Journal of Groundwater Science and Engineering
ISSN 2305-7068
Indexed by ESCI CABI CSA Scopus GeoRef AJ CNKI

**Effectiveness of groundwater extraction in Beijing since the ingauration of the first phase of the South-to-North Water Diversion Project, China**

Yuan-yuan Gao, Qing-yu Sun, Ai-xin Wen, Yan-pei Cheng

Citation:
Gao YY, Sun QY, Wen AX, *et al*. 2023. Effectiveness of groundwater extraction in Beijing since the ingauration of the first phase of the South-to-North Water Diversion Project, China. Journal of Groundwater Science and Engineering, 11(3): 294-307.

View online: https://doi.org/10.26599/JGSE.2023.9280024

*Journal of Groundwater Science and Engineering* 11(2023) 294–307

Journal homepage: http://gwse.iheg.org.cn

Research Paper

# Effectiveness of groundwater extraction in Beijing since the ingauration of the first phase of the South-to-North Water Diversion Project, China

Yuan-yuan Gao[1], Qing-yu Sun[1], Ai-xin Wen[2], Yan-pei Cheng[2*]

[1] *Bureau of South to North Water Transfer of Planning, Designing and Management, Ministry of Water Resources, Beijing* 100038, *China.*
[2] *Institute of Hydrogeology and Environmental Geology, Chinese Academy of Geological Sciences, Shijiazhuang* 050061, *China.*

**Abstract:** This study assess the effectiveness of groundwater pressure extraction in Beijing since the opening of the first phase of the South-to-North Water Diversion Project, using survey and evaluation methods. Firstly, an analysis of water consumption structure and the usage of diverted river water in Beijing in recent years was conducted. Secondly, the volume of groundwater pressure extraction in Beijing after the project's inauguration was examined, revealing a decrease from 1.96 billion $m^3$ in 2014 to 1.35 billion $m^3$ in 2020. The proportion of water supply reduced from 52.3% in 2014 to 33.3% in 2020, leading to an optimized water supply structure. By the end of 2020, groundwater pressure extraction in Beijing is estimated at 446 million $m^3$, with a substantial reduction in over-exploitation of groundwater. Groundwater resources have been effectively replenished, and the strategic reserve capacity has been enhanced. Furthermore, this study evaluates the change in groundwater levels as an indicator of the effectiveness of pressure extraction. The declining trend of groundwater levels in Beijing has been effectively mitigated, and there has been a consistent rebound in groundwater levels over the past five years.

**Keywords:** Beijing City; South-to-North Water Diversion; Groundwater Over-exploitation; Groundwater Pressure Extraction

Received: 25 Oct 2022/ Accepted: 27 Jun 2023/ Published: 15 Sep 2023

## Introduction

North China is facing a severe water shortage, making it the region with the most critical water challenges in China (Qin et al. 2019; Chen et al. 2021; Sun et al. 2021; Cao et al. 2023a; Cao et al. 2023b). The region has long relied on over-exploitation of groundwater to support rapid economic and social development, resulting in a serious problem of groundwater over-exploitation in North China, particularly in the capital city of Beijing (Cao et al. 2020a; Pang et al. 2020; Zhao et al. 2021; Zhou et al. 2023). In recent years, North China has implemented a series of initiatives to address groundwater over-exploitation, and some progress has been achieved in managing the issue (Zhao et al. 2020). Given the significant role of North China in the country's political and economic landscape, research on the effectiveness of groundwater pressure extraction has gained considerable attention among scholars in recent years. Several Chinese scholars have conducted research on groundwater exploitation in North China. Hao et al. (2012) established a groundwater model to study groundwater regulation and storage in the alluvial fan of Yongding River in Beijing by analyzing hydrogeological conditions. Xu et al. (2020) examined the causes of groundwater over-exploitation of in Hebei, assessed the effectiveness of pilot projects and identified the characteristics of over-exploitation in urban and rural areas, proposing ideas and countermeasures for the managing groun-

*Corresponding author: Yan-pei Cheng, *E-mail address*: chengyanpei@mail.cgs.gov.cn

DOI: 10.26599/JGSE.2023.9280024

Gao YY, Sun QY, Wen AX, et al. 2023. Effectiveness of groundwater extraction in Beijing since the ingauration of the first phase of the South-to-North Water Diversion Project, China. Journal of Groundwater Science and Engineering, 11(3): 294-307.

dwater over-exploitation. Chen et al. (2020) reviewed specific extraction management measures adopted by national initiatives in recent years and evaluated their current effectiveness, while also introducing strategic countermeasures and main measures for managing groundwater over-exploitation in North China. Additionally, they analyzed prominent challenges currently faced in the management of groundwater over-exploitation in the region. Hu (2017) conducted an analysis of water resources and geology in the Beijing-Tianjin-Hebei region, identifying problems in groundwater resource utilization and proposing groundwater prevention and control policies. Liu (2020) analyzed the implementation of ecological water recharge in the South-to-North Water Diversion Central Route Project and its effectiveness in comprehensive in comprehensive management of groundwater over-extraction in North China.

Internationally, vander Hout's (Hout, 2015) studied groundwater management practices in the Rotterdam metropolitan area and predicted the risk of unintended impacts of groundwater overdraft and unsustainable groundwater use. Adams et al. (2015) identified significant long-term changes in evapotranspiration near groundwater withdrawal points, assessing the ecological risk posed by groundwater withdrawal to native vegetation on the Tomago Sandbeds.

In the current study, there has been a lack of systematic analyses on the volume of pressurized groundwater extraction and the corresponding changes in groundwater level in Beijing in recent years. However, it is important to note that the groundwater level in Beijing has shown significant rebound, and the reserves have undergone notable changes. While groundwater is a valuable resource, it can be depleted through over-exploitation. Nevertheless, its exploitation should not be minimized without reason, but rather be managed rationally. It is crucial to establish a reasonable threshold for groundwater level recovery in areas affected by over-extraction. Setting a higher groundwater level recovery target may lead to undesirable consequences such as soil salinization and adverse impacts on underground infrastructure facilities. Additionally, a higher water level recovery can trigger changes in the chemical composition of groundwater due to water-rock interactions, potentially causing re-entry of heavy metals and other pollutants into the aquifer, leading to a decline in groundwater quality. To ensure effective groundwater management in the capital city, it is necessary to conduct comprehensive statistical analyses of pressurized groundwater extraction volumes and systematically study water level changes in recent years. This information will be vital in providing policy recommendations for the comprehensive management of groundwater over-exploitation in Beijing and the entire North China region.

## 1 Study area

Beijing, as a megacity, faces a severe water resource shortage with a multi-year average precipitation of 585 mm. The city's multi-year average total water resources amount to 3.74 billion $m^3$, including 1.77 billion $m^3$ of surface water resources, 2.56 billion $m^3$ of underground water resources, and the 590 million $m^3$ of double-counting volume of surface water and underground water (Fig. 1) (Yang et al. 2015; Yang et al. 2017; Ge et al. 2022). Groundwater serves as the primary source of urban water supply in Beijing, accounting for about 50% of the city's water supply and nearly 80% in some years (Li et al. 2022; Wang et al. 2022). Before the implementation of the South-to-North Water Division Project, Beijing's annual over-exploitation of groundwater reached approximately 500 million $m^3$ to meet the city's water supply demands. The groundwater over-exploitation in Beijing before the commissioning of the Central Route Project was analyzed, using data from the base years 2006 to 2010. During this period, Beijing extracted a total of 2.313 billion $m^3$ of groundwater, with 510 million $m^3$ used for urban life, 231 million $m^3$ for rural life, 393 million $m^3$ for industry, and 1.179 billion $m^3$ for agriculture. The average annual over-exploitation was around 599 million $m^3$, with an actual extraction coefficient of 1.34. The long-term large-scale exp-

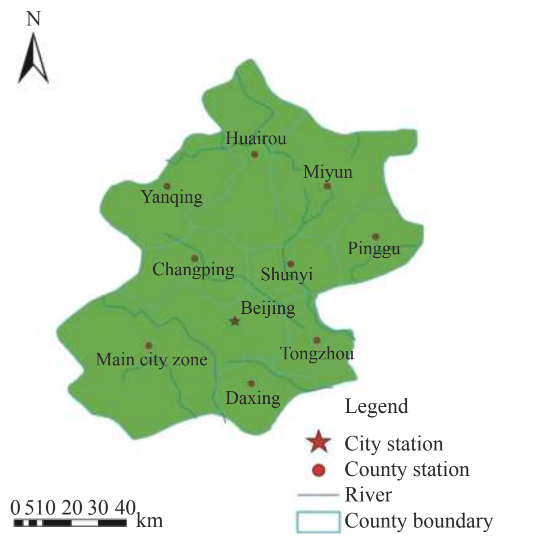


**Fig. 1** Extent of the study area

loitation of groundwater has resulted in ecological, environmental and geological issues, including continuous decline in groundwater levels, aquifer depletion in some areas, weakened storage capacity, and a significant threat to urban and rural water supply during severe droughts (Wang et al. 2019; Qin, 2021; Du et al. 2021). By 2010, Beijing's groundwater fallout funnel covered an area of 1 057 $km^2$, and the thin aquifers of the quaternary strata were on the verge of depletion or semi-depletion (Luo et al. 2019; Cao et al. 2020b). The over-exploitation of groundwater has also led to ground subsidence, ground collapse and ground cracks, posing serious hazards to urban infrastructure, regional transportation and communications, flood safety and agricultural production (Si et al. 2018; Guo et al. 2021; Zheng et al. 2022).

In December 2014, the first phase of the South-to-North Water Diversion Project was officially opened, providing a significant alleviation to the water scarcity situation in Beijing. This project also offered an important water source to address the long-term over-exploitation of groundwater pressure extraction (Liu, 2020; Liao et al. 2021; Zhang et al. 2023). The water diverted from the south to the north is primarily used to fulfill the growing demand for domestic and industrial water consumption. The surplus water is then supplemented with local surface water and groundwater to meet the needs of urban life and industry. Reclaimed water is mainly utilized for environmental purposes, with a small portion used for municipal water supply.

## 2 Research methods

### 2.1 Methodology for assessing pressurized extraction

Groundwater pressure extraction in Beijing has primarily occurred in urban areas in recent years. Due to the relatively standardized management of water abstraction permits in the city, urban areas are mainly allocated for industrial and domestic water use, and their water supply is less affected by precipitation. Since December 2017, Beijing has implemented the water resource fee to tax reform, leading to higher groundwater extraction metering rate and easier access to data on the amount of groundwater extraction and pressure extraction. The assessment of groundwater pressure extraction is conducted based on the difference between the amount of groundwater extracted in the current year and the previous year.

$$\Delta Q = Q_1 - Q_2 \tag{1}$$

Where: $\Delta Q$ represents the amount of groundwater pressure extraction; $Q_1$ is the amount of groundwater extraction in the previous year; and $Q_2$ is the amount of groundwater extraction in the current year.

In specific calculations, the amount of groundwater pressure extraction is further evaluated in relation to the amount of new surface water supply and the amount of water withdrawn from capped wells. Generally, the amount of groundwater pressure extraction is expected to be less than the amount of new surface water use, considering factors such as new water demand and pipeline leakage. If the amount of groundwater suppression exceeds the amount of new surface water use, further assessment is carried out considering economic situation, the level of water use by industrial enterprises, and large-scale industrial restructuring. The amount of groundwater extracted from sealed wells in recent years is also used as a reference for verifying the amount of groundwater pressure extraction. This is calculated by examining the annual sealed well records, water abstraction permits, electricity consumption, payments of water fee and other relevant information. The average annual amount of groundwater extracted from each sealed well in the past 2–3 years is determined to obtain the average annual volume of groundwater extracted from the sealed wells. The calculated amount of groundwater extraction obtained through the above methods is further reviewed for reasonableness in conjunction with precipitation and groundwater levels.

### 2.2 Methods for analyzing water level changes

Groundwater level changes provide a direct indication of the annual variations in groundwater extraction and replenishment, serving as a key indicator to assess the effectiveness of groundwater pressure extraction. In this study, analysis of water level changes involves the selection of groundwater monitoring wells for assessment, guided by principles of uniform distribution and reasonable density. Based on the end-of-year water level data from Beijing's groundwater level monitoring wells from past years, this study examines annual water level variations, including changes from the current water level to the initial period of water supply. The calculation of groundwater levels employs both the arithmetic average method for monitoring wells and the area-weighted average method. Utilizing dynamic groundwater level monitoring data, the study generates annual distribution maps illustrating changes in groundwater level, which delineate regions of groundwater level rebound, stabilization and decline. The percentage of each area is computed, revealing the proportion of rebound, stabilization and decline zones. The process involves several specific steps: Calculating groundwater level alterations for each monitoring well, and subsequently employing the Kriging interpolation method to visualize the distribution of groundwater level fluctuations.

## 3 Results and discussion

### 3.1 Analysis of changes in the structure of water supply in Beijing

#### 3.1.1 Allocation and utilization of water from the central route of South-North Water Diversion Project

The South-to-North Water Diversion Project comprises the east, central and west routes, connecting four major rivers, i.e. the Yangtze River, Yellow River, Huaihe River and Haihe River. This forms China's comprehensive water resources allocation pattern, known as the "four horizontal and three vertical" scheme (Su et al. 2022). The central route draws water from Danjiangkou Reservoir in the middle reaches of the Yangtze River, travering Henan Province, Hebei Province, Beijing Municipality and Tianjin Municipality, to supply water for domestic, industrial, ecological, and agricultural use to 19 large and medium-sized cities and 100 counties (or county-level cities) within these regions, covering a total distance of 1 432 km (Liu et al. 2023). The first phase of the Central Route Project is designed to transfer a total of 9.5 billion $m^3$ of water annually (from the head of Taoqiao canal). From this transferred water, Beijing receives a gross water supply (from the head of Taoqiao canal) of 1.24 billion $m^3$, and net water supply of 1.05 billion $m^3$ from the mainline diversion gates.

The initial phase of the Central Route Project began delivering water in December 2014, maintaining surface water quality at Class II over the past years. Beijing's water utilization strategy emphasizes water conservation follows the principle of "Drinking, Storing and Replenishing". The amount of South-North Water Diversion water utilized annually is shown in Fig. 2. For instance, in 2020–2021, 840 million $m^3$ of water was supplied to water treatment plants for "Drinking", constituting 64% of the incoming water volume (Fig. 3). About 0.5 billion $m^3$ of water was directed to reservoirs such as Miyun and Huairou for water storage, making up 4% of the inflow volume. To enhance water source, river and lake ecological environments, "Replenishing" involved 426 million $m^3$ (173 million $m^3$ for water sources, 171 million $m^3$ for river and lake ecological environments, and 82 million $m^3$ for Yongding River ecological restoration), comprising 32% of inflow volume. More than 60% of the water diverted from the south to the north is allocated for urban tap water supply in Beijing. In fact, and the South-to-North transferred water accounts for over 70% of the city's daily water demand, benefiting around 13 million urban residents. Consequently, the city's per capita water resources have increased from 100 $m^3$ to 150 $m^3$, while the safety coefficient of water supply in the central city (daily water supply capacity of the city/highest daily water demand) has risen from 1.0 to 1.2. Notably, the water storage capacity of Miyun Reservoir has exceeded 3.5 billion $m^3$, making a significant boost in Beijing's water resources reserve.

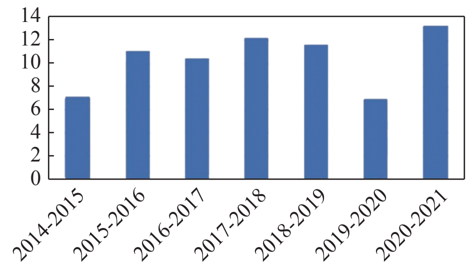


**Fig. 2** Utilization of South-to-North water transfer in Beijing since the opening of the first phase of the South-to-North Water Transfer Project

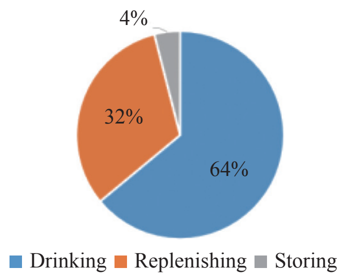


**Fig. 3** Consumption of water from the first phase of the South-to-North Water Diversion Project in Beijing in 2020–2021

#### 3.1.2 Analysis of the structure of water supply in recent years

The structure of water supply in Beijing was analyzed from 1986–2020 (Fig. 4). During recent years, Beijing's total water consumption has remained relatively stable at around 4 billion $m^3$. In terms of water supply sources, prior to the operation of the first phase of the Central Route Project, groundwater contributed over 2 billion $m^3$ of water supply, reaching its peak at 2.764 billion $m^3$ in 1994. Regarding water supply structure, groundwater accounted for a substantial share of 77.6% in 2004. However, this proportion has steadily declined since 2014, dropping from 52.3% in 2014 to 33.3% in 2020. This shift indicates that the optimization of Beijing's water supply structure has been facilitated by the inauguration of the first phase of Central Route Project, which has led to improved water resources allocation and enhanced water security capacity.

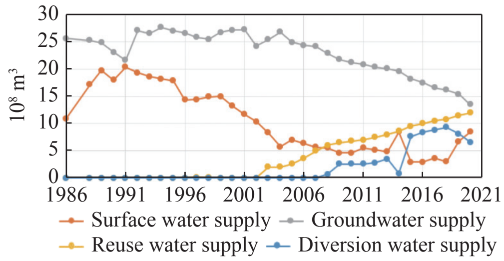


**Fig. 4** Water supply in Beijing (1986–2020)

Water usage in Beijing across various industry from 1986 has been analyzed (Fig. 5). Groundwater in Beijing is mainly used for domestic and industrial water needs as well as agricultural irrigation. The proportion of groundwater allocated for domestic and industrial purposes relative to the total groundwater supply has shown an upward trend in recent years, ascending from 60% in 2015 to 70% in 2019. Conversely, the percentage of groundwater allocated for irrigated agriculture has exhibited a decline during this period, dropping from 35% in 2015 to 24% in 2019. This dual shift reflects the recent restructuring of Beijing's industrial landscape, incorporating more efficient water-saving practices in agriculture, such as employing high-efficiency irrigation methods and cultivating crops with low-water-consumption. Furthermore, it also indicates that with the initiation of the South-to-North Water Diversion Project, groundwater previously used by industrial and domestic sectors has gradually been reallocated for agricultural

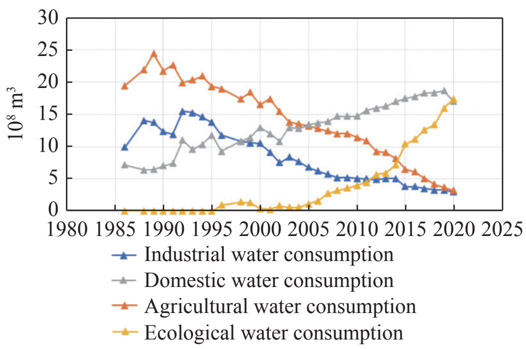


**Fig. 5** Groundwater utilization by sector since 2015

irrigation, consequently reducing the groundwater exploitation by the agricultural sector.

## 3.2 Groundwater pressure extraction

Groundwater extraction data has been primarily sourced from the Beijing Water Resources Bulletin and the Beijing Water Statistics Yearbook (Fig. 6). Based on calculation, by the end of 2020, the cumulative volume of groundwater suppression and extraction within Beijing's water receiving region has reached 446 million $m^3$. Cumulatively, it has completed the replacement of 1 204 self-supplied wells in various units (districts), the transformation of the internal water supply pipe networks in 1 251 old districts, and has sealed and filled 7 791 extraction wells.

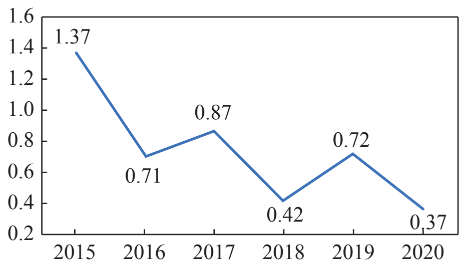


**Fig. 6** Statistics on annual groundwater pressure extraction in Beijing since 2015

In 2015, there was a notable reduction in groundwater extraction in Beijing, totaling 1.819 billion $m^3$. This marked a decline of 137 million $m^3$ from 1.956 billion $m^3$ in 2014. This reduction included 0.89 billion $m^3$ in domestic and industrial sectors, 0.45 billion $m^3$ in agriculture, and 0.03 billion $m^3$ for environmental purposes. Regional groundwater levels displayed modest change, with groundwater depth in the plains remaining largely consistent as in 2014.

In 2016, 1.748 billion $m^3$ of groundwater were extracted in Beijing, reflecting an annual decrease of 0.71 billion $m^3$. This comprised 0.43 billion $m^3$ in domestic and industrial sectors, 0.41 billion $m^3$ in agriculture, and a 0.13 billion $m^3$ increase for environmental water use. Groundwater levels in the Plains ceased declining and began to rise in 2016, with the annual decline in groundwater levels slowing from 1.14 m in 2014 to 0.09 m in 2015. By the end of 2016, groundwater levels had rebounded by 0.52 m per year.

In 2017, the extraction volume reached 1.661 billion $m^3$ in Beijing Municipality, marking a reduction of 0.87 billion $m^3$ per year. Groundwater level in the Plain District rebounded by 0.26 m per year.

In 2018, Beijing's groundwater extraction amounted to 1.619 billion $m^3$, showing an annual reduction of 0.42 billion $m^3$. Groundwater level in the Plain District rebounded by 1.94 m per year.

In 2019, groundwater extraction volume in Beijing was 1.547 billion $m^3$, reflecting a decline of 0.72 billion $m^3$ per year. This reduction included 0.13 billion $m^3$ in domestic and industrial sectors, 0.39 billion $m^3$ in agriculture, and 0.20 billion $m^3$ for environmental water use. Groundwater level in the plains area rebounded by 0.32 m yearly.

In 2020, the amount of groundwater extraction in Beijing decreased by 0.37 billion $m^3$.

### 3.3 Analysis of groundwater levels changes since water supply commencement

Groundwater level monitoring data from 114 groundwater monitoring wells within Beijing's plain area has been collected since 2014 for the purpose of analyzing water level fluctuation.

The geographical distribution of these 114 monitoring wells is shown in Fig. 7, illustrating that a greater concentration of monitoring wells is found in the urban vicinity, while they are more evenly distributed in the agricultural lands. Table 1 provides an overview of groundwater level changes within monitoring wells. Additionally, a month-by-month buried depth data changes for monitoring wells from January 2013 to December 2019 is plotted based on water level data, as detailed below.

Since the commencement of the first phase of the South-to-North Water Diversion Center River water into Beijing in late 2014, the long-standing trend of declining groundwater levels over the years has been effectively halted. This effect is particularly prominent from 2016 onwards, where groundwater levels have consecutively risen for five years. Specifically, the groundwater levels in

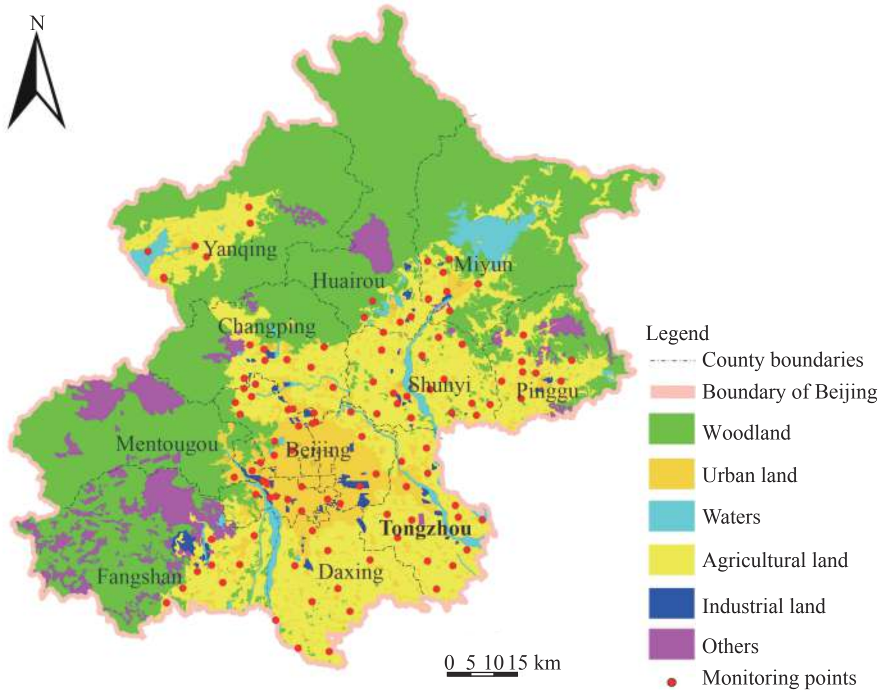


**Fig. 7** Distribution of monitoring wells in the Beijing Plain

**Table 1** Changes in groundwater levels in 114 monitoring wells in the Beijing plain area

| Number of water level change monitoring points | Annual end-of-December water level | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2015 minus 2014 | 2016 minus 2015 | 2017 minus 2016 | 2018 minus 2017 | 2019 minus 2018 | 2020 minus 2019 | 2020 minus 2014 |
| Rising water level | 31 | 50 | 38 | 42 | 45 | 47 | 79 |
| Water level stabilization | 40 | 47 | 49 | 53 | 29 | 42 | 17 |
| Water level drop | 43 | 17 | 27 | 19 | 40 | 25 | 18 |
| Average water level/m | Decrease of 0.12 | Increase of 0.52 | Increase of 0.26 | Increase of 1.94 | Increase of 0.32 | Increase of 0.68 | Increase of 3.72 |

the Plains region have exhibited annual rebounds of 0.52 m, 0.26 m, 1.94 m, 0.32 m, and 0.68 m from 2016 to 2021, respectively. At the end of 2020, the average groundwater level in the city's plains was 22.03 m, signifying a rebound of 0.68 m compared to the previous year, and a cumulative rebound of up to 3.72 m compared to the equivalent period in 2015. This rebound is accompanied by a substantial reduction of 2 479 km$^2$ in the area of groundwater over-exploitation zone, coupled with an expansion of the groundwater extraction and replenishment balance zone from 287 km$^2$ in 2015 to 2 766 km$^2$, marking an augmentation of 8.6 times.

The variation in groundwater depth from December 2015 to 2020, both compared to the same period in the previous year and December 2020 in comparison to December 2014 are depicted in Fig.s 8-13. Compared with December 2014, at the end of December 2015, a decline in groundwater

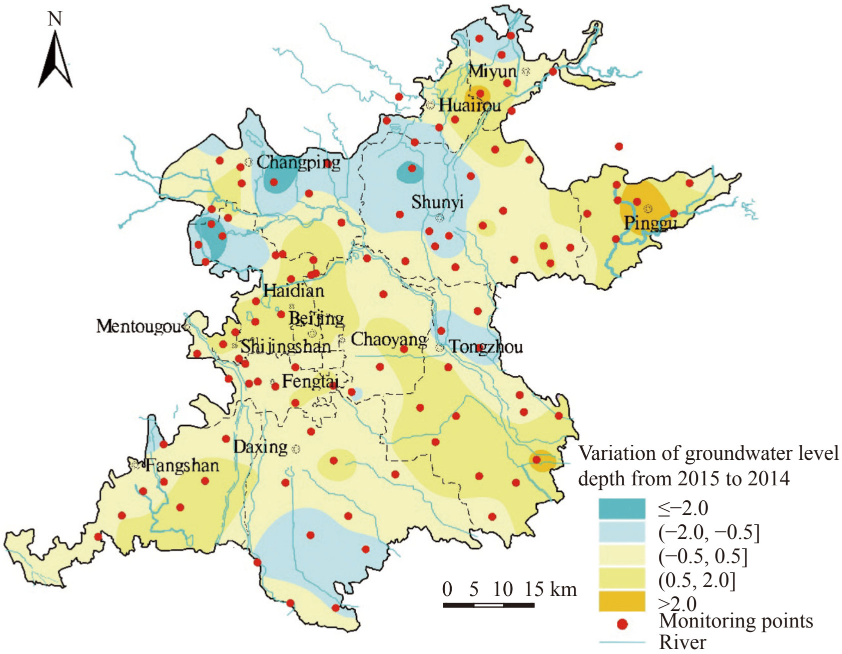


**Fig. 8** Variation of groundwater level depth from 2015 to 2014

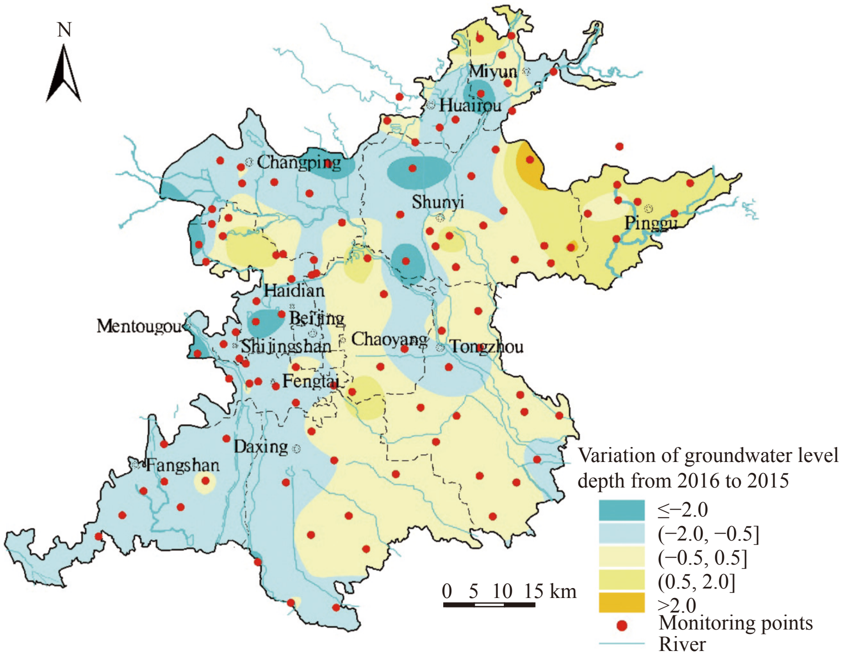


**Fig. 9** Variation of groundwater level depth from 2016 to 2015

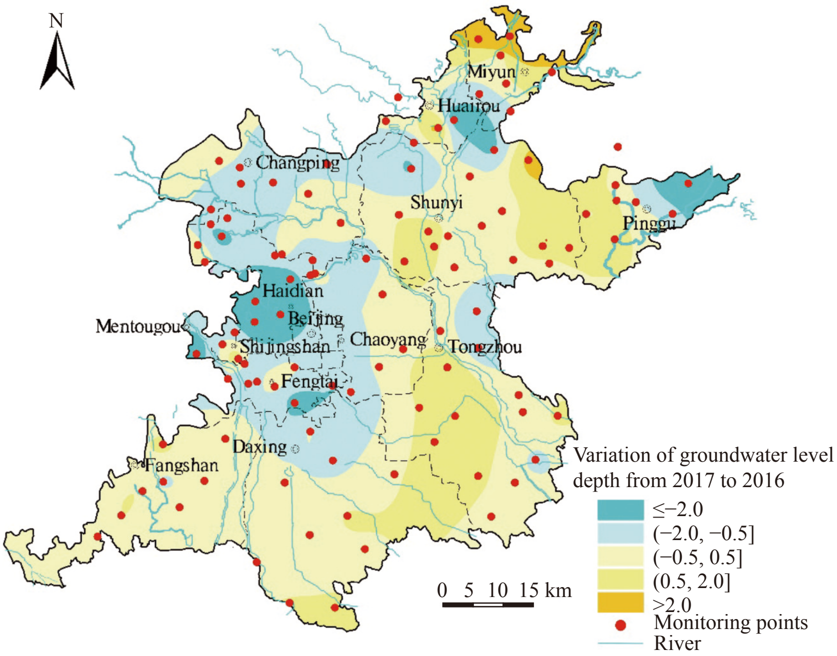


**Fig. 10** Variation of groundwater level depth from 2017 to 2016

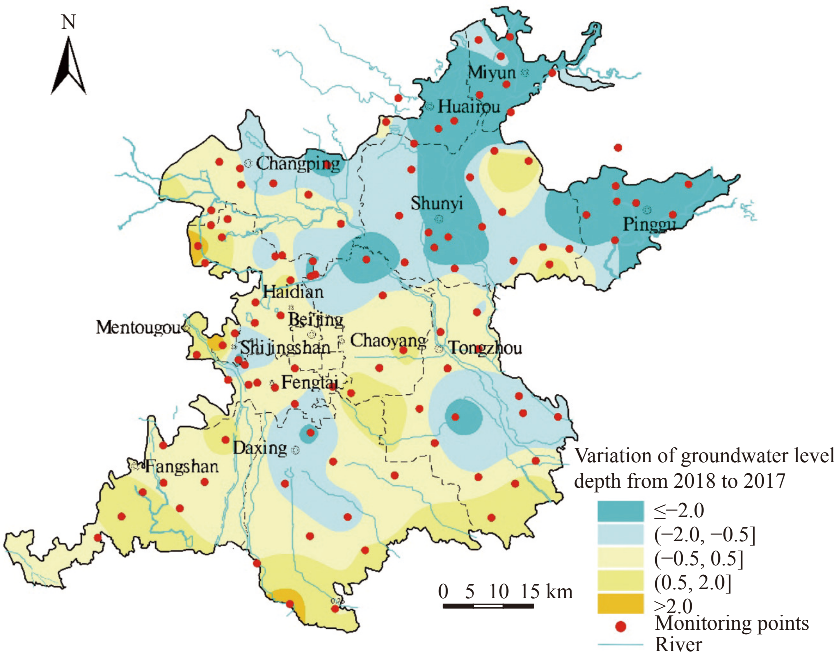


**Fig. 11** Variation of groundwater level depth from 2018 to 2017

levels was observed across various areas, including Tongzhou, the junction of Pinggu, Miyun and Huairou, the vicinity around the Shijingshan-Haidian-Chaoyang-Changping junction, the southeastern section of Fangshan, the eastern part of Changping, the western part of Shunyi, the southern part of Daxing, and the northern part of Miyun. Conversely, other regions maintained stable groundwater levels during this period. When compared to December 2015, the regions experiencing a rise in water levels at the end of December 2016 was mostly distributed in the western half of the Plains area. In comparison of December 2016, the distribution of water level rise zones in 2017 was similar to that of 2016, but with a reduction in water levels in the Fannin District. As opposed to December 2017, the majority of the areas displaying an increase in water levels at the end of December 2018 were located in the northern part of the plains area. Some areas within the central part of Tongzhou and Daxing also exhibited rising water levels, while other areas either maintained stability or

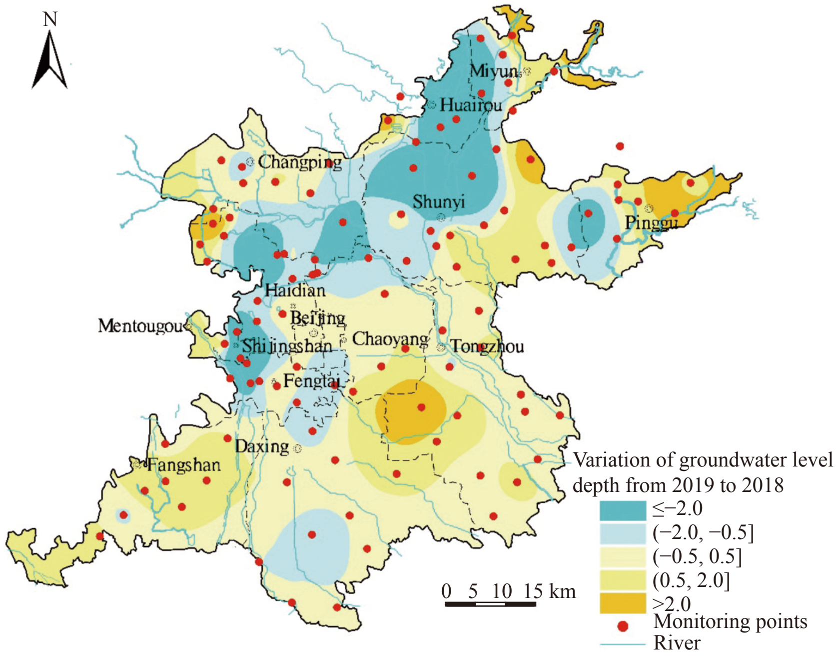


**Fig. 12** Variation of groundwater level depth from 2019 to 2018

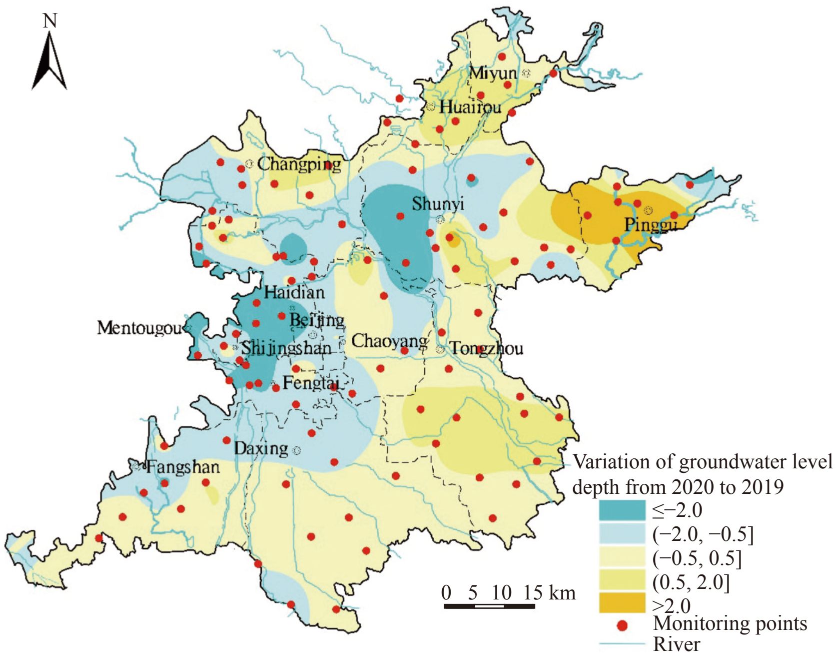


**Fig. 13** Variation of groundwater level depth from 2020 to 2019

experienced declining water levels. In contrast to December 2018, most of the areas with rising water levels in December 2019 were located in the northern part of the Plains District. Additionally, a significant portion of the southern Daxing District also experienced water level increases. Finally, a similar pattern was observed when comparing December 2019 to December 2020, where the majority of the areas displaying a rise in water levels were located in the western section of the Plains. Comparing water levels between December 2014 and December 2020, a general trend of water level rebound was evident across most regions within the Beijing plains, while certain areas, including Fangshan, Tongzhou, Shunyi and the southern part of the Pinggu, experienced a decline in water levels.

The distribution of Beijing's shallow ground-

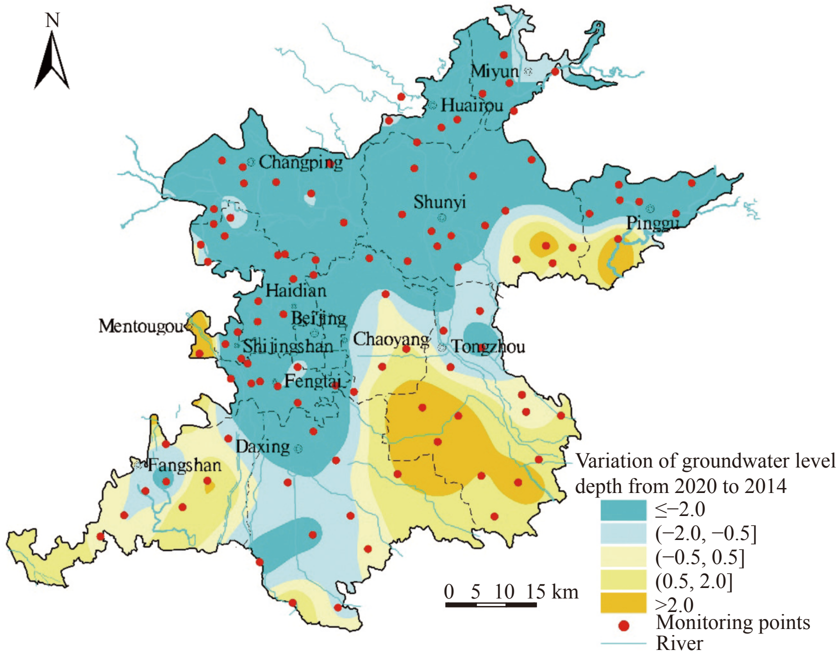


**Fig. 14** Variation of groundwater level depth from 2020 to 2014

water across various depth intervals was analyzed from 2014 to 2020 (Table 2). The results show a gradual shift in the distribution pattern during this period. Specifically, the proportion of the area occupied by depth intervals ranging from 10 m to 30 m gradually increased from 49.15% to 71.95%, and the proportion of the area with depth intervals greater than 30 m experienced a decline, decreasing from 37.23% to 15.47%.

## 3.4 Analysis on causes of water level changes

The annual reduction in groundwater extraction is a key factor contributing to the continued rebound of groundwater levels in the Beijing Plain from 2015 to 2020. Since 1999, most years experienced precipitation levels below the long-term average. During this period, the economy and society are were undergoing rapid development. To address the growing imbalance between water resource availability and demand, there was a necessity to resort to excessive groundwater extraction to meet the increasing water needs of various sections such as industry, agriculture and domestic use within the city. From 1999 to 2007, Beijing experienced a drastic decline in groundwater levels. The depth of groundwater increased from 11.88 m at the beginning of 1999 to 22.8 m by the end of 2007, marking a cumulative decline of 10.92 m and an average annual decline of 1.36 m. From 2008 to 2014, the rate of decline in groundwater levels moderated, and the depth of groundwater increased from 22.79 m in early 2008 to 24.81 m by the end of 2014 when Ji water entered Beijing in 2008. In 2015–2020, groundwater level was stabilized and rebounding. The inauguration of the South-to-North Water Diversion Project in late 2014 played

**Table 2** Statistics on the proportion of shallow groundwater with different depth intervals in Beijing from 2014 to 2020 / %

| Timing | Depth of burial ≤10 m | Depth of burial 10–20 m | Depth of burial 20–30 m | Depth of burial 30–40 m | Depth of burial 40–50 m | Depth of burial > 50 m |
|---|---|---|---|---|---|---|
| December 2014 | 13.62 | 27.73 | 21.42 | 32.00 | 4.39 | 0.85 |
| December 2015 | 13.17 | 28.51 | 20.86 | 31.80 | 4.69 | 0.97 |
| December 2016 | 14.66 | 28.45 | 22.08 | 29.22 | 4.62 | 0.98 |
| December 2017 | 14.06 | 29.94 | 24.58 | 26.62 | 4.04 | 0.76 |
| December 2018 | 14.07 | 30.80 | 32.40 | 20.35 | 2.21 | 0.17 |
| December 2019 | 11.80 | 34.59 | 35.82 | 15.50 | 2.00 | 0.29 |
| December 2020 | 12.58 | 36.30 | 35.65 | 13.95 | 1.43 | 0.08 |

a significant role in mitigating the water resource supply-demand imbalance. It increased ecological water replenishment, and contributed to the stabilization and rebound of groundwater levels. Additionally, the city also experienced higher-than-average precipitation for three consecutive years from 2016 to 2018, which further facilitated the upward trend in groundwater levels.

Precipitation is an important influencing factor for groundwater level fluctuation (Fig. 15). By comparing and analyzing variations in groundwater depth and the contour map of precipitation in Beijing, a strong correlation in their distribution is evident, indicating the statistical characteristics of precipitation and underground water resources from 2014 to 2020. During 2014 and 2015, groundwater resources were insufficient to meet the demand, resulting in a negative equilibrium that led to a decline in groundwater levels. However, from 2016 to 2020, the available groundwater resources exceeded the demand the groundwater supplies, leading to a rebound in groundwater levels. Comparing the amount of available groundwater resources to the amount of groundwater supplied provides a general indication of groundwater equilibrium. In the years 2015, 2017, and 2018, the recorded precipitation was 583 mm, 592 mm, and 590 mm, respectively. In December 2015, the average water level decreased by 0.12 m compared to December 2014, However, there was a rebound in the average water level by 0.25 m in 2017 and by 1.52 m in 2018, respectively. The underlying reason for the different changes in groundwater levels under similar precipitation conditions was the gradual reduction in groundwater extraction over the years.

### 3.5 Impact of South-North Water Supply on groundwater levels

The amount of water supplied by the South-to-North Water Diversion accounts for about 20% of Beijing's total water supply, making it a crucial component of the city's water resources. This supply plays a vital role in either mitigating the decline in groundwater levels or accelerating their recovery. Based on the data related to groundwater level change and groundwater storage change in the groundwater dynamic briefing, it can be calculated that, over the period of 2015 to 2020, the water supply from the South-to-North Water Diversion could prevent groundwater levels from decreasing by 1.49 m, 1.65 m, 1.72 m, 1.82, 1.59 m, and 1.30 m, respectively, if it were supplied by groundwater exploitation. A specific yield to 0.08 can be estimated in the Beijing plain area based on the above numbers given an area of 6 032 km$^2$. Moreover, the aforementioned pressurized extraction volumes for the years from 2014 to 2020 could raise groundwater levels by 0.732 m, 1.024 m, 1.171 m, 1.351 m, 1.436 m, 1.602 m, and 1.996 m, respectively. This signifies a noticeable recovery of groundwater levels and underscores the positive effect of pressurized extraction practices.

## 4 Conclusions

This study analyzes the effectiveness of groundwater pressure extraction in Beijing since the first phase of the South-to-North Water Diversion Project by means of investigation and assessment methods, and the study obtains the following conclusions:

(1) Since the inauguration of the initial phase of the South-to-North Water Diversion Project, the per capita water resources in Beijing have increased from 100 m$^3$ to 150 m$^3$. The proportion of groundwater supply has exhibited a continuous decline, from 52.3% in 2014 to 33.3% in 2020. This transformation in water supply structure indicated an optimization that has significantly enhanced the allocation of water resources and effectively improved water security. By the end of

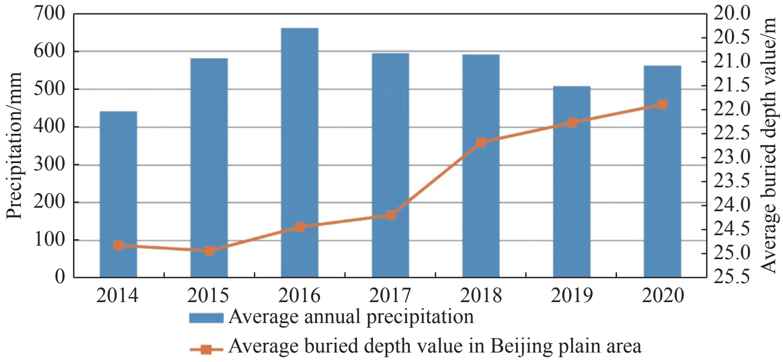


**Fig. 15** Changes in groundwater depth and precipitation in the plain area of Beijing from 2014 to 2020

2020, the cumulative volume of suppressed and extracted groundwater will have reached 446 million $m^3$.

(2) The water supply has effectively curbed the trend of continuous decline of groundwater level in Beijing. At the end of 2020, the average groundwater level in the city's plains was 22.03 m, with a cumulative rebound of up to 3.72 m compared with the same period in 2015. Additionally, the area of groundwater over-exploitation zone was significantly reduced by 2 479 $km^2$.

(3) The fundamental reason for the sustained rebound of groundwater levels in the Beijing Plain Area from 2015 to 2020 can be attributed to the reduction in the amount of groundwater supply. The South-North Water Diversion contributes around 20% of the total water supply, which plays an indispensable role in slowing down the rate of groundwater level decline.

## Acknowledgements

This study was funded by the projects "Impacts of water transfer from the western route of the South-to-North Water Diversion Project on the ecological environment of the Yangtze and Yellow Rivers and coping strategies" (No. 2022YFC3202400) and "Ecological Compensation Mechanism and Biological Invasion Risk Analysis of Water Transfer from the Western Route Project" (No. 2022YFC 3202404).

## References

Adams M, Smith PL, Yang XH. 2015. Assessing the effects of groundwater extraction on coastal groundwater-dependent ecosystems using satellite imagery. Marine and Freshwater Research, 66(3): 226. DOI: 10.1071/mf14010.

Cao WG, Wen AX, Nan T, et al. 2023. Evaluation of the suitability of groundwater recharge in typical areas of the Haihe River Basin. Advances in Water Science, 34(2): 227−237. (in Chinese) DOI: 10.14042/j.cnki.32.1309.2023.02.007.

Cao WG, Zhang Z, Guo HM, et al. 2023. Spatial distribution and controlling mechanisms of high fluoride groundwater in the coastal plain of Bohai Rim, North China. Journal of Hydrology, 617: 128952. DOI: 10.1016/j.jhydrol.2022.128952.

Cao WG, Yang HF, Gao YY, et al. 2020. Prediction of groundwater quality evolution in the Baoding Plain of the SNWDP benefited regions. Journal of Hydraulic Engineering, 51(8): 924−935. (in Chinese) DOI: 10.13243/j.cnki.slxb.20200035.

Cao YB, Wei YN, Fan W, et al. 2020. Experimental study of land subsidence in response to groundwater withdrawal and recharge in Changping District of Beijing. PLoS One, 15(5): e0232828. DOI: 10.1371/journal.pone.0232828.

Chen F, Ding YY, Li YY, et al. 2020. Practice and consideration of groundwater overexploitation in North China Plain. South-to-North Water Transfers and Water Science & Technology, 18(2): 191−198. (in Chinese) DOI: 10.13476/j.cnki.nsbdqk.2020.0042.

Chen XJ, Wang LF, Jia LQ, et al. 2021. China's water resources in 2020. China Geology, 4: 536−538. DOI: 10.31035/cg2021063.

Du ZY, Ge LL, Ng AHM, et al. 2021. Analysis of the impact of the South-to-North water diversion project on water balance and land subsidence in Beijing, China between 2007 and 2020. Journal of Hydrology, 603: 126990. DOI: 10.1016/j.jhydrol.2021.126990.

Ge YX, Wu J, Li BH, et al. 2022. Analysis and evaluation of variation characteristics in groundwater resources carrying capacity in Beijing between 2010 and 2020. Sustainability, 14(15): 9200. DOI: 10.3390/su14159200.

Guo L, Gong HL, Ke YH, et al. 2021. Mechanism of land subsidence mutation in Beijing plain under the background of urban expansion. Remote Sensing, 13(16): 3086. DOI: 10.3390/rs13163086.

Hao QC, Shao JL, Xie ZH, et al. 2012. A Study of the artificial adjustment of groundwater storage of the Yongding River alluvial fan in Beijing. Hydrogeology & Engineering Geology, 39(4): 12−18. (in Chinese) DOI: 10.16030/j.cnki.issn.1000-3665.2012.04.016.

Hout EVD, Doelder BD. 2015. Urban groundwater management as risk reduction tool for groundwater extractions. Ebook. IOS Press: Geotechnical Safety and Risk V: 139−143. DOI: 10.3233/978-1-61499-580-7-139.

Hu Q. 2017. Utilization and prevention of groundwater resources in Beijing-Tianjin-Hebei region. Chinese & Foreign Entrepreneurs, (18): 51,57. (in Chinese)

Li C, Men BH, Yin SY. 2022. Analysis of groundwater chemical characteristics and spatiotemporal evolution trends of influencing factors in southern Beijing plain. Frontiers in Environmental Science, 10: 913542. DOI: 10.3389/fenvs.2022.913542.

Liao ZM, Zang N, Wang X, et al. 2021. Machine learning-based prediction of chlorophyll-a variations in receiving reservoir of world's largest water transfer project—a case study in the Miyun Reservoir, North China. Water, 13(17): 2406. DOI: 10.3390/w13172406.

Liu XL. 2020. Role of Middle Route Scheme of South to North Water Diversion to control overexploitation of groundwater in North China. China Water Resources, (13): 31−32. (in Chinese) DOI: 10.3969/j.issn.1000-1123.2020.13.018.

Liu YY, Zheng H, Wan WH, et al. 2023. Optimal operation toward energy efficiency of the long-distance water transfer project. Journal of Hydrology, 618: 129152. DOI: 10.1016/j.jhydrol.2023.129152.

Luo Y, Chen BB, Lei KC, et al. 2019. Optimum design of level monitoring points for land subsidence. Bulletin of Engineering Geology and the Environment, 78(7): 5135−5146. DOI: 10.1007/s10064-018-01442-6.

Pang YJ, Zhang H, Cheng HH, et al. 2020. The modulation of groundwater exploitation on crustal stress in the North China Plain, and its implications on seismicity. Journal of Asian Earth Sciences, 189: 104141. DOI: 10.1016/j.jseaes.2019.104141.

Qin HH, Zheng CM, He X, et al. 2019. Analysis of water management scenarios using coupled hydrological and system dynamics modeling. Water Resources Management, 33(14): 4849−4863. DOI: 10.1007/s11269-019-02410-9.

Qin HH. 2021. Numerical groundwater modeling and scenario analysis of Beijing plain: Implications for sustainable groundwater management in a region with intense groundwater depletion. Environmental Earth Sciences, 80(15): 499. DOI: 10.1007/s12665-021-09795-0.

Si Y, Chen BB, Gong HL, et al. 2018. Temporal and spatial evolution of land subsidence induced by groundwater exploitation and construction in the eastern Chaoyang district, Beijing, China. Journal of the Indian Society of Remote Sensing, 46(10): 1657−1665. DOI: 10.1007/s12524-018-0821-z.

Su QM, Chang HS, Chen X, et al. 2022. Metacoupling of water transfer: The interaction of ecological environment in the middle route of China's south-north project. International Journal of Environmental Research and Public Health, 19(17): 10555. DOI: 10.3390/ijerph191710555.

Sun L, Zhang YB, Si HY, et al. 2021. Simulation and prediction of shallow groundwater depth in the North China Plain based on regional periodic characteristics. Environmental Earth Sciences, 80(18): 635. DOI: 10.1007/s12665-021-09933-8.

Wang LH, Jia BH, Xie ZH, et al. 2022. Impact of groundwater extraction on hydrological process over the Beijing-Tianjin-Hebei region, China. Journal of Hydrology, 609: 127689. DOI: 10.1016/j.jhydrol.2022.127689.

Wang SF, Li J, Liu YZ, et al. 2019. Impact of South-to-North Water Diversion on groundwater recovery in Beijing. China Water Resources, (7): 26−30. (in Chinese) DOI: 10.3969/j.issn.1000-1123.2019.07.008.

Xu BT, Yang YL, Geng JK, et al. 2020. Analysis on countermeasures about treatment of groundwater over-abstraction in Hebei Province. Haihe Water Resources, (6): 6−8. (in Chinese) DOI: 10.3969/j.issn.1004-7328.2020.06.003.

Yang L, Zhu QL, Sun J, et al. 2017. Water supply benefit evaluation of Middle Route Project of South-to-North Water Diversion in Beijing City. Yangtze River, 48(10): 44−46,78. (in Chinese) DOI: 10.16232/j.cnki.1001-4179.2017.10.010.

Yang ZW, Liu HL, Yang TT, et al. 2015. A path-based structural decomposition analysis of Beijing's water footprint evolution. Environmental Earth Sciences, 74(3): 2729−2742. DOI: 10.1007/s12665-015-4484-6.

Zhang XY, Chen JF, Yu C, et al. 2023. Emergency risk assessment of sudden water pollution in South-to-North Water Diversion

Project in China based on driving force–pressure–state–impact–response (DPSIR) model and variable fuzzy set. Environment, Development and Sustainability. DOI：10.1007/s10668-023-03468-7.

Zhao K, Qi JX, Chen Y, et al. 2021. Hydrogeochemical characteristics of groundwater and pore-water and the paleoenvironmental evolution in the past 3.10 Ma in the Xiong'an New Area, North China. China Geology, 4: 476−486. DOI：10.31035/cg2021058.

Zhao Y, Wang LZ, Li HH, et al. 2020. Evaluation of groundwater overdraft governance measures in Hengshui city, China. Sustainability, 12(9): 3564. DOI：10.3390/su12093564.

Zheng YZ, Peng JH, Chen X, et al. 2022. Spatial and temporal evolution of ground subsidence in the Beijing plain area using long time series interferometry. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 16: 153−165. DOI：10.1109/JSTARS.2022.3223027.

Zhou H, Dai M, Wei M, et al. 2023. Quantitative assessment of shallow groundwater sustainability in North China plain. Remote Sensing, 15(2): 474. DOI：10.3390/rs15020474.