Water scarcity in Beijing and countermeasures to solve the problem at river basins scale

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Abstract. Beijing has been subject to water scarcity in recent decades. Over-exploitation of water resources reduced water availability, and water-saving measures were not enough to mitigate the water scarcity. To address this problem, water transfer projects across river basins are being built. This paper assessed water scarcity in Beijing and the feasibility of solving the problem at river basins scale. The results indicate that there was an average annual water deficit of 13×10^8 m^3 y^{-1} in Beijing, which totaled 208.9×10^8 m^3 for 1998–2014, despite the adoption of various measures to alleviate water scarcity. Three of the adjacent four sub-river basins suffered a serious water deficit from 1998–2014. It was therefore impossible to transfer enough water from the adjacent river basins to mitigate the water scarcity in Beijing. However, the annual water deficit will be eliminated after the comprehensive operation of the world's largest water transfer project (the South-to-North Water Transfer Project, SNWTP) in 2020, but it will take approximately 200 years before Beijing's water resources are restored to the 1998 levels.

1. Introduction

Beijing is a megacity located in the semi-arid and semi-humid climate zone in north China. Water scarcity has constantly afflicted the city in recent decades, because the limited water resources cannot meet the demand for sustainable development in this area [1-3]. The annual freshwater availability is less than 119 $m^3 \cdot y^{-1}$ per capita in Beijing, far below the international water criterion of 1,000 $m^3 \cdot y^{-1}$ per capita [4]. Long-term over-exploitation of water resources has aggravated the severity of water scarcity. The over-exploitation of underground water was 2.6–2.7 billion $m^3 \cdot y^{-1}$ in Beijing, resulting in declining underground water levels of approximately 1 $m^3 \cdot y^{-1}$ in recent decades [5-10]. Underground water levels in the eastern part of Beijing were approximately 1 m below land surface in 1950, but then declined to 25 m in 2010 [11]. Because of the long-term over-exploitation, rivers have started to dry up, the level of underground water is declining, the lakes and wetlands in the regions around Beijing have been degraded [12-14]. This situation has caused a concern that water resource will be exhausted, resulting in increasing water scarcity.

Solving the water scarcity of Beijing is a major challenge. The average annual precipitation is only 420 mm–630 mm in most regions of Beijing [15], and the precipitation has decreased gradually at a rate of 4.96 mm/10a in recent years because of climate change [16]. Lack of precipitation is an important cause of water scarcity. Although many measures have been adopted to cope with water scarcity, such as re-using wastewater, utilizing recycled water, transferring water from adjacent regions, and cropping pattern changes, it is difficult to further reduce water demand (or water consumption) in Beijing because of its economic development and population growth [17-19]. The availability of water resources in the adjacent river basins declined in recent decades because of environmental changes [20].

However, an assessment of the feasibility to solve water scarcity by transfers from the adjacent river basins has not been done, and it is unclear whether the world's largest water transfer project (the South-to-North Water Transfer Project (SNWTP)) will ensure a comprehensive solution to water scarcity in Beijing. In this paper, the balance between water supply and demand in the adjacent river basins for 1998–2014 will be examined. The water scarcity and the feasibility of solving Beijing's water problems will be assessed at river basin scale. The role of the SNWTP in solving the water scarcity is also discussed. This study will contribute to solve water scarcity in larger cities by providing a practical case study of adaptation strategies.

2. Study Area

The study area covers not only the region of Beijing but also the adjacent Haihe River basin, and the other large river basins (the Yellow, the Huaihe, and the Yangze Rivers) through which the world's largest water transfer project (the SNWTP) runs.

Beijing is a megacity in northern China, located in the Haihe River basin (Fig. 1). The population in Beijing reached twenty-one million and seven hundred thousand in 2015, but its area is only 16,400 square kilometers approximately, with a mountain area of 10,000 square kilometers, and a plain area of 6,400 square kilometers. The climate belongs to the transition region between a semi-arid and semi-humid continental monsoon climate. The average annual temperature is 11–13°C in the plain area, and 9–11°C in mountain area. The average annual precipitation was 571.6 mm for 1961–2006 [16], but the average annual evaporation was 1791.5 ~ 1632.3 mm/y for 1960–2009.

The Haihe River basin, where Beijing is located, consist of four sub-river basins (the Luanhe, North Haihe, South Haihe, and Tuhai River basins). The western Haihe River basin are mountain ranges (Taihang and Yanshan Mountains) with temperate deciduous broad-leaved forest, and the eastern Haihe River basin is a vast plain (Haihe Plain) with crops of winter wheat and summer maize [21, 22] (**Fig. 1**). Irrigated-agriculture consumes a large amount of water [23, 24]. The average annual precipitation is 590 mm, and the potential evaporation is three times that of precipitation [25, 26].

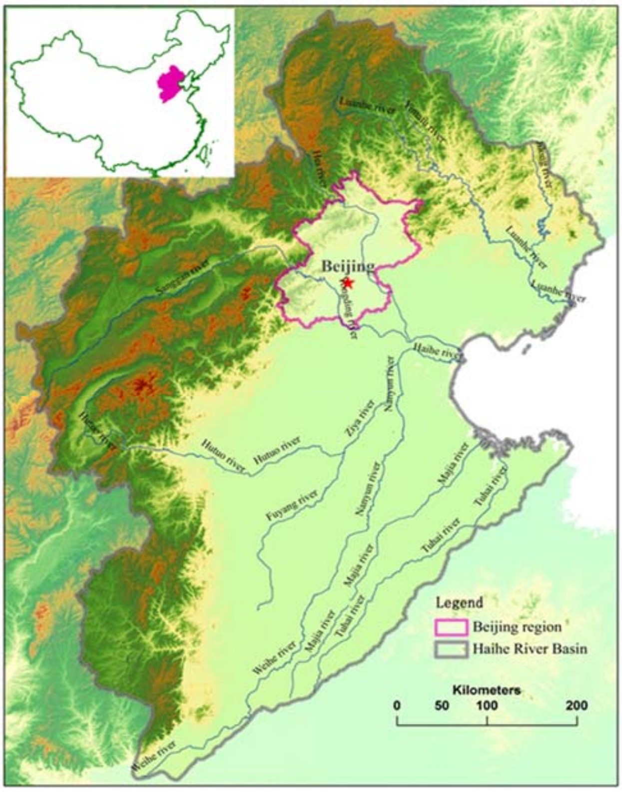

Figure 1. The location of Beijing and the Haihe River basin

The Chinese government launched the SNWTP in the 1980s to relieve the water shortage in North China, including Beijing [27]. The SNWTP consists of the east route project, the middle route project, and the west route project, running through the river basins of the Yangze, Huaihe, Yellow, and Haihe Rivers (**Fig. 2**). The SNWTP will be capable of transferring 44.8 billion m^3/y of water from the Yangze River into North China. The building of the east and middle route projects was completed in 2014, and are expected to be fully operational by 2020. The middle route project (running for 1,230 km) is planned to supply water to Beijing according to the original plan.

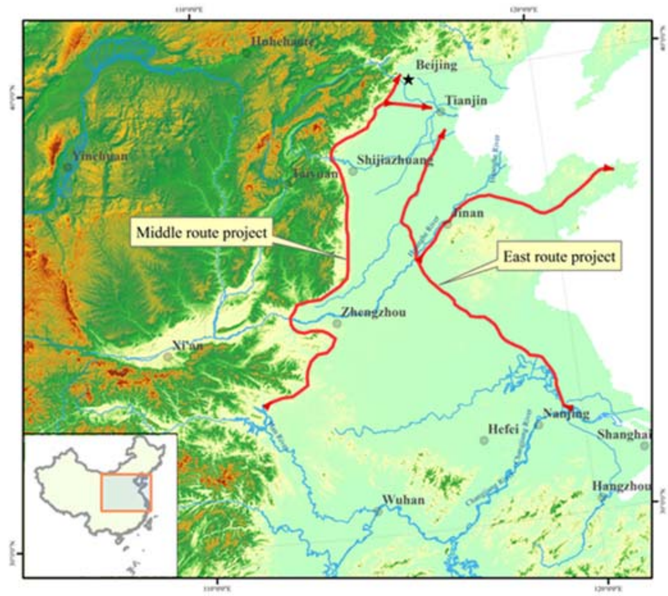

Figure 2. East Route and Middle Route of the South-to-North Water Transfer Project (SNWTP)

3. Material and Methods

The water supply-demand balance method was used to identify water scarcity. Annual water demand and supply at river basin scale were calculated. Water demand was determined from the actual consumption by agriculture, industry, service industries, and domestic use in one year. Water supply was determined from the annual renewable water resource.

(1) Quantity of water demand (Q_{wd})

The quantity of water demand was calculated by the original water volume taken directly from three water sources, including surface water, groundwater, and other water resources (such as treated wastewater, rainwater harvesting by cellars, rainwater tanks, and desalinated sea water). It was calculated as follows:

$$Q_{wd} = Q_S + Q_g + Q_o$$

Water demand from surface water resources (Q_s) was calculated as follows:

$$Q_s = Q_{st} + Q_d + Q_p + Q_t + Q_n$$

where Q_s is the volume of surface water, Q_{st} is the water volume from storage engineering, Q_d is the water volume from diversions storage engineering, Q_p is the water volume from pumping storage engineering, Q_t is the water volume from transfers storage engineering, and Q_n is the water volume from no-engineering.

Water demand from underground water resources (Q_g) was the sum of water volumes taken from wells, including shallow and deep wells.

Water demand from other water resources (Q_o) was the sum of water volumes taken from reused water after treatment (excluding water reused within a factory), rainwater gathered by rainwater harvesting facilities such as cellars and tanks, and fresh water from desalinated sea water.

(2) Quantity of water supply (Q_{ws})

The quantity of water supply was determined from the sum of surface runoff and infiltration from local precipitation.

In the mountain area, the total water supply was calculated by the drainage method. The formula is as follows:

$$W_1 = R + Q_g - R_g$$

where W_1 is the total water supply in the mountain area, R is the river runoff, Q_g is the total ground water drainage in the mountain area, and R_g is the river baseflow.

For the plain and plateau, the total water supply was calculated using the replenishment method. The formula is as follows:

$$W_2 = R + U_p - Q_{up}$$

$$Q_{up} \approx Q_r \left(U_p / U_t \right)$$

where W_2 is the total water supply for the plain and plateau, R is the river runoff, U_p is the infiltration from precipitation, Q_{up} is the river drainage resulting from infiltration, Q_r is the total river drainage, and U_t is the total ground water replenishment.

The water supply-demand balance method was used to assess water scarcity as a water deficit when annual water demand exceeded annual water supply for a given river basin. Water scarcity was also quantified by the Water Supply Stress Index (WSSI) which is defined as a ratio of water demand to water supply [28].

4. Results and discussion

4.1.Water scarcity and its causes in Beijing

The average annual water demand (or consumption) was 36.6×108 m3, and the average annual water supply was 23.6 × 108 m3 in the Beijing region from 1998–2014. In most years, annual water demand was higher than annual water supply (Fig. 3). The annual water demand varied between 40.5×108 m3 and 37.5×108 m3, with a slight decreasing trend as the result of water-saving measures. Annual water supply varied between 14.2×108 m3 and 39.5×108 m3 from 1998–2014. The imbalance between water demand and supply resulted in an average annual water deficit of 13×108 m3 y-1, totaled 208.9 ×108 m3 for the 1998–2014 period, despite the adoption of various water-saving measures.

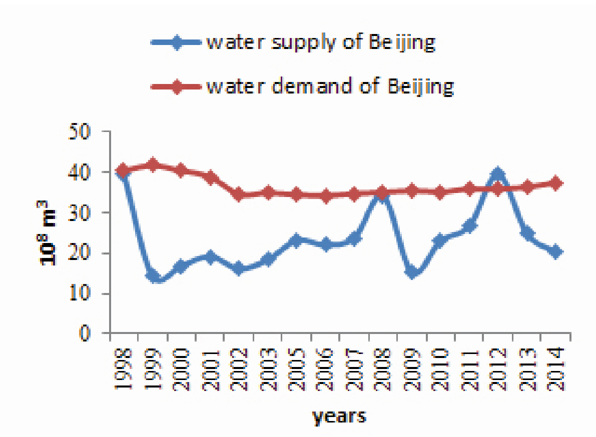

Figure 3. The annual water supply and demand in Beijing from 1998–2014

To explain the major causes of water scarcity in the Beijing region, the Pearson correlation analyses was applied to the relationships between water deficit, annual rainfall, annual average temperature, resident population, industrial water consumption, agricultural water consumption, and tertiary industrial and domestic water consumption. The analyses revealed that the water deficit was significantly correlated with annual precipitation (at the 0.01 level), industrial water consumption (at the 0.05 level) and agricultural water consumption (at the 0.05 level) (Table 1). The key factor affecting water scarcity was the annual precipitation. The average annual precipitation varied from 420 mm to 600 mm in different regions of Beijing [15], and the annual precipitation declined at a rate of 4.96 mm/10a in recent years [2]. However, the increasing population did not exert a significant effect on the water deficit because water-saving measures contributed to reducing water demand.

Table 1. Pearson correlation between water deficit and other factors in Beijing

	annual precipitation	annual temperature	resident population	industrial consuption water	agricultural consuption water	tertiary industrial and domestic consuption water
Pearson correlation coefficient	-.861**	-.101	-.414	.512*	.501*	-.403
Sig. (2-tailed)	.000	.698	.098	.036	.041	.109
n	17	17	17	17	17	17

4.2.The efforts to solve Beijing's water scarcity by water-saving measures

Efforts have been made to combat the water scarcity by implementing various water-saving measures, such as re-using wastewater, utilizing recycle water, and cropping pattern changes [2, 18, 29]. The water-saving measures have achieved results. On the one hand, the annual water demand was reduced, leading to a decreasing water demand in Beijing since 1998 (**Fig. 3**). The decreasing water demand mainly resulted from the shrinking of water consumption in agricultural and industrial sectors [3, 30]. Water use efficiency in the agricultural sector was improved as a result of factors such as better-educated farmers, improved irrigation management, and advanced crop gene technologies [2, 22]. The implementation of water saving measures reduced the annual water demand by 4×10^9 m^3 in the last 20 years [26]. On the other hand, water supply increased as a result of the reclaiming of municipal wastewater and water recycling. Large numbers of municipal wastewater treatment plants have been constructed since 1990, promoting the large-scale use of reclaimed water in agricultural irrigation. The wastewater treatment capacity amounted to 3.56×10^6 m^3 per day in 2009 [31, 32]. The industrial sector improved water recycling. The efficiency of reclaimed water use reached 60% in 2009 in comparison to almost zero before 2000 [4].

Water-saving measures alleviated, but ultimately could not prevent water scarcity because there was no potential for further reductions in water demand, and there was still an average annual water deficit of 13×10^8 m^3 y^{-1} in Beijing after adopting water-saving measures.

4.3.The feasibility of solving water scarcity in Beijing by using transfers from adjacent river basins

To explore the feasibility of solving water scarcity of Beijing by transferring water from adjacent river basins, we examined the annual water supply and demand of the four sub-river basins (the Luanhe, North Haihe, South Haihe, and Tuhai river basins) in the Haihe river basin. A water deficit occurred in all of the sub-river basins, except for the Luanhe river basin (Fig. 4 and Table 2). There was an average water deficit of 20.01×108 m3 y-1 in the North Haihe river basin, 65.97×108 m3 y-1 in the South Haihe river basin, and 28.46×108 m3 y-1 in the Tuhai river basin. For the Haihe river basin as a whole (the four sub-river basins), there was a water deficit of 109.17 ×108 m3 y-1. Thus, the adjacent river basins have no surplus water to transfer to Beijing, except for the Luanhe river basin. Even if all the surplus water of 5.27×108 m3 y-1 in the Luanhe river basin was transferred to Beijing, it would be insufficient to offset the water deficit of 13×108 m3 y-1.

The water scarcity of the sub-river basins was also quantified by the WSSI (ratio of demand to supply). If WSSI >1, water scarcity occurred. The most severe case of water scarcity occurred in the Tuhai river basin (WSSI = 1.69), followed by the South Haihe river basin (WSSI =

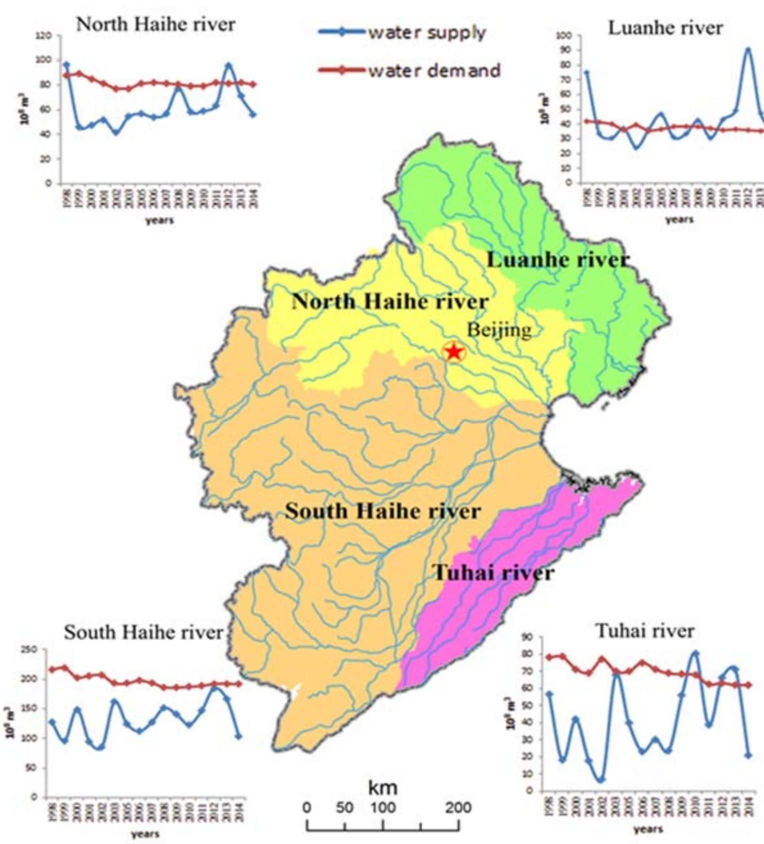

Figure 4. Annual water supply and demand for the four sub-river basins in the Haihe river basin from 1998–2014

1.50) and the North Haihe river basin (WSSI = 1.32). The Luanhe river basin, with relatively abundant water resourced, had a smaller WSSI of 0.88 (**Table 2**). In terms of the Haihe river basin as a whole there existed an obvious water scarcity (WSSI = 1.39).

It is, therefore, clear that a comprehensive solution to water scarcity in Beijing cannot be achieved by transferring water from the adjacent river basins.

Table 2. The average annual water supply and demand for the four sub-river basins in the Haihe River Basin from 1998–2014

	Luanhe river basin	North Haihe river basin	South Haihe river basin	Tuhai river basin	total
water supply (10^8 m^3 yr^{-1})	42.88	61.62	130.76	41.22	276.48
water demand (10^8 m^3 yr^{-1})	37.61	81.63	196.73	69.68	385.65
water deficit (10^8 m^3 yr^{-1})	no	20.01	65.97	28.46	109.17
WSSI (ratio of demand and supply)	0.88	1.32	1.50	1.69	1.39

4.4.The feasibility of solving Beijing's water scarcity by the SNWTP

The SNWTP was designed to transfer water from the Yangtze River to North China. The middle route project of the SNWTP has enabled Beijing to obtain an extra 10 ×10^8 m^3 y^{-1} since 2014 [33-35], and has greatly alleviated the water scarcity; the water from the SNWTP offsets 77% of Beijing's annual water deficit of 13×10^8 m^3 y^{-1}. It is expected that Beijing will receive 14×10^8 m^3 y^{-1} of water when the comprehensive operation of the SNWTP in 2020. If this is the case, the transferred water will exceed the average annual water deficit, and the water scarcity will be eliminated. However SNTWP transfers will take approximately 200 years to restore Beijing's water resources to their 1998 levels because there was an accumulated water deficit of 208.9 ×10^8 m^3 in Beijing during the 1998–2014 period.

5. Conclusions

Beijing has suffered serious water scarcity. There was an average water deficit of 13×10^8 m^3 y^{-1}, which totals 208.9 ×10^8 m^3 in Beijing from 1998–2014 even with the adoption of various water-saving measures. Insufficient annual precipitation was the key factor leading to insufficient water supply, and there was no potential for further reductions in water demand. Therefore, it was practically impossible to solve the water scarcity problem only by relying on water-saving measures. Three of the adjacent four sub-river basins in the Haihe River basin suffered serious water scarcity from 1998–2014. It would have been impossible to ensure a comprehensive solution to the water scarcity problems of Beijing by transferring water from the adjacent river basins. The comprehensive operation of the SNWTP has the capacity to ultimately eliminate water scarcity. However, it will take approximately 200 years before Beijing's water resources are restored to the 1998 levels. In summary, it is feasible to eliminate water scarcity in Beijing with the comprehensive operation of the SNWTP after 2020, although the restoration of water resources in Beijing will take a very long time.

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