Emergency Plan for Water Supply in Consecutive Droughts and Sustainable Water Resources Management in Beijing

LI Wenpeng¹, ZHENG Yuejun 1-*, YE Chao² and LI Haitao 1

1 China Institute for Geo-Environmental Monitoring, Beijing100081, China
2 Beijing Geo-Environment Monitoring Station, Beijing100037, China

Abstract: Beijing, the capital city of China, has suffered from acute water shortage, with only 300 m³/a of water resources available per capita. In addition, Beijing has experienced a prolonged period of consecutive droughts from 1999 to 2010. Water crisis has constrained the socio-economic development of Beijing. Meanwhile, the national “South-to-North Water Transfer” (STNWT) project, which is expected to provide some relief to the water crisis in Beijing, is still under development. In order to ensure the security of water supply in Beijing before the completion of the STNWT project, several measures have been implemented to cope with droughts, including pumping groundwater from emergency well fields, water saving, recycling of water, rain and flood water harvesting, and the diversion of water from neighboring rivers and groundwater basins. Groundwater from four emergency well fields contributes the most to the public and domestic water supplies in Beijing, supplying a total volume of 1.8×10⁸ m³. The water crisis is supposed to be mitigated by the completion of the STNWT project. After the completion of this project, more sustainable management of water resources will be implemented, including the use of aquifers as groundwater reservoirs and conjunctive use of surface water and groundwater resources.

Key words: Emergency water supply, groundwater resources, natural disasters, groundwater reservoir, sustainable water resources management, Beijing

1 Introduction

Beijing, the capital city of China, with a population of more than 20 million and only about 300 m³/a of water resources available per capita, is one of the cities facing serious water shortage (Ruan Benqing et al, 2004). The water crisis has become one of the most important factors which constrain economic and social development in Beijing. In addition, Beijing has experienced a 12-year consecutive drought period since 1999. Meanwhile, the national “South-to-North Water Transfer” (STNWT) project, which is supposed to provide some relief to the water crisis of Beijing, was completed in 2014. Therefore, the most urgent task for the water resources management authority in Beijing is to take necessary measures and ensure the security of water supply for agriculture, industry, and domestic needs.

Several sources of water for dealing with severe consecutive droughts have been proposed, including water resources from water-saving measures, recycled water, rainwater harvesting, diversion from neighboring provinces, and water from emergency well fields. For different sources, different methods are needed and should be used conjunctively and concurrently. Finally, a sustainable water resources management strategy should be implemented in Beijing after the completion of the STNWT project.

2 Overview of the Water Resources and Water Supply in Beijing

Beijing city is located in the northwest part of the North China Plain. The total area of Beijing municipality is about 16,800 km² including a mountainous area of 10,400 km² and two plains with areas of around 6,000 km² for the larger plain and 400 km² for the plain of Yanqing county, respectively (Fig. 1) (Zhang Anjing et al., 2008).

2.1 Climate

With a typical continental semi-humid monsoon
climate, the annual average rainfall in Beijing is around 600 mm (averaged value from 1950 to 2016). From 1999 to 2010, Beijing has experienced a consecutive drought period. The average annual rainfall of that period (442 mm) is only 73% of the average value over a longer time period (Fig. 2).

2.2 Surface water
The Beijing area belongs to the Haihe River Basin and can be divided into five river catchments named, from east to west, the Jiyun River Catchment, the Chaobai River Catchment, the Beiyun River Catchment, the Yongding River Catchment, and the Dashi River Catchment (Fig. 1). All the rivers originate in surrounding mountains. Table 1 shows the inflows of the main rivers in Beijing.

A total of 85 surface reservoirs have been constructed in Beijing since the 1950s, with a total storage volume of $9.3 \times 10^9$ m$^3$. The largest two reservoirs are the Miyun Reservoir and the Guanting Reservoir, with storage volumes of $4.38 \times 10^9$ m$^3$ and $4.16 \times 10^9$ m$^3$, respectively. Most reservoirs are located in the mountains. Therefore, water in the rivers is diverted to the reservoirs in the mountains and is used by local governments for economic and social development in the upper reaches of the catchments. This results in the decline of inflows of rivers into the Beijing area. For example, since the 1980s the inflow in the Chaobai River catchment, has decreased from $1.70 \times 10^8$ m$^3$/a to $0.56 \times 10^8$ m$^3$/a, and in the Yongding River catchment, has decreased from $1.98 \times 10^8$ m$^3$/a to $0.31 \times 10^7$ m$^3$/a (Local history compiling committee, 2000).
The Miyun Reservoir, the largest surface water reservoir in Beijing, is the most important water supply source for the city and is fed mainly by the inflow of the Chaobai River. In recent years, the Miyun Reservoir has become nearly dry, since there is not enough incoming water.

The Guanting Reservoir, the second largest reservoir in Beijing, which is fed largely by the inflow of the Yongding River, is no longer suitable for use as a water supply because of river pollution.

2.3 Groundwater

The groundwater in the alluvial media of the Quaternary deposits (pore groundwater) and groundwater in the limestone field aquifers of the surrounding mountain areas (limestone groundwater) are the most important groundwater resources in the Beijing area (Fig. 3, Fig. 4).

The pore water of the Quaternary deposits in the Beijing plains area mainly exists in the sand and sand gravel layers which have resulted from river alluvial deposition. These layers are continuous, with different waters resource in different regions (Chen Jiansheng 2016). The groundwater system of the Quaternary deposits is divided into five sub-system, which is consistent with the divisions of the surface water system (Fig. 1). In general, the characteristics of Quaternary sediment deposition along each river are more or less the same. From the top of the alluvial fan to the alluvial plain area, the particle size of sediments in the aquifers changes from coarse to fine. The aquifer system changes from a single layer aquifer system to a multi-layer aquifer system, with 5–7 layers. The single aquifer system is a gravel aquifer with a shallow groundwater table. The thickness of the aquifer changes from a few meters to tens of meters. Infiltration from precipitation and rivers is good. The single aquifer system is largely recharged from the plains area, with which it has good connectivity. The water yield of a single well is generally greater than 5000 m³/d (drawdown is 5 m). In the upper and middle parts of the alluvial fan, the aquifer system becomes sand and gravel aquifers with 2–3 layers. Sand, gravel, and clay layers are interbedded. Groundwater moves from unconfined to confined layers with good connectivity. The water yield of a single well is generally 3000–5000 m³/d (drawdown is 5 m). In the middle and lower parts of the alluvial fan, as well as in the plains area, the aquifer system becomes a multi-layered structure. The pore media changes gradually from coarse sand, to medium sand, to fine sand, to silt. The water yield of a single well is 500–1500 m³/d. The aquifers become confined as sediments fine.

Carbonate rocks occur widely in the Beijing area, mainly in middle and upper Proterozoic Changcheng and Jixian strata, and Paleozoic Cambrian and lower Ordovician strata. Changcheng and Jixian strata exist in the mountains, with large areas of exposure. These strata show characteristic lithology (high SiO₂) and low solubility. Through the action of internal and external geological processes, fractures are well developed and allow good rainfall infiltration. Paleozoic Cambrian and lower Ordovician strata exist in the southwest mountains, with small areas of exposure, high thickness, and high solubility. Karst features are well developed in exposures of these strata.

In order to assess the groundwater resources, the study region is divided into a mountain area and a plains area. In the assessment, hydrogeology and groundwater exploitation are considered, and the assessing period
Fig. 3. Types of aquifers in the Beijing area.

Fig. 4. Cross sectional map of the Beijing Plain.
chosen was 1980–2000. According to the groundwater system, the plain is divided into several relatively independent zones. The assessment method is the groundwater dynamic equilibrium method, which requires some parameters such as precipitation infiltration coefficient, specific yield, hydraulic conductivity, and irrigation infiltration coefficient. These parameters are cited from research results from hydrogeological surveys and tests in the Beijing area from 1950–2000. The assessment results are shown in Table 2.

The potential amount of groundwater abstraction in the mountains is calculated according to the method of groundwater abstraction. Groundwater in the mountains is pumped at a rate of $0.18 \times 10^8$ m$^3$/a and after several years this has not resulted in any environmental problems. Therefore, the potential amount of groundwater abstraction in mountains is determined to be the current pumped value of $0.18 \times 10^8$ m$^3$/a. The potential amount of groundwater abstraction in the plains was calculated by Zhang and Ye, 2008. A water balance was calculated by considering groundwater pumping, distribution of wells, environmental factors, city planning, and the security of city water supply. They concluded that the potential amount of groundwater abstraction in the plains area is $2.22 \times 10^8$ m$^3$/a. Therefore, the total potential amount of groundwater abstraction in the Beijing area is $2.4 \times 10^8$ m$^3$/a.

### 2.4 Water supply

The mean annual water usage in Beijing is $4.13 \times 10^8$ m$^3$, of which groundwater supplies around $2.63 \times 10^8$ m$^3$ and surface water $1.5 \times 10^8$ m$^3$. In 2000, the total amount of water usage was $4.05 \times 10^8$ m$^3$, of which surface water supplied $1.33 \times 10^8$ m$^3$ and groundwater $2.72 \times 10^8$ m$^3$, accounting for 32.8% and 67.2%, respectively, of the total amount of water usage.

Since the 1980s, the over abstraction of groundwater in the Beijing Plain has reached about $1–2 \times 10^8$ m$^3$/a. As a result, the regional groundwater level in the Beijing Plain has continuously declined and led to land subsidence (Figs. 5–7) (Zhang Anjing et al., 2008). After 1999, the rate of decline of groundwater level decreased. In some areas, the groundwater water level has recovered to some extent.

### Table 2 Averaged recharge amounts for the Beijing area Items

<table>
<thead>
<tr>
<th>Recharge from mountains</th>
<th>Quantity ($10^8$ m$^3$/a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation</td>
<td>1.33</td>
</tr>
<tr>
<td>River</td>
<td>0.31</td>
</tr>
<tr>
<td>Channel</td>
<td>0.1</td>
</tr>
<tr>
<td>Irrigation</td>
<td>0.34</td>
</tr>
<tr>
<td>Total</td>
<td>3.60</td>
</tr>
</tbody>
</table>

Fig. 5. Development of groundwater cones of depression in the Beijing Plain between 1975 and 2001.
Since the development of social economy, especially the development of industry and agriculture, the water demand has increased gradually. With limited surface water resource, the groundwater resource has been exploited, leading to a sharp decrease in groundwater level.

Zhang and Ye (2008) carried out research on the relationship between ground deformation and quaternary confined water head by using long term monitoring data on land subsidence and dynamic groundwater table variation. The results show that the excessive exploitation of groundwater is the main reason for the occurrence of land subsidence in Beijing. The rate and quantity of land
subsidence are influenced by the rate of decline and height of the groundwater table. The rate of land subsidence changes with the rate of groundwater table decline. The quantity of land subsidence shows a high correlation to the declining height of the groundwater table. Meanwhile, land subsidence mainly occurred in the middle and lower parts of the alluvial fans and alluvial plain areas in Beijing city. As has been addressed in the previous sections, the stratum structure of these regions is mainly multi-layer sand, gravel, and clay. In the multi-layer structure, there are gravel layers with coarse particles and good connectivity, as well as clay layers with fine grains and high compression capacities. The research shows that the quantity of land subsidence is large in clay layers and small in sand and gravel layers. Groundwater pumping results in the drop of groundwater table and the clay layers are compressed after the groundwater in those layers is pumped, resulting in land subsidence.

3 Methods of Securing Water Supply in Emergency

In order to address the serious water shortage since 1999, as well as to create strategies and policies for the sustainable development of water resources management in the Beijing area at the beginning of the 21st century, Beijing and its neighboring provinces and cities were called together by the State Council of China in 2001 to establish a water emergency plan. The suggestions and measures proposed in this plan include water saving techniques, recycled water utilization, rain water and flood water harvesting, water diversion, and well fields for emergency groundwater supply (Ma Dongchun, 2006; Chen Zhikai, 1996). The total water supply in the year 2000 was around $4.0-4.2 \times 10^8$ m³/a and decreased to around $3.4-3.5 \times 10^8$ m³/a by 2006 (Fig. 8) (Beijing Statistical Bureau and Beijing Water Service Bureau, 2006; Beijing Water Bureau, 2012). The above-mentioned measures will be discussed in the following chapters.

3.1 Well fields for emergency water supply

In order to meet the urgent demand of urban water supply, an investigation into the potential of well fields for water supply in an emergency has been launched and a relevant plan has been proposed. This plan includes six well fields, which are located above three types of groundwater body, as shown in Fig. 9 and Table 3. The total capacity for water supply from the six well fields could reach about $3.9 \times 10^8$ m³/a in an emergency situation, but this level of production would not be sustainable. The extraction of groundwater must be stopped after the emergency period (maximum pumping period is two years).

Fig. 10 shows the annual exploitation of groundwater in the Huairou well field, the Zhangfang-Changgou well field, and the Pinggu-Shunyi well field. In the Huairou well field the total groundwater supply reached $12.65 \times 10^8$ m³/a by 2017, in the Zhangfang-Changgou well field $3.24 \times 10^8$ m³/a by 2017, in the Changping well field $1.13 \times 10^8$ m³/a by 2010, and in the Pinggu-Shunyi well field $0.89 \times 10^8$ m³/a by 2016.

In fact, use of groundwater as an emergency water source is the kind of measure used for short term water supply security in some conditions, which could result in further water shortage. However, as an emergency measure, it can supply water in continuous dry years in the short term to alleviate crises in city water supply, whilst in wet years it can recover through artificial recharge, to be ready for future use.

3.2 Water saving

With the aim of further improving water resource savings, in 2000 the Municipal Water Office of Beijing laid out the conditions for efficient water resources management. The following responsibilities of the administrative section are highlighted: to develop water saving plans and associated water saving policies, codes,
and standards, to supervise the implementation of water saving activities, and to provide advice on water saving for Beijing stakeholders, considering industrial, agricultural, and public and domestic water supply sectors. The goal of water saving is to control total water consumption, make more effective use of water for agriculture, maintain sufficient water use for industry, and support public and domestic use of water resources for drinking purposes. In recent years water usage components have changed considerably (Fig. 11).

As shown in Fig. 11, from 2001, agricultural water consumption decreased year by year, domestic water consumption increased year by year, industrial water consumption was essentially maintained at a stable level.

Table 3 Well fields launched or proposed for emergency water supply in the Beijing area (after Zhang and Ye, 2008)

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Capability for water supply (10^7 m³/a)</th>
<th>Current status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Huairou well field</td>
<td>pore groundwater</td>
<td>0.12</td>
<td>Constructed</td>
</tr>
<tr>
<td>Juna Well field</td>
<td>pore groundwater</td>
<td>0.02</td>
<td>Not yet constructed</td>
</tr>
<tr>
<td>Zhangfang-Changgou Well field</td>
<td>karst groundwater</td>
<td>0.07</td>
<td>Constructed</td>
</tr>
<tr>
<td>Xijiai Well field</td>
<td>karst groundwater</td>
<td>0.04</td>
<td>Not yet constructed</td>
</tr>
<tr>
<td>Changping Well field</td>
<td>karst groundwater</td>
<td>0.04</td>
<td>Constructed</td>
</tr>
<tr>
<td>Pinggu-Shunyi Well field</td>
<td>upper pore and lower karst</td>
<td>0.1</td>
<td>Constructed</td>
</tr>
<tr>
<td></td>
<td>groundwater</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>0.39</td>
<td></td>
</tr>
</tbody>
</table>
after 2007, and environmental water consumption increased year by year, with an especially rapid increase after 2014.

3.2.1 Water saving from agriculture
From 1999 to 2004, the irrigated area around Beijing decreased from $3.38 \times 10^6$ ha to $23.6 \times 10^4$ ha. After 2004, the irrigated area remained almost constant, within the range of $23.3 \times 10^4$ ha to $22.1 \times 10^5$ ha (Li Lun et al., 2011). Agricultural water use accounts for 60% of the total consumption of water resources in the Beijing area for the year 2000. In order to save water in agricultural activities, the following measures have been taken. Firstly, agricultural production has been gradually adjusted and the ratio of agricultural crops with less water demand increased. Secondly, intelligent flow meters were adopted to monitor water utilization in the field and an irrigation quota for water has been implemented. Currently, all agricultural wells in Beijing are equipped with flow meters. Prepaid

Table 4 Change of water use structure in some districts (counties) in Beijing (Unit: $10^4$m$^3$)

<table>
<thead>
<tr>
<th>Year</th>
<th>Urban area</th>
<th>Huaireou District</th>
<th>Miyun County</th>
<th>Business area</th>
<th>Huaireou District</th>
<th>Miyun County</th>
<th>Business area</th>
<th>Domestic use</th>
<th>Huaireou District</th>
<th>Miyun County</th>
<th>Business area</th>
<th>Water for environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>4292</td>
<td>4936</td>
<td>3742</td>
<td>7902</td>
<td>35336</td>
<td>1368</td>
<td>639</td>
<td>591</td>
<td>36983</td>
<td>14008</td>
<td>2936</td>
<td>1292</td>
</tr>
<tr>
<td>2007</td>
<td>4017</td>
<td>3999</td>
<td>7415</td>
<td>33601</td>
<td>1807</td>
<td>657</td>
<td>367</td>
<td>45594</td>
<td>1315</td>
<td>1870</td>
<td>1214</td>
<td>64286</td>
</tr>
<tr>
<td>2008</td>
<td>3442</td>
<td>4283</td>
<td>7211</td>
<td>29481</td>
<td>1250</td>
<td>565</td>
<td>404</td>
<td>48449</td>
<td>1408</td>
<td>1785</td>
<td>1429</td>
<td>72437</td>
</tr>
<tr>
<td>2009</td>
<td>4522</td>
<td>4251</td>
<td>7164</td>
<td>30185</td>
<td>620</td>
<td>551</td>
<td>341</td>
<td>51222</td>
<td>1618</td>
<td>1735</td>
<td>1513</td>
<td>29619</td>
</tr>
<tr>
<td>2010</td>
<td>3254</td>
<td>4607</td>
<td>6991</td>
<td>28432</td>
<td>551</td>
<td>556</td>
<td>290</td>
<td>51222</td>
<td>1702</td>
<td>1915</td>
<td>1499</td>
<td>32556</td>
</tr>
<tr>
<td>2011</td>
<td>2408</td>
<td>4003</td>
<td>6886</td>
<td>27001</td>
<td>704</td>
<td>577</td>
<td>356</td>
<td>52281</td>
<td>1933</td>
<td>1916</td>
<td>1508</td>
<td>33623</td>
</tr>
<tr>
<td>2012</td>
<td>4230</td>
<td>3628</td>
<td>5429</td>
<td>24826</td>
<td>844</td>
<td>590</td>
<td>354</td>
<td>54094</td>
<td>1929</td>
<td>2021</td>
<td>2015</td>
<td>32626</td>
</tr>
<tr>
<td>2013</td>
<td>5219</td>
<td>3467</td>
<td>5219</td>
<td>25802</td>
<td>890</td>
<td>624</td>
<td>361</td>
<td>56302</td>
<td>1828</td>
<td>1976</td>
<td>1828</td>
<td>31947</td>
</tr>
<tr>
<td>2014</td>
<td>895</td>
<td>2468</td>
<td>3183</td>
<td>4926</td>
<td>671</td>
<td>648</td>
<td>359</td>
<td>58407</td>
<td>1887</td>
<td>2068</td>
<td>1744</td>
<td>38914</td>
</tr>
<tr>
<td>2015</td>
<td>969</td>
<td>2367</td>
<td>3653</td>
<td>4644</td>
<td>873</td>
<td>563</td>
<td>350</td>
<td>49344</td>
<td>1820</td>
<td>2024</td>
<td>1617</td>
<td>41159</td>
</tr>
<tr>
<td>2016</td>
<td>997</td>
<td>1970</td>
<td>2807</td>
<td>4396</td>
<td>829</td>
<td>426</td>
<td>350</td>
<td>49381</td>
<td>2319</td>
<td>2022</td>
<td>1889</td>
<td>53715</td>
</tr>
</tbody>
</table>
memory cards have been connected to the flow meters to control the operation of irrigation wells. Thirdly, the traditional irrigation method of flood irrigation has been substituted by more efficient spray, drip, and micro irrigation methods. Through these methods the irrigation efficiency has been increased to 85–90%, and the irrigated area where the water saving irrigation methods are applied is now 2.04×10^6 ha, accounting for 90% of the total irrigated area. Through the activities described above, the quantity of water used for agricultural activities decreased from 1.7×10^8 m^3 in 2001 to 6.0×10^7 m^3 in 2016 (a decrease of 32.5%, see Fig. 12).

3.2.2 Water saving in industrial activities

Three measures were taken in order to save water in the industrial sector. Firstly, a regulation was issued in 2004 to constrain and forbid massive water consumption for water intensive industrial products. Secondly, from 2004, factories with high water consumption were moved into Beijing’s neighboring provinces and cities. Thirdly, the quota system of industrial production was introduced and implemented more strictly in the Beijing area. Industrial water consumption decreased from 9.2×10^8 m^3 in 2001 to 4.9×10^8 m^3 in 2012 (Beijing Statistical Bureau and Beijing Water Service Bureau, 2005; Beijing Water Bureau, 2012).

3.2.3 Water saving from domestic use

Two measures were implemented in order to save water in domestic use. Firstly, publicity activities were staged to improve the awareness of water saving among citizens in Beijing. Secondly, water saving taps were installed in the tap water system. By the end of 2005, the installation of the equipment in official buildings and households had reached 90% and 77%, respectively. However, it is very hard to give an accurate value of how much water was saved in domestic use since the population of Beijing is constantly changing.

3.3 Recycled water

Recycled water refers to treated sewage water or rain water. Since 2000, more than 30 sewage water treatment plants (biological treatment and chemical treatment) have been built and put into operation with a treatment capacity of 9.78×10^8 m^3/a. The rate of sewage water treated in Beijing city is now more than 90%. The recycled water is discharged to rivers and reused for irrigation. The amount of recycled water increased from around 6.4×10^6 m^3/a in the year 2000 to 7.5×10^6 m^3/a in 2012 (Beijing Statistical Bureau et al., 2005; Beijing Water Bureau, 2012).

3.4 Rain and flood water harvesting

Rain and flood water harvesting in Beijing consists of three types: the courtyard, the road and square, and green rain and flood water harvesting. The courtyard rain and flood water harvesting is focused on flood detention engineering in the process of planning new residential districts and reconstructing the old city districts. It aims to recharge groundwater through many infiltration pathways (e.g., infiltration wells and trenches), and to build rain and flood water harvesting facilities in order to store rain water for ecosystem conservation (Liu Jianping et al. 2009). The road and square rain and flood water harvesting is focused on the construction of parking lots and squares and the paving of sidewalks with permeable material in order to reduce rainfall runoff, while increasing the precipitation infiltration recharge of groundwater. The green rain and flood water harvesting is focused on changing the distribution of plants to increase precipitation infiltration over the green land.

Rain and flood water harvesting systems applied in the year 2000 are the major measures used to alleviate and control the risk and impact of floods during the flood periods in Beijing. By 2006, five types of rain and flood water collection systems had been established in six pilot areas, covering an area of 60 ha. (Zhang Shuhan et al., 2012).

Before 2004, the capacity for storing the rain and flood water in Beijing was 13×10^6 m^3/a. Through further efforts and construction of rain and flood water collection infrastructure, the quantity of rain water and flood water collected for utilization reached 30×10^6 m^3/a in the year 2006. The water collected from rain and floods is used as a substitute for fresh water in the irrigation of gardens.

3.5 Diversion of water from surrounding provinces

According to incomplete statistics, 2.3×10^8 m^3 of water was diverted from Shanxi province and Hebei province to
the Beijing area from 2003 to 2005. The amount of diverted water increased gradually from $4.3 \times 10^8$ m$^3$ in the year 2006 to $8.6 \times 10^8$ m$^3$ in 2012 (Beijing Statistical Bureau et al., 2005; Beijing Water Bureau, 2012).

4 Plan for Conjunctive Utilization of Local Groundwater and Diverted Surface Water

4.1 The features of the groundwater reservoir in the Beijing area

Groundwater overexploitation has resulted in the decrease of regional groundwater levels, especially in unconfined aquifers in alluvial fans and deep confined aquifers in the alluvial plain over the last 30 years or more. A huge storage space is available for artificial aquifer recharge in alluvial fans. By comparison of the groundwater level in December 1983 with that of June 2006, the total storage volumes in the alluvial fans of Chaobai river and Yongding river are calculated as about $1.62 \times 10^7$ m$^3$ and $7.97 \times 10^8$ m$^3$, respectively, in 2006, and both can serve as groundwater reservoirs. The groundwater reservoir for the Chaobai river catchment is about 397 km$^2$ in areal extent, with a thickness of about 65–160 m and a water table depth of 50–80 m. Infiltration tests showed that the river channel infiltration capacity is up to 37.82 m$^3$/s. The groundwater reservoir for the Yongding river catchment is about 333 km$^2$ in areal extent, with a thickness of 40 m and a water table near the aquifer base. The river channel infiltration capacity is up to 21.05 m$^3$/s.

4.2 Regulation of local groundwater and diverted surface water

It is planned to divert $1.0 \times 10^8$ m$^3$/a of water to Beijing after the completion of the STNWT project (Xu Xinyi, 2001; Zhao Shen, 2008). This is an average value over the long term. In fact, the diversion amount will be different from year to year according to the availability of water in the source region of the STNWT project. In a normal year, less groundwater resource will be needed since it will be replaced by the surface water resource, and during these times the regional groundwater level can recover gradually. In a wet year, not only will less groundwater abstraction be needed, but more diverted water can be used to recharge aquifers. Thus, in a dry year, more groundwater can be abstracted from the groundwater reservoirs, making effective conjunctive use of local groundwater and diverted surface water.

4.3 An effective groundwater monitoring network

The sustainable management of groundwater is dependent on reliable data. Among the most important data are groundwater level and quality. Therefore, it is important to set up and operate a monitoring network. Fig. 13, Fig. 14, and Fig 15 show the groundwater monitoring network which was established in the Beijing plain by the end of 2013, with a total of 615 monitoring wells, of which 303 are automated and 310 are manually measured. Along with groundwater level, temperature and water quality (including seven in-situ physical analytes and 28 inorganic and 36 organic chemical analytes) are observed. The monitoring frequency of groundwater level and its temperature in manual monitoring wells is every five days, and per hour in automated monitoring wells. The frequency of water quality monitoring is twice per year (Li Wenheng et al., 2010).

From Fig. 14, the rate of decline of groundwater level in the unconfined aquifer is less than that in the confined aquifer. This is because groundwater pumping is largely from the confined aquifer. The water in the unconfined aquifer is rarely pumped since the water quality is not good. After 2009, the head of confined aquifer began to stabilize due to a decrease in groundwater exploitation.

From Fig. 15, the rates of decline in groundwater level in the unconfined aquifer and shallow confined aquifers are lower than those in the deep confined aquifer. After 2014 the head in the confined aquifer began to stabilize due to a decrease in groundwater exploitation and other reasons, and the head in the third confined aquifer began to recover.

4.4 Sustainable development and management of groundwater resources

Sustainable development and management of groundwater resources depends on a number of factors: (1) pumping rates and patterns; (2) dynamic response of the aquifer system to pumping; and (3) potential socio-economic and environmental constraints. Groundwater simulation modeling is one of the best tools to analyze the dynamic response of the aquifer systems to pumping rates and locations. Therefore, a numerical model of the Beijing Plain was set up. The range of the model in the plains area of Beijing covers the whole of the pore groundwater system, with an area of about 6000 km$^2$. Aquifers of the plains area in Beijing are modeled as non-homogeneous and anisotropic in space. The main hydrological parameters consist of permeability coefficient, specific yield, and water storage coefficient. Hydrological parameters within each model partition are treated as homogeneous. Model partitions are assigned parameters based on appropriate geomorphologic units, sediment types, and formation lithologies. The initial parameters in each partition are estimated based on characteristics such as pumping test results, sediment types, formation
Fig. 13. Groundwater monitoring network in the Beijing area.

Fig. 14. Groundwater level fluctuation in the Chaobai river catchment for the period 1984 – 2017.

Fig. 15. Groundwater level fluctuation in the Yongding river catchment for the period 1984 – 2017.
lithology, etc., while also taking into account the parameters of the regional model. Generally, the vertical permeability coefficient is estimated as one-tenth of the horizontal permeability coefficient. Permeability coefficients are adjusted to calibrate models for steady flow and specific yield, and water storage coefficient is adjusted to calibrate models for unsteady flow.

According to many analyses of drilled rock, the aquifer system of the plains area of Beijing is divided into a multi-layer aquifer system, including five aquifers and four aquitards.

The model region is subdivided into an even grid of 1000 m × 1000 m. The model simulation period is from 1995 to 2005 and all groundwater recharge and discharge volumes are calculated monthly over the 11-year period of the model. We have used 11-year monthly observations of groundwater level to verify values calculated by the model during model calibration. A digital conceptual model was established using the GMS software, and groundwater flow was stimulated by a MODFLOW model.

Thus, the simulation model was used to estimate the increase in groundwater recharge and the decrease in discharge. The results show that artificial aquifer recharge and conjunctive use of groundwater and surface water are all suitable approaches to achieve sustainability in groundwater resources exploitation.

The exploitation of groundwater resources is not only related to economic and social benefits, but also related to technology, resources, environment, and other issues. According to the actual situation in Beijing, ten different strategies for groundwater exploitation are suggested. Based on the numerical model, the ten different strategies are modeled and compared via variation of groundwater amount, declination of groundwater level, and phreatic evaporation, and the optimal strategy of groundwater exploitation is determined.

The optimized strategy is to maintain the present total water supply of 34×10⁶ m³/a in Beijing city (Fig 9), of which, 3.0×10⁶ m³/a from local surface reservoirs, 6.0×10⁶ m³/a directly from the STNWT (this is the available amount of water in dry years in the diversion region), 18.0×10⁶ m³/a from groundwater, 7.0×10⁶ m³/a from recycled water. Meanwhile, the extra 2.2×10⁶ m³/a of the local surface reservoirs will be used for river channel ecological systems. Another 4.0×10⁶ m³/a from the STNWT will be recharged to the aquifer systems in the alluvial fans of Yongding river and Chaobai river through natural river channels with better permeability. 2.0×10⁶ m³/a groundwater exploitation will be reduced. Therefore, 6.0×10⁶ m³/a of water is available for aquifer recovery. The model shows that the groundwater level gradually restored through above joint use of surface water and groundwater for more than 40 years.

Overall, the STNWT project is function now. Until the middle of June in 2015, 0.27×10⁶ m³ water has been diverted to Beijing through the middle line of STNWT project, which accounts for 70% of total water consumption in Beijing. Around 10 million people benefit from it. Conjunctive use of surface and groundwater and the use of aquifers as a groundwater reservoir are important strategies to achieve sustainable management of water resources and to secure drinking water supplies for Beijing. Aquifers as groundwater reservoirs will reduce the evaporation and will also reduce and control land subsidence and earth fissures induced by differential settlement. Nowadays, our urgent task is to make efforts to transmit our project proposals into reality.

Beijing is located in the northwest of the north China plain, and the groundwater has a natural connection channel with the surrounding Hebei province and Tianjin city in terms of hydraulic connection. The exploitation of groundwater in Beijing will certainly have a certain impact on the groundwater resources in the surrounding provinces, especially the inter-basin water transfer has a greater impact on the surrounding water resources, but limited to the data reason, the quantitative conclusion is not yet available.

5 Conclusions

Beijing, a megacity plagued by acute water shortage, suffered from a consecutive drought period during 1999–2010, as well as from a significant decrease in incoming water due to the economic and social development in the upstream areas of the two largest rivers in the area: Yongding and Chaobai.

(1) Several measures were implemented to cope with the droughts, including pumping groundwater from emergency well fields, water saving, recycling of water, rain and flood water harvesting, and diverting water from neighboring rivers and groundwater basins. Among those measures, the pumping of groundwater from four emergency well fields contributes the most to the public and domestic water supplies in Beijing, providing a total volume of 1.78×10⁶ m³.

(2) The overexploitation of groundwater over a long time has resulted in some environmental problems, such as land subsidence and associated earth fissures. Those problems should be improved after the completion of the STNWT project. Under this project, more sustainable management of water resources will be implemented, including the use of aquifers as groundwater reservoirs and conjunctive use of surface water and groundwater resources.
Further research should be focused on the improvement and implementation of the methods for conjunctive use of local groundwater and surface water resources.

Acknowledgements

This article funding by Survey and evaluation of geological and mineral resources project: the Construction and Service of the National Groundwater and Land Subsidence Information System (No.DD2060299). The authors appreciate the help in English language made by Professor Zheng Chunmiao.

Manuscript received Oct. 12, 2017 accepted Jan. 20, 2018 edited by Liu Lian

References


Zhang Shuhan and Ding Yueyuan, 2012. Research and demonstration on techniques of rain and flood water collection and utilization, the second forum of science and technique of youth (in Chinese).


About the first author

LI Wenhong, male, han nationality, born in 1959, Shanxi Province, Wanrong county, have a long career in arid and semi-arid area hydrogeology survey, monitoring and research work.