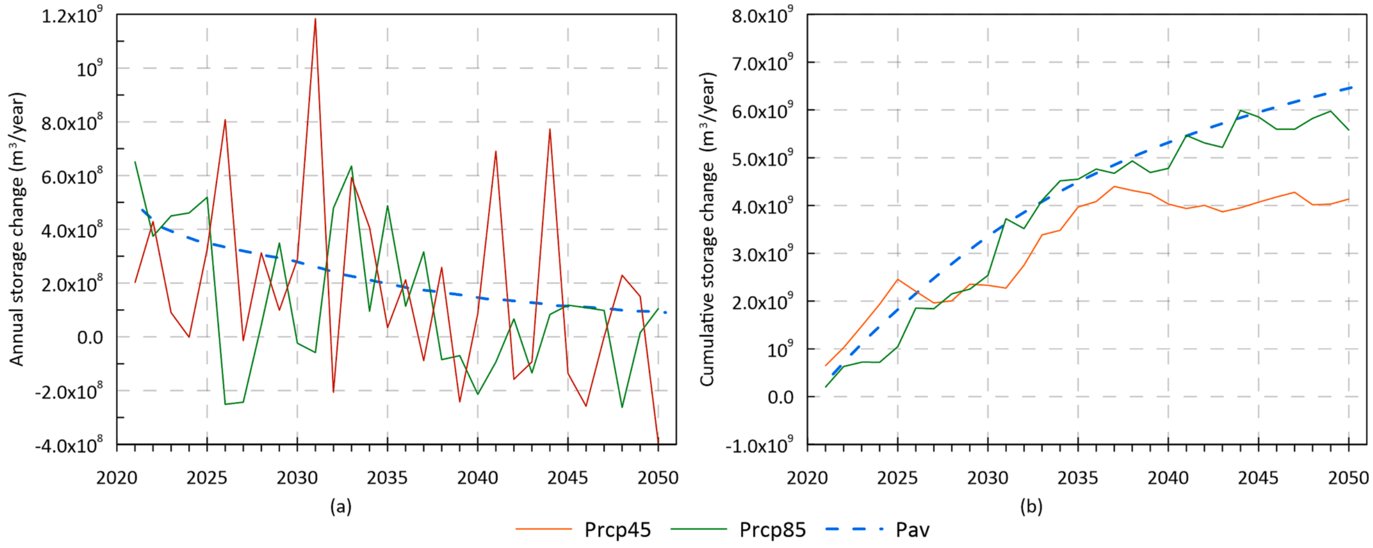


Fig. 12. Annual groundwater storage change (a) and cumulative storage change (b) predicted by the Prcp45 and Prcp85 model from 2021 to 2050.

River area, accounting for over 50 % of total groundwater abstraction (Liu et al., 2022b). The EFR project in Yongding River not only benefits the riparian ecosystem (Zhai et al., 2022), but also enhances groundwater recharge through river leakage which balances the recharge and abstraction in this area (Liu et al., 2023).

While the long-term groundwater management strategies described above indicate a positive trajectory towards more sustainable groundwater usage in Beijing Plain, it is important to acknowledge that the assessment of groundwater sustainability should consider multiple dimensions. As highlighted by Llamas et al. (2006), apart from the hydrological and groundwater-dependent ecological perspectives, institutional, economic, and social constraints were not considered in this study. Therefore, further investigation is necessary to comprehensively understand and address these additional aspects of groundwater sustainability.

4.2. Uncertainties and limitations

Uncertainties and limitations in this study need to be addressed from two perspectives.

Firstly, there are uncertainties associated with the climate model projection and bias correction method. In this study, there are large discrepancies between the precipitation projected by the RCM models and measured precipitation at meteorological stations. Additionally, the bias correction method employed in this study introduces its own uncertainties, as different methods may have varying assumptions and limitations. For future research on the impact of climate change on groundwater recharge, it is recommended to incorporate multiple GCMs and employ different bias correction methods to minimize uncertainties.

Secondly, uncertainties and limitations of the groundwater prediction model consist of three primary components: simplification of the simulation of precipitation infiltration, simulation of groundwater evapotranspiration (EVT), and the simplification of projected groundwater withdrawal scenarios that do not consider socio-economic factors. In the model settings, precipitation infiltration is treated as an instantaneous process at monthly time scale, thereby not accounting for the delayed recharge dynamics through the unsaturated zone. In the deep-water table area, infiltration water may take a number of months to reach the water table. Unsaturated zone model should be used to investigate the delayed recharge process and compute monthly groundwater recharge as a cumulative effect of previous monthly precipitations. In the climate change prediction model, impact of future change of EVT was not considered. According to the projected temperature increase, the maximum EVT flux will increase. Especially, groundwater level depth will become shallower due to the implementation of groundwater conservation polices. Therefore, it is necessary to investigate impacts of EVT on groundwater resources in consideration of future temperature increase and groundwater level rise. In regard to the projected scenarios of future groundwater withdrawal, the current model assumes that total abstraction rate will remain constant at the current level. However, as reported by Wu et al. (2022), an increase in temperature by one degree is projected to result in an additional 177 million m^3 of domestic water consumption in Beijing, an aspect that was not taken into account in the prediction model. Temperature variations also have the potential to impact agricultural water usage, particularly in regions where groundwater serves as the primary source for irrigation. Temperature increase opens a new direction for groundwater development in connection with the MAR: not only as resources, but also as geothermal energy (Epting et al., 2023). Furthermore, the design of future scenarios should be integrated with the long-term development plans of Beijing municipality in order to provide a more accurate estimation of future groundwater usage.

4.3. Concerns of rising water table

A rising water table close to the surface may have negative impacts on the underground infrastructure in urban areas, induced groundwater pollution from unprotected solid waste disposal sites, sceptic tanks, and agriculture source, and soil salinization. Long et al. (2020) projected an average water table depth of 10 m by 2030. In our prediction model, the predicted water table depth varies in between 5 m in the southeast plain area and above 25 m in the west and north high elevation areas by 2050. In Beijing urban area, the predicted water table depth is about 15 m by 2050. Li et al. (2022) has reported the increase of NO3-N during the high water level period in Daxing District, southeast area of Beijing Plain. Thus, future strategies for urban groundwater management in the region should progressively adapt, with an increased emphasis on identifying and addressing the impacts of rising groundwater levels.

5. Conclusions

Groundwater use in Beijing Plain has increased greatly due to rapid socio-economic development and consequently groundwater reserves have been heavily depleted since the 1980 s. Severe negative impacts forced Beijing municipality to take drastic measures to reverse the trend. The first measure was the reduction of groundwater abstraction by substituting urban and industrial groundwater supply with transferred surface water from the south-to-north water transfer scheme since 2015. The second measure was the increase of groundwater recharge by implementing MARs in two major rivers. Pilot infiltration basin has been constructed in Chaobai River and operated since 2015. EFR in Yongding River has been conducted since 2019. Rising groundwater levels in these two areas have been observed in recent years. This study aimed to assess if the combined two measures can lead to long-term sustainable groundwater development in Beijing Plain.

First, a 3-D transient groundwater flow simulation model was developed and checked with historical groundwater level measurement from 1995 to 2020. The simulation model is capable to simulate trends of groundwater level and budget changes. Second, monthly rainfalls projected from three downscaled regional climate models under two scenarios (RCP4.5 and RCP8.5) were calibrated and validated with 30 years and 15 years measured monthly rainfalls from 14 meteorological stations, respectively. The average monthly rainfalls from the three models with the variance-based bias-correction statistically represent measured rainfalls very well in 45 years. Therefore, monthly groundwater recharge and lateral inflow were updated with the average monthly rainfalls from the three models under two scenarios from 2021 to 2050. Third, a transient groundwater flow prediction model was constructed with the estimated recharge and lateral inflow from 2021 to 2050. The prediction model used the reduced abstraction at the level of year 2020 and included a planned large-scale MAR in Chaobai River and EFR in Yongding River. Fourth, the prediction model was used to simulate the effects of the combined measures of abstraction reduction and artificial recharge from 2021 to 2050. From the analysis of the predicted groundwater levels and water budget, conclusions can be drawn. When groundwater abstraction is controlled at the current level (about 1.5 billion m^3/year), implementation of large-scale MARs in Chaobai and Yongding Rivers can lead to long-term sustainable groundwater development in Beijing plain. Reduction of groundwater abstraction for urban and industrial water supply is a deciding factor to reverse the trend of groundwater level decline, especially in deep confined aquifers. MARs in two major rivers are effective in restoring cones of depression in shallow aquifers and maintaining groundwater abstraction in these areas. Climate variation has large impacts on groundwater resources, especially, consecutive dry years can cause rapid groundwater storage depletion. The projected monthly precipitation from 2021 to 2050 is not significantly different from the past. Therefore, the projected future precipitation has minor impacts on groundwater resources in the next 30 years.

The findings of this study provide science-based information for Beijing municipality to strictly control groundwater abstractions and implement large-scale groundwater recharge schemes in Chaobai and

Yongding rivers. Furthermore, methods used in this study can be applied in other regions facing similar challenges and opportunities for sustainable groundwater management, making it a valuable contribution to the global scientific community.

CRediT authorship contribution statement

Sida Liu: Writing – original draft, Visualization, Software, Formal analysis, Conceptualization. **Yangxiao Zhou:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Fatima Eiman:** Software, Formal analysis, Data curation. **Michael E. McClain:** Writing – review & editing, Validation, Supervision, Conceptualization. **Xusheng Wang:** Writing – review & editing, Supervision, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2024.130951.

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