Quantitative Impact and Research on Water Supply Management and Demand in Beijing under the WEAP Model

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Abstract. Predicting the future water supply and demand is an important basis for achieving optimal water resource allocation and serves as an effective methodology to solve the imbalances between water supply and demand in cities and achieve long-term stable supply and efficient water resource utilization. In this study, we use the water evaluation and planning (WEAP) model to quantitatively analyze the effects of the water resource policies on the balance between the supply and demand of water resources in Beijing and predict the water demand and shortages in Beijing from 2019 to 2035. The simulation results indicate that at the watershed scale, different levels of water shortage can be observed in the five major watersheds under different scenarios. By 2035, the unmet demand in the Beiyunhe river basin will be the most serious, accounting for $\geq 45.48\%$ of the total unmet demand. The policy constraints play a crucial role in alleviating the supply-and-demand imbalance of water resources. Different policies can be used to reduce the total water demand; however, the population growth control policies exhibit the greatest effect on the alleviation of water resource shortage in Beijing and can reduce the water demand by 3.42 million m\textsuperscript{3} when compared with that in a scenario without any control policy. The results of this study can provide important references to solve the urban water resource supply and demand imbalances and realize rational allocation of the water resources.

1. Introduction
As is typical for most cities, a prominent disparity can be observed between the supply and demand of water in Beijing; it has the lowest number of water resources per capita both in China and worldwide. The development of a city is directly influenced by the balance between the supply and demand of water [1]. According to the Beijing Water Resource Bulletin statistics, 2018, Beijing possesses per capita water resources of only 165m\textsuperscript{3}/person, which is considerably lower than the internationally recognized “extreme water shortage standard” of 500m\textsuperscript{3}/person and is less than 1/10 of China’s national average (1969m\textsuperscript{3}/person) [2]. This water scarcity is one of the primary constraints to Beijing’s sustainable development and is seriously affecting the coordinated development of Beijing–Tianjin–Hebei. Therefore, the Municipal People’s Government of Beijing has introduced the 13th Five-Year
Water Development Plan [3], which makes the scientific and accurate assessment of the gap between water supply and demands an urgent task, to resolve the shortage of water resources in Beijing, achieve rational allocation of the water resources, and ensure Beijing’s sustainable development.

Studies that have investigated the future water supply and demand can realize an important scientific basis for managing and allocating water resources [4]. Researchers have conducted many urban water resource prediction studies using various methods and models, including the artificial neural network models [5-8], time series prediction models [9-10], nonlinear dynamics methods [11], system dynamics models [12-14], and an analytic hierarchy process-fuzzy comprehensive evaluation method (AHP–Fuzzy) [15]. In addition, Mohamed [16] and Tiwari [17] conducted significant research on models to predict the water quantity. Although all these models have attempted to predict the water supply and demand, they suffer from major problems such as short prediction periods, complex application, and low accuracy. Currently, researchers increasingly favor the water resource assessment and planning (WEAP) model, which has been extensively and successfully applied worldwide [18-24]. The WEAP model can predict the water resource supply and demand much further into the future than other models and can be easily operated. However, compared with its application in other countries, the WEAP model is less commonly used in water resource research in China. Yang et al. [25]; Li et al. [26]; Song et al. [27]; Wang et al. [28]; Li and Li [29]; Wang et al. [30]; Yang et al. [31] and Xu and Zhang [32] explored the application of the WEAP model for studying the water resources in Beijing, the Tianjin Binhai New Area, Longkou, Dongzhi Loess Tableland, Zhejiang Xitiaoxi watershed, Shiyang River, Yarkant River, and the main stream of the Tarim River. In addition, some researchers have examined the influencing factors, such as population growth [33-34], land use change [35-36] and climate change [37-39], which result in water shortage.

Current research indicates the lack of in-depth quantitative analysis with respect to the impacts of the control policy on water supply and demand [40]. The governments of China and Beijing have presented a series of new policies, i.e., “The Coordinated Development Plan for the Beijing–Tianjin–Hebei Region”, [41] “General Office of the CCP Beijing Municipal Committee and General Office of the Beijing Municipal People’s Government: Opinions on Implementing “The Coordinated Development Plan for the Beijing–Tianjin–Hebei Region”, [42] and “Beijing Urban Master Plan (2016–2035)”, [43] to solve the challenge of water shortage with respect to Beijing’s development. These policies can control the rapid growth of population. Furthermore, the policy of “Opinions on Comprehensively Promoting the Construction of a Water-Conserving Society” [44] is intended to strengthen the industrial and agricultural water conservation management in Beijing. However, the impact of these water resource policies on Beijing’s water security remains unclear. Therefore, in this study, we explore the quantitative effects of the policy constraints on the supply and demand of water resources. The specific objectives of this study are to assess the quantitative impact of the policy constraints on water demand and water shortage in Beijing, considering the accurate evaluation of the gap between water supply and demand as the breakthrough point, and introduce proposals to ensure Beijing’s water security in the future (2020–2035).

2. Study area
Beijing is located in the northern part of the North China Plain (39°28′N–41°05′N; 115°25′E–117°30′E), backed by the Yan mountains, and is adjacent to the Tianjin and Hebei Province (Fig. 1). It has a typical warm-temperate continental monsoon climate with four seasons. Between 2010 and 2018, the average annual temperature was approximately 12.9°C and the average annual precipitation was 588 mm, which was primarily concentrated between June and September, accounting for >80% of the annual precipitation.

2.1. Watershed distribution
Beijing is located in the Haihe river basin, which comprises five major river systems, i.e., the Daqing, Yongding, Beiyun, Chaobai, and Jiyun river systems, flowing from west to east. Apart from the Beiyunhe river system, which originates within the boundaries of the Beijing municipality, the
remaining rivers flow into the city from other provinces. The five major river systems include five main rivers, i.e., Jumahe, Yongdinghe, Beiyunhe, Chaobaihe, and Jiyunhe, the Guanting and Miyun reservoirs, the Yongding Canal, the Jing-Mi Channel, and the Tonghuihe and Beiyunhe water-crossing channels (Fig. 1).

Figure 1. Administrative districts and counties and catchment distribution of the Beijing municipality.

2.2. Water supply

The water resources that are available in Beijing comprise surface water, groundwater, reclaimed water, and water transfer from the south to the north. Beijing’s water supply is primarily based on groundwater, accounting for 51% of its total water consumption, whereas the proportion of surface water and reclaimed water is considerably less. Herein, we will not consider exotic water resources, such as water transfer from the south to the north, because we examine the supply of natural water resources in Beijing and focus on the effects of the policies that control population growth as well as industrial and agricultural water conservation.

The groundwater and surface water recharge in Beijing primarily depends on precipitation. Recently, decreased precipitation (Fig. 2) has resulted in similar trends with respect to the surface water and groundwater in Beijing. Based on the Beijing Water Resource Bulletin statistics, the average annual amount of surface water resources from 2010 to 2018 was 907 million m³, whereas the amount of groundwater resources was 1.699 billion m³. Thus, the total amount of surface water and groundwater resources was 2.606 billion m³, which is 30.3% less than the multiyear average (1956–2000) of 3.739 billion m³ (Fig. 3).

Figure 2. Yearly precipitation in Beijing between 2010 and 2018.
2.3. Water demand
The water use situation of Beijing was analyzed based on the data obtained from the Beijing Water Resource Bulletin. The water use structure, including domestic water, environmental water, industrial water, and agricultural water, was stable between 2010 and 2018. The domestic water consumption initially increased and subsequently decreased, peaking in 2015. It drastically increased from 28.5% to 33% during 2010–2015. This can be attributed to the population growth and the changes in the way in which people use water. Domestic water consumption remained unchanged between 2016 and 2018 because of controlled population growth. Both agricultural and industrial water consumption showed declining trends. This can be attributed to the implementation of water-saving policies in industry and agriculture. However, environmental water consumption has increased annually to ensure the ecosystem’s ecological health and increased public green space area, and its share in the total water consumption has gradually increased (Fig. 4).

2.4. Analysis of Beijing’s water resource policies

2.4.1. Policies affecting domestic water use. Beijing’s population growth has decreased the per capita water resources. The policies, including “Coordinated Development of Beijing–Tianjin–Hebei Region,” issued by the Political Bureau of the Central Committee (March 23, 2015), “Opinions on Implementing ‘Coordinated Development Plan of Beijing–Tianjin–Hebei Region’ (July 12, 2015),” and “Beijing Urban Master Plan (2016–2035) (September 29, 2017),” issued by the General Office of the CCP Beijing Municipal Committee and the General Office of the Beijing Municipal People’s Government, have strictly proposed controlling the population growth by “control” and “evacuation”
to maintain the population within 23 million by 2020. The aim is to reduce the population growth rate, i.e., control the number of people, for relieving the pressure on water supplies caused by the considerably rapid population growth in Beijing. Therefore, in this study, a quantitative method is used to focus on the impact of the population control policies on the balance between the supply and demand of water resources.

2.4.2. Policies for regulating the industrial water use. “Opinions on Comprehensively Promoting the Construction of a Water-Conserving Society,” issued by the Beijing Municipal People’s Government (February 5, 2016), stated that the water consumption per 10,000-yuan industrial added value will be reduced to less than 10 m³ by 2020 and that the efficiency of water use will be significantly improved to become greater than the 18.5 m³ level in 2010, reducing the industrial water consumption. Therefore, this study has adopted a quantitative method to focus on the impact of the management policy with respect to the water consumption per 10,000-yuan industrial added value on the balance between water supply and demand.

2.4.3. Policies affecting agricultural water use. Currently, the agricultural water in Beijing is primarily used for irrigation. We can reduce the agricultural water use using two approaches, i.e., by changing the crop planting area and the effective utilization coefficient of irrigation water. According to “Opinions on the Development of High-Efficiency and Water-Saving Agriculture by Adjusting the Structure and Transforming the Mode” (September 4, 2014) issued by the General Office of the CCP Beijing Municipal Committee and the General Office of the Beijing Municipal People’s Government, the planting area of water-intensive winter wheat can be considerably reduced by adjusting the planting structure. According to the “Opinions on Comprehensively Promoting the Construction of a Water-Conserving Society” issued by the Beijing Municipal People’s Government (February 5, 2016), the agricultural water consumption in Beijing will be controlled to become less than 500 million m³ by 2020. Furthermore, the effective utilization coefficient of the farmland irrigation water will increase from 0.684 in 2010 to >0.75 in 2020. Thus, agricultural water consumption will decrease annually through efficient water-saving irrigation. Therefore, the quantitative effects of the crop planting area and effective utilization coefficient of the irrigation water on supply and demand balance of water are discussed.

The aforementioned policies have clear requirements with respect to domestic, industrial, and agricultural water usage. However, this study will not discuss the environmental water policy because there is no specific management policy with respect to environmental water.

3. Methods and data
First, we preprocessed the collected data; then, to satisfy the requirements of the WEAP model, the preprocessed data were further processed through gridding and masking in ArcGIS. Subsequently, the scenario analysis of the WEAP model was used to simulate the effects of policies on Beijing’s future water resources and compare the effects of different policies. Finally, we evaluated the results based on the research requirements and obtained conclusions.

3.1. Data sources
The data used in this study included the water supply and demand sides and influencing factors. The water supply side included hydrological distribution, surface runoff, groundwater, reservoirs, wastewater treatment plants, and meteorological data. The water demand side included domestic water, industrial water, agricultural water, and environmental water. The influencing factors included policies, population, water consumption per 10,000-yuan industrial added value, and crop planting area (Table 1).
Table 1. Data sources used in the Beijing’s WEAP generalization model.

| Data type               | Scale               | Description                                           | Source                                                                 |
|-------------------------|---------------------|-------------------------------------------------------|------------------------------------------------------------------------|
| Water supply            | Hydrology           | 1:250,000                                            | Rivers; reservoir distribution                                          | National Administration of Surveying, Mapping and Geoinformation       |
|                         | River flow          | Daily (2010–2018)                                    | Streamflow (Chaobaihe; Beiyunhe; Yongdinghe; Jumahe; Jiyunhe)          | Beijing Water Authority                                               |
|                         |                     |                                                      |                                                                        | http://www.bjwater.gov.cn/                                           |
|                         | Groundwater         | Yearly (2010–2018)                                   | Ground water initial storage; maximum withdrawal                       | Beijing Water Statistical Yearbook; Beijing Water Resource Bulletin; Ground Water Dynamic Monthly |
|                         | Reservoir           | Daily (2010–2018)                                    | Reservoir’s volume, elevation, and inflow (Miyun, Guanting)            | Beijing Water Authority                                               |
|                         |                     |                                                      |                                                                        | http://www.bjwater.gov.cn/                                           |
|                         | Wastewater treatment plant | Yearly (2010–2014)                                   | Daily capacity; consumption                                           | Beijing Water Statistical Yearbook                                    |
|                         | Meteorology         | Daily (1951–2018)                                    | Precipitation; Temperature; Humidity; Wind speed; Cloudiness           | National Meteorological Information Center                           |
|                         |                     |                                                      |                                                                        | http://data.cma.cn/                                                   |
| Water demand            | Domestic water      | Yearly (2010–2018)                                   | Annual water use rate; consumption; reuse rate                         | Beijing Water Saving Data Compilation                                 |
|                         | Environmental water | Yearly (2010–2018)                                   | Annual water use rate; consumption; reuse rate                         | Beijing Water Saving Data Compilation                                 |
|                         | Industrial water    | Yearly (2010–2018)                                   | Annual water use rate; consumption; reuse rate                         | Beijing Water Saving Data Compilation                                 |
|                         | Agricultural water  | Yearly (2010–2018)                                   | Annual water use rate; consumption; reuse rate                         | Beijing Water Saving Data Compilation                                 |
| Influence factors       | Policies            | Yearly (2010–2018)                                   | Annual water use rate; consumption; reuse rate                         | Beijing Water Saving Data Compilation                                 |
|                         | Population          | Yearly (2009–2018)                                   | Population of each administrative district                             | Beijing Statistical Yearbook                                           |
|                         | Industrial added value | Yearly (2009–2017)                              | Ten thousand yuan                                                     | Beijing Statistical Yearbook                                           |
|                         | Water consumption of per ten thousand yuan industrial added value | Yearly (2009–2017)                                  | Cubic meter / ten thousand Yuan                                        | Beijing Water Saving Data Compilation                                 |
|                         | Land use             | 1:250,000                                            | Forest land, construction land, grassland, farm land, water area       | National Administration of Surveying, Mapping and Geoinformation      |
|                         | Farmland             | Yearly (2009–2017)                                   | Crop planting area                                                    | Beijing Water Authority                                               |
|                         |                     |                                                      |                                                                        | http://www.bjwater.gov.cn/                                           |
|                         | Unit irrigation water | Yearly (2009–2017)                              | Cubic meter / acre; Effective utilization coefficient                  | Beijing Water Saving Data Compilation                                 |
3.2. Data conversion and mask using ArcGIS

The data regarding water usage for each watershed formed a crucial part of the demand-side input of the WEAP model; thus, this data must be obtained based on the existing data. ArcGIS is used to process the base map of 16 administrative districts in Beijing and convert the vector data into a grid. The vector data of each watershed are extracted, and the raster data of the administrative regions are masked. The number of administrative districts and cells in each watershed are estimated; subsequently, in accordance with the proportion of administrative districts in each watershed, the water usage of each watershed was calculated based on that of the administrative district.

3.3. WEAP model

3.3.1. WEAP model description. The WEAP model, developed by the Stockholm Environment Institute’s US Center (SEI–US) [45], is unique because it can give equal weight age to the demand and supply sides of the equation and evaluate the water supply policy and water resource planning for a single watershed or complex trans-boundary basin systems. Furthermore, the priorities for allocating water for specific demands or from particular sources may be specified by the user. The basis of the WEAP model is scenario analysis, which can be used to evaluate the water resource availability, social and economic activities related to water resources, and current and future allocation of water resources.

3.3.2. Beijing’s WEAP generalization model. The water system of Beijing’s five watersheds is generalized as a network comprising water supply systems, including rivers, groundwater units, wastewater treatment plants, and reservoirs, and water demand systems, such as domestic usage, industrial usage, agricultural usage, and environmental usage. The water system is characterized by five watershed nodes, five rivers, five groundwater nodes, five wastewater treatment plant nodes (one for each watershed area), two reservoir nodes, 20 demand site nodes, 10 runoff/infiltration links, 25 transmission links, and 20 return flows (Fig. 5). The reservoir water resources are currently used only for emergency response because of their decrease in successive years; thus, there is no relation between the reservoirs and the generalization model.

![Figure 5. The schematic model of the Beijing WEAP.](image)

3.4. Model verification

Here, we verify the model based on the calculation results of current accounts (2010) using the WEAP model with the relevant statistical data in 2010. The total water demand of Beijing in 2010 calculated
by the WEAP model was 2.828 billion m³, with an unmet demand of approximately 621 million m³. Beijing had a water shortage of 532 million m³ in 2010 based on the statistics of water demand and survey. This is approximately equal to the unmet demand calculated using the WEAP model; thus, the Beijing hydrological generalization model established in this study is reliable.

3.5. Key assumptions
Based on the characteristics of Beijing’s water use structure, the population growth rate, rate of change in water consumption per 10,000-yuan industrial added value, the rate of water use per unit of irrigation change, and the change rate in crop planting area were selected as key assumptions (Table 2). This study selected 2010 as the current accounts and used 2019–2035 as the planning period to quantitatively assess the effects of the implementation of various policies on the balance between future water supply and demand in Beijing. In 2010, the State Council formally approved the Beijing Municipal People’s Government’s request to adjust the administrative divisions of the capital’s functional core zone. It agreed to combine Beijing’s Dongcheng and Chongwen districts into a new Dongcheng District and to combine the Xicheng and Xuanwu districts into a new Xicheng District. The following is the basis for setting each parameter.

The basis of parameters of current accounts (2010) is as follows. Based on the population, crop planting area, effective utilization coefficient of irrigation water, and water withdrawal per 10,000-yuan of industrial added value in the statistical yearbook of 2009–2010, the population growth rate, change rate of crop planting area, change rate of water consumption per unit of irrigation (eqn (1)), and change rate of water use per 10,000-yuan of industrial added value in 2010 were calculated to be 5.48%, −0.89%, −4.11%, and −18.14%, respectively.

The effective utilization coefficient of irrigation water refers to the ratio of the water $W_e$ (net irrigation water) that can be used by crops in the field to the total amount of irrigation water $W_a$ (the amount of irrigation water) obtained from the water source and can be expressed as follows [46]:

$$\eta_w = \frac{W_e}{W_a} \tag{1}$$

where $W_e$ is the water that can be used by crops in the irrigation area (m³) obtained through the field monitoring, test results, field research, and other methods, whereas $W_a$ is the total amount of irrigation water obtained from the water source in the irrigation area (m³). The well irrigation area is measured by installing a water meter in the first part of the well, and the irrigation area combined with surface and well water can be calculated using the water level–flow relation.

Parameter settings of the reference years (2019–2035).

(1) Population growth rate: “Coordinated Development Plan of Beijing–Tianjin–Hebei Region,” issued in 2015, stipulates that the population should be controlled to be within 23 million by 2020. Therefore, this study considers 2015 as the time node and divides the time span into two periods, i.e., 2010–2015 and 2015–2020. At the end of 2010 and 2015, the resident population of Beijing was 19.6 and 21.7 million, respectively. The real annual growth rate from 2010 to 2015 was 2.04%, which was set for the calculation as the population growth rate without any policy constraints. The theoretical average annual growth rate from 2015 to 2020 was 1.17%, and this parameter was set as the population growth rate under the policy constraint (Table 3).

(2) The change rate of crop planting area: In 2014, “Opinions on the Development of High-Efficiency and Water-Saving Agriculture by Adjusting the Structure and Transforming the Mode” proposed significant reduction in the planting area of water-intensive winter wheat; however, the planting area expected by 2020 was not specified. Based on the collected data, 2014 was used as the time node, and the time span was divided into two periods, i.e., 2010–2014 and 2014–2017. The crop planting areas in 2010, 2014, and 2017 were 317,270, 199,961, and 125,907 hectares, respectively. The average annual change rate from 2010 to 2014 was −10.9%, which was set as the change rate of the crop planting area without a policy constraint parameter. From 2014 to 2017, the average annual
The change rate was $-14.29\%$, which was set as the change rate of the crop planting area under the policy constraint parameter (Table 3).

(3) Change rate of per unit of irrigation: “Opinions on Comprehensively Promoting the Construction of a Water-Conserving Society” proposes that the effective utilization coefficient of farmland irrigation water will increase from 0.706 in 2014 to $>0.75$ in 2020. Therefore, considering 2014 as the time node, the time span can be divided into two periods, i.e., 2010–2014 and 2014–2020. The effective utilization coefficients of irrigation water in 2010, 2014, and 2020 were 0.684, 0.706, and 0.75, respectively. The actual average annual change rate from 2010 to 2014 was 0.79%; thus, a parameter of $-0.79\%$ was set as the change rate of per unit irrigation water (eqn (1)) without any policy constraints. From 2014 to 2020, the theoretical average annual change rate was 1.01%; thus, a parameter of $-1.01\%$ was set as the change rate of per unit irrigation water under the policy constraint (eqn (1)) (Table 3).

(4) Change rate of water consumption per 10,000-yuan industrial added value: “Opinions on Comprehensively Promoting the Construction of a Water-Conserving Society” proposed reducing Beijing’s water consumption per 10,000-yuan industrial added value, and it was decreased from 13.6m³ in 2014 to $<10$m³ in 2020. By 2017, it had decreased to 7.98m³. Therefore, 2014 was considered to be the time node, and the time span was divided into two periods, i.e., 2010–2014 and 2014–2017. In 2010, 2014, and 2017, the water consumption per 10,000-yuan industrial added value was 18.5, 13.6, and 7.98m³, respectively. The average annual change rate from 2010 to 2014 was $-7.4\%$. Thus, this parameter was set as the change rate of water use per 10,000-yuan industrial added value without any policy constraints. From 2014 to 2017, the average annual change was $-16.28\%$, and this parameter was set as the water use change rate per 10,000-yuan industrial added value under policy constraints (Table 3).

### Table 2. Key assumptions of Beijing’s WEAP generalization model (unit: %).

| Key assumptions                                      | Current Accounts (2010) | Reference scenario (2019-2035) without policy control | Reference scenario (2019-2035) with policy control |
|------------------------------------------------------|------------------------|------------------------------------------------------|---------------------------------------------------|
| Population growth rate                               | 5.48                   | 2.04                                                 | 1.17                                              |
| The rate of change of water use per unit of irrigation change | $-4.11$                | $-0.79$                                              | $-1.01$                                           |
| The rate of change in crop planting area             | $-0.89$                | $-10.9$                                              | $-14.29$                                          |
| The rate of change of water consumption per 10,000-yuan industrial added value | $-18.14$               | $-7.4$                                                | $-16.28$                                          |
Table 3. Three Scheme comparing.

| Code | Scenario          | Population growth rate | The rate of change of water use per unit of irrigation change | The rate of change in crop planting area | The rate of change of water consumption per 10,000-yuan industrial added value | Parameter setting basis                                                                 |
|------|-------------------|------------------------|-------------------------------------------------------------|----------------------------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|
| 1    | Reference         | 5.48                   | −4.11                                                      | −0.89                                  | −18.14                                                                         | Same as the Current Accounts (2010)                                                   |
| 2    | Population without policy control | 2.04                   | −4.11                                                      | −0.89                                  | −18.14                                                                         | Beijing Statistical Yearbook; the real annual growth rate from 2010 to 2015          |
| 3    | Population with policy control | 1.17                   | −4.11                                                      | −0.89                                  | −18.14                                                                         | "Coordinated Development Plan of Beijing-Tianjin-Hebei region"; the theoretical average annual growth rate from 2015 to 2020 |
| 4    | Water use of irrigation without policy control | 5.48                   | −0.79                                                      | −0.89                                  | −18.14                                                                         | Beijing Water Saving Data Compilation; the actual average annual change rate from 2010 to 2014 |
| 5    | Water use of irrigation with policy control | 5.48                   | −1.01                                                      | −0.89                                  | −18.14                                                                         | “Opinions on Comprehensively Promoting the Construction of a Water-Conserving Society”; the theoretical average annual change rate from 2014 to 2020 |
| 6    | Crop planting area without policy control | 5.48                   | −4.11                                                      | −10.9                                  | −18.14                                                                         | Beijing Water Authority; the average annual change rate from 2010 to 2014            |
| 7    | Crop planting area with policy control | 5.48                   | −4.11                                                      | −14.29                                 | −18.14                                                                         | “Opinions on the Development of High-efficiency and Water-saving Agriculture by Adjusting the Structure and Transforming the Mode”; the average annual change rate from 2014 to 2017 |
| 8    | Water use of industry without policy control | 5.48                   | −4.11                                                      | −0.89                                  | −7.4                                                                           | Beijing Statistical Yearbook; the average annual change rate from 2010 to 2014       |
| 9    | Water use of industry with policy control | 5.48                   | −4.11                                                      | −0.89                                  | −16.28                                                                         | The “Opinions on Comprehensively Promoting the Construction of a Water-Conserving Society”; the average annual change rate from 2014 to 2017 |
4. Results and analysis

4.1. Effects of population growth rate regulation

Only the changes in population growth rate were analyzed to quantitatively study the effects of population growth rate on the balance between supply and demand of water in Beijing, with the remaining influencing factors set to be unchanged. The population is estimated to become 30.35 million by 2035 without control policies (growth rate of 2.04%); thus, the water demand will show an increasing trend. The impact of high population growth on water demand is reflected in an increase from 2.828 billion m³ in 2010 to 4.4 billion m³ in 2035. However, the population is expected to reach 21.04 million by 2035 if it is strictly controlled by policies (growth rate of 1.17%). Furthermore, water demand shows an upward trend in this scenario even though it is significantly slower than that with no policy control. The total water demand in the policy control scenario increased from 2.828 billion m³ in 2010 to 4.058 billion m³ in 2035 (Fig. 6). We can observe that the policy for regulating the population growth plays an important role by analyzing the water resource demand under different population growth rates. However, even with a low population growth rate, there will still be water shortage with an estimated unmet demand of approximately 923 million m³ by 2035. From the watershed scale perspective, the water shortage in the Beiyunhe river basin is the most significant (456 million m³), accounting for 49.43% of the total unmet demands (Fig. 7). It is likely that the six central districts of Beijing are concentrated in the Beiyunhe river basin and have a greater population density than the other watersheds.

![Figure 6. Water demand under different population growth rates.](image)

![Figure 7. Unmet water resource demand in a population-controlled policy scenario in 2035.](image)
4.2. Effects of the industrial water-saving policy

We quantitatively determined the influence of the industrial water-saving policy on the balance of supply and demand of water by changing the water use per 10,000-yuan industrial added value and keeping the remaining influencing factors unchanged. In a scenario without policy control (rate of change of −7.4%), the overall water demand shows a decreasing trend, with a total water demand of 3.213 billion m³ being observed in 2035. There is a local increasing trend from 2019 to 2021, which can be attributed to the impact of industrial water saving on the overall water demand being less than the impact of industrial value-added growth of 10,000 yuan on the overall water demand. The scenario with policy constraints (rate of change of −16.28%) shows a downward trend in water demand, with the total water demand expected to become 3.137 billion m³ by 2035 (Fig. 8). A comparison of these two scenarios shows that the effect of the industrial water-saving policy is not obvious. By 2035, the total policy-controlled water demand will be only 76 million m³ lower than the uncontrolled demand, whereas the unmet demand (778 million m³) will still be large. The biggest gap between supply and demand is in the Beiyunhe river basin (354 million m³), accounting for 45.48% of total unmet demand (Fig. 9). The reason for this is that the industrial added value of the Beiyunhe river basin is significantly higher than those of the other river basins. Therefore, the use of industrial water is most required.

4.3. Effects of agriculture-related policies

4.3.1. Change rate of irrigation water per unit. In our analysis, we only changed the per unit irrigation water and maintained other influencing factors unchanged. We analyzed the influence of
different per unit irrigation water scenarios on the balance between supply and demand of water in Beijing using quantitative techniques. Our results indicate that the two scenarios show an increasing trend followed by a decreasing trend, which may be because the agricultural irrigation water saving is lower than the increase in environmental water use increase. By 2035, the water demands under the scenario without policy control (change rate of −0.79%) and the policy constraint scenario (change rate of −1.01%) will be 3.756 and 3.715 billion m³, respectively, for a water demand difference of only 0.41 billion m³ between these two scenarios (Fig. 10). This demonstrates that the water-saving irrigation policy does not obviously affect the water resource pressure. Under the policy constraint, the unmet demand is 801 million m³, and the largest gap between supply and demand is still observed with respect to the Beiyunhe river basin (420 million m³), accounting for 52.45% of the total unmet demand (Fig. 11).

4.3.2. Change rate of the crop planting area. We quantitatively studied the effects of another agricultural policy on water balance by changing the crop planting areas and maintaining the other factors unchanged. The WEAP model’s calculations denote that water demand decreases in both the scenarios. By 2035, the water demand under the policy control scenario (change rate of −10.9%) and a scenario without policy control (change rate of −14.29%) will be 2.877 billion m³ and 2.849 billion m³, respectively. Thus, the difference in water demand between the two scenarios is small (Fig. 12). Therefore, adjustment of the planting structure (i.e., reducing crop planting area) does not have an obvious effect on the pressure of water resources. Under the policy constraint scenario, the unmet demand is 384 million m³, and the largest gap between supply and demand is still observed in the Beiyunhe river basin (306 million m³), accounting for 79.53% of the total unmet demand (Fig. 13).

Figure 10. Water demand under different water use of per unit irrigation.

Figure 11. Unmet demand of agricultural water saving policy in 2035.
This is because the Beiyunhe river basin exhibits the largest planting area and the greatest demand for agricultural water.

5. Discussion

5.1. Selection of the influencing factors
Currently, some researchers have studied the effect of population growth on water resources [47]. The population growth rate parameters are set using census data or projections, without considering the policy control impacts. This study discusses the effect of population growth rate on Beijing’s future water supply and demand balance under different policy constraints. Through comparative analysis, the population growth rate is observed to play an important role in reducing the water demand and alleviating water shortages. Once a policy is invoked, the growth rate based on census data or forecasts will lose its reference value. Thus, the setting of parameters must consider policy constraints to scientifically and accurately predict the effects on water balance.

In addition, some researchers who used quantitative research methods discussed the effects of influence factors, such as the industrial production value, agricultural production value, and urban population, on the water resource carrying capacity40. This study selects various influencing factors, including population, crop planting area, unit irrigation water, and water consumption of 10,000-yuan industrial added value, which affect different water sectors. The selection of influencing factors is based on the statistical yearbook data. For example, in the statistical yearbook, industrial water conservation is achieved by reducing the water consumption per 10,000-yuan industrial added value. Industrial water consumption is measured by two indicators, i.e., water consumption per 10,000-yuan
5.2. Shortage of research
In this study, we applied the WEAP model to study the effects of the policy constraints on water supply and demand in Beijing; although the selection of influencing factors was innovative, there were still some deficiencies. The level of data detail directly affects the prediction precision of the model, and the agricultural water input in the WEAP model’s demand side in this study is annual data. Because of a lack of monthly data for agricultural water consumption, the monthly changes in agricultural water consumption were obtained using the monthly distribution of the annual water demand calculated for each day using the WEAP model. However, the crop irrigation in Beijing is primarily concentrated in February, March, November, and December. Thus, the monthly data on agricultural water consumption are quite varied, and the lack of data will undoubtedly affect the model’s prediction accuracy.

This study only considers the effects of policy constraints on water resources and not natural factors. Further study is needed to deeply study the manner in which natural factors, such as climate change, will affect Beijing’s water supply because natural factors affect water resources. In addition, this study uses the WEAP model to quantitatively predict the gap between water supply and demand in Beijing’s five major river basins at the watershed level, and the analysis has a single perspective. In a follow-up study, research will be conducted from the administrative district perspective, and results will be analyzed to explore the possible differences between the results of different spatial divisions and determine whether there is a contradiction between the administrative and watershed management approaches.

6. Conclusion
In this study, we quantitatively simulated the effect of policies on Beijing’s future water supply and demand by building the Beijing WEAP2010 model. Our results denote that by 2035, policies controlling the population growth rate, industrial water saving, per unit irrigation water use, and crop planting area can reduce the water demand by 3.42, 0.76, 0.41, and 0.28 million m³, respectively, when compared with scenarios without policy control. The highest unmet demand was in the Beiyunhe river basin in all the scenarios, accounting for 49.43%, 45.48%, 52.45%, and 79.53% of the total unmet demand for these policy scenarios, respectively. The policies play a significant role in improving the water use efficiency, rationally regulating the water supply and demand. This provides a strong scientific basis for solving Beijing’s water crisis and clarifies key control and management points to formulate water security management countermeasures for the capital. Based on these conclusions, we present the following suggestions:

1) The government should control the number of migrants who move to Beijing to reduce the population growth rate, relieve the pressure of excessive population growth on the water supply, and realize sustainable utilization of water resources.

2) Among the five studied river basins, the Beiyunhe river basin is observed to exhibit the most serious water shortage; therefore, relevant departments of the government must focus on this basin. The Beiyunhe river basin flows through the largest number of districts and counties (13 districts and counties, including the six central districts of Beijing and the Mentougou, Tongzhou, and Shunyi districts). A method combining river basin management and administrative management can be adopted to establish a water resource utilization system, improve the water resource utilization rates, reasonably distribute the water resources, realize water supply security in the Beiyunhe river basin, and alleviate serious water resource shortages.

3) Environmental water constitutes an important part of Beijing’s water use structure, and its share in total water consumption has gradually increased. However, there is no specific policy on environmental water usage at present. Therefore, environmental water use should be considered when formulating water-resource-related policies. We can meet the water demands of different departments,
realize the rational allocation of water resources, and achieve the coordinated development of resources and the economy by comprehensively considering the water consumption with respect to different departments.

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