



What drove water demands in Beijing?: implications for macroeconomic structure and policy reform

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Abstract

The water system of Beijing is a coupled human and natural systems (CHANS) featured by the interactions of the two components. An integrated system dynamics (SD) model is adopted to analyze the systematic structure of CHANS for megacities. The feedback and interactive relationships for different components can be fully understood through this model. The novelty of this study is reflected in the combination of quantitative and qualitative methods adopted to simulate and analyze the structure of water demands in Beijing using the SD model. The driving forces of water demand and their effects on water demand variation are obtained based on both the modeling results and the literatures. The structural change in water use of Beijing showed the following trends: total water demand was stable; industrial and agricultural water demands decreased; domestic water demand rapidly increased. Implications, such as adjusting macroeconomic structure, keeping population growth stable, promoting new and advanced technologies' application, and encouraging the use of economic lever measures, are valuable lessons should be taken by other megacities with similar water shortages as Beijing. Only with the government, the public and the enterprises effectively working together will the water shortage problems be solved in such megacities like Beijing.

Keywords Coupled human and natural systems · System dynamics · Driving forces · Macroeconomic structure adjustment · Policy reform

1 Introduction

Beijing is a megacity facing severe water shortages throughout the past few decades (Qin et al., 2012; Hyndman et al., 2017). Due to its high-speed economic development, rapid population growth and huge change in land use overlain on a backdrop of climate change (Hyndman et al., 2017), the water shortage crisis in Beijing has already become and will

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be one of the most important key constraints to economic development. Therefore, the societal and economic development of Beijing needs the support and guarantee of water resources. This has created great pressure and challenges for the sustainable development of water resources and social economy in Beijing (Wang et al., 2015). The annual average total water use (TWU) of Beijing is 3.70 billion m^3 for 1996–2014, while the annual average total water resources (TWR, refers to the surface and subsurface water yield caused by precipitation and it is the sum of surface runoff and precipitation infiltration recharge) is 2.63 billion m^3 , and the water deficit is up to 1.07 billion m^3 (Fig. 1a). The TWR fluctuates and is significantly less than the TWU for most years, resulting in groundwater over-exploitation and aquifer storage depletion. The water resources per capita (TWR divided by total population) in Beijing is about 300 m^3/year , which is markedly less than the national and world average values and is significantly below the internationally recognized water shortage floor level (1000 $\text{m}^3/\text{capita}/\text{year}$) (Qin et al., 2012). The relative share of all water users to total water demand (Fig. 1b) showed that the agricultural and industrial water use decreased with time, while the domestic and environmental water use increased with time for the period 1996–2014. As a part of the North China Plain (NCP), Beijing is an important food production area in China. Agricultural area plays an important role in Beijing for the food safety of the NCP and China. As for the reason of population growth and economic development, the cultivated land use area decreased from $3.44 \times 10^3 \text{ km}^2$ in 1996 to $2.20 \times 10^3 \text{ km}^2$ in 2014, while the urban land use area increased from $1.89 \times 10^3 \text{ km}^2$ in 1996 to $3.03 \times 10^3 \text{ km}^2$ in 2014 (Fig. 1c). The agricultural area's role has been diminished with each passing year since Chinese economic reform in 1978, which results a decline of the proportion of agricultural water use to total water demand. Generally speaking, as the total water demand keeps a steady downward trend (Fig. 1a), the decline in the proportion of agricultural water use means the decline of crop production. The industrial structure of Beijing is also gradually changing, and the proportion of agricultural output value in GDP is gradually replaced by industry and the tertiary industry. The population of Beijing has increased from 12.6 million in 1996 to 21.5 million in 2014, which results the domestic water use increases from 1.02 billion m^3 in 1996 to 1.70 billion m^3 in 2014.

Understanding the variation in trend and the driving forces of water demands are extremely necessary for Beijing's sustainable development and it is essential to do so rationally and scientifically in order to establish water resources exploitation and utilization planning. There are several studies on such aspects. Huang et al. (2009) has analyzed the trend of gross agricultural water consumption of Beijing from 1986 to 2007. The results indicated that area, production, and climate were the three major factors which influenced the change in agricultural water consumption. However, these studies are mainly statistical ones based on the analysis of statistical data. This study focuses on the qualitative causality relationship (in form of Casual Loop Diagram (CLD)) and quantitative causality relationship (in form of Stock and Flow Diagram (SFD)) analysis using system dynamics (SD) simulation methodology, which is very different from traditional methods and can provide an effective attempt to study the aforementioned issues in Beijing.

Global changes pose major threats to water sustainability around the world. These threats are magnified in megacities and are likely to extend well beyond the boundaries and catchment areas of individual megacities due to cascading effects on regional water supplies and the profound regional and global influences of these megacities (Deines et al., 2016; Hyndman et al., 2017; Liu et al., 2017; McDonald et al., 2014). Most research on water sustainability in megacities has been fragmented and not able to effectively elucidate the interactive and synergistic effects of global change factors (Hyndman et al., 2017). Therefore, an innovative approach is necessary to help policy makers understand

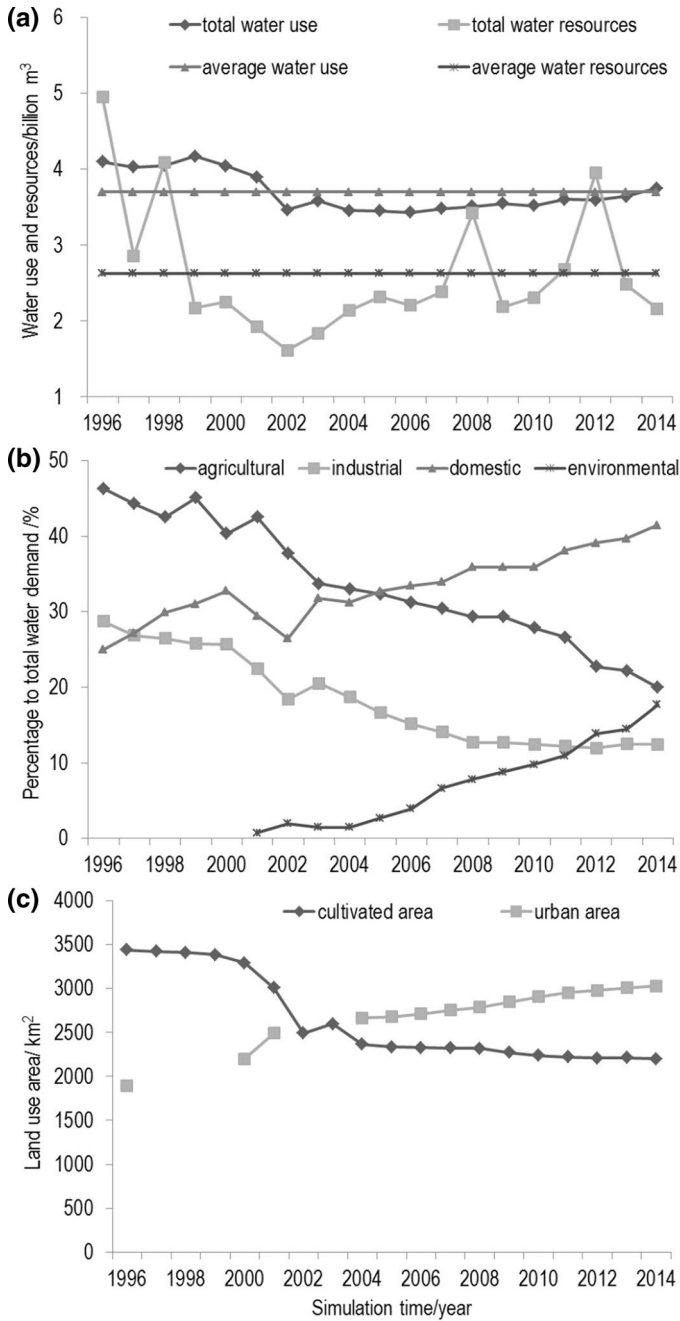


Fig. 1 **a** The annual and average total water use and total water resources, **b** percentages of sectoral water demands to total water demand and **c** cultivated and urban land use areas of Beijing for the period 1996–2014

the complex and long-term dynamics of water sustainability in megacities. Simulating the potential impacts of global changes in coupled human and natural systems (CHANS), which is the interaction system between human and natural components (Liu et al., 2007a, b), on water sustainability provides a strong foundation for improved adaption and mitigation strategies to address water challenges amplified by global changes.

SD is an approach that can integrate numerous natural and human factors into one model (Kotir et al., 2016; Qin et al., 2012). The behaviors of CHANS in megacities can be systematically understood upon the quantitative analysis of the feedbacks and interactions among these factors using SD. The SD applications have shifted their spatial scales from regional (Qin et al., 2012; Sušnik et al., 2012; Yang et al., 2015) to national (Sun et al., 2016; Wang et al., 2014) to global (Davies & Simonovic, 2011; Kojiri et al., 2008). SD is a useful tool in analyzing water sustainability issues in megacities with its wide range of powerful applications. SD modeling can locate these factors and analyze their effects on driving the changes in water demands. Policy reform suggestions on water use in megacities can be achieved based on this modeling.

In this study, an integrated SD model considering different social-economic and natural factors is adopted to analyze the systematic structure of CHANS in Beijing. The feedbacks and interactive relationships can be fully understood in this model. The water demand driving forces and their quantitative effects on water demand variations in Beijing are obtained based on both the SD modeling and the literatures. The experiences from Beijing can hopefully be extended to other megacities with general water shortage issues as Beijing.

2 Methodologies and model structure

2.1 SD methodology

SD, which was introduced in the 1950's and used to analyze complex industrial processes (Zhang & Yuan, 2010), is a modeling framework used to understand the reciprocal interactions and feedbacks in CHANS. These reciprocal relationships can be qualitatively and quantitatively in a SD model. The SD advantage lies in dealing with high degree of nonlinear, interdependent, and multivariable problems. The SD application field is very broad, such as urban planning, eco-environmental planning, land carrying capacity evaluation, and wastewater reuse assessment (Qin et al., 2012; Rahmani & Zarghami, 2015; Sun et al., 2016; Wang et al., 2017; Xie et al., 2014). There are numerous SD studies on water resources assessment and management over the past decades. Wang et al. (2017) have proposed an integrated approach of SD, orthogonal experimental design and inexact optimization modeling for water resources management under uncertainty. Sun et al. (2016) simulated water supply and demand conditions and future changes in the gap between supply and demand from 2005 to 2020 for China using a SD model.

SD has been selected here for several reasons. Many studies have proved that SD has the capability to deal with water sustainability problems with both interactive and nonlinear relationships as well as complex behaviors in CHANS (Dai et al., 2013; Qin et al., 2012). The complex factors can be integrated into one holistic model and simulated systematically to investigate the general water demand performance. The quantitative modeling technology with friendly graphical user interface software is suitable for the water systems analysis in CHANS. The readers can easily understand the relationships among the various factors in CHANS with the help of the software.

2.2 Model structure

There are several reasons to conduct research on the water sustainability of Beijing. First, Beijing exemplifies the global water shortage in megacities worldwide due to its rapid population growth, economic development and land use change over the past decades (Hyndman et al., 2017). Secondly, the region surrounding Beijing is predominantly an agricultural region. Further, Beijing is seeking to meet its water needs with major engineering projects to divert water from other regions (e.g., South to North Water Diversion Project, SNWDP) (Qin et al., 2013). Finally, Beijing's sustainability challenges have significant implications worldwide, especially for regions with similar situations as Beijing.

The model developed here considered various factors that influence the water sustainability. The human system includes all water demands and the water diversion project, while the natural system includes the water supply. Figure 2a shows the conceptual model involving the human system, the natural system and their coupled interaction. Total water supply (TWS) includes surface-water, groundwater, diverted water and wastewater reuse while total water demand (TWD) contains domestic, industrial, agricultural and environmental water demands. The balance between TWD and TWS determines the water sustainability. There are five sub-systems in the model: the domestic one represents water required by the urban and rural population; the industrial one describes water demand of the industrial sector; the agricultural one includes irrigation and livestock water demands; the environmental one considers the reuse of wastewater generated by all sectors; the water resources one summarizes water demand and supply and describes the water balance and sustainability of the whole system.

Domestic water demand (DWD) is affected by total population, economic development, domestic water price and water scarcity. Industrial water demand (IWD) is determined by GDP, GDP per capita, water use technology improvement, and industrial water price. Irrigation water demand (IrriWD) is calculated as the sum of all crops' water requirements while livestock water demand (LWD) is estimated as the product of livestock and their water use quota. The calculation methods involve socioeconomic, hydrologic and agronomic factors that affect the water demands. Please refer to Qin et al. (2018) for more details.

The elements and their causal relationships are identified in the CLD (Fig. 2b), which includes the presence of a feedback loop, loop dominance, and presence of time delays (Mirchi et al., 2012) and considers the socioeconomic, technologic, agronomic, hydrologic, meteorological and engineering factors with all sub-systems. The quantitative relationships are represented by the SFD, which describes the system's dynamic behaviors in terms of stocks and flows. The system processes can be graphically characterized by the SFD through a series of quantitative relationships represented by equations.

Data from the period 2000–2011 are used to calibrate the model. The goal of the calibration process is to provide a satisfactory match between simulation results and historical observations. Overall, the DWD, IWD, AWD and TWD simulations all adequately reflect historical trends. The domestic and industrial water demands generally agree with the historical data, while discrepancies exist between the agricultural and total water demands and the associated historical data. More details can be found in Qin et al. (2018).

2.3 Sensitivity analysis methodologies

The sensitivity analysis approach used here is OFAT, namely changing one-factor-at-a-time (Borgonovo & Plischke, 2015). The concept of sensitivity degree is used to describe the quantitative result of sensitivity analysis (Sun et al., 2002).

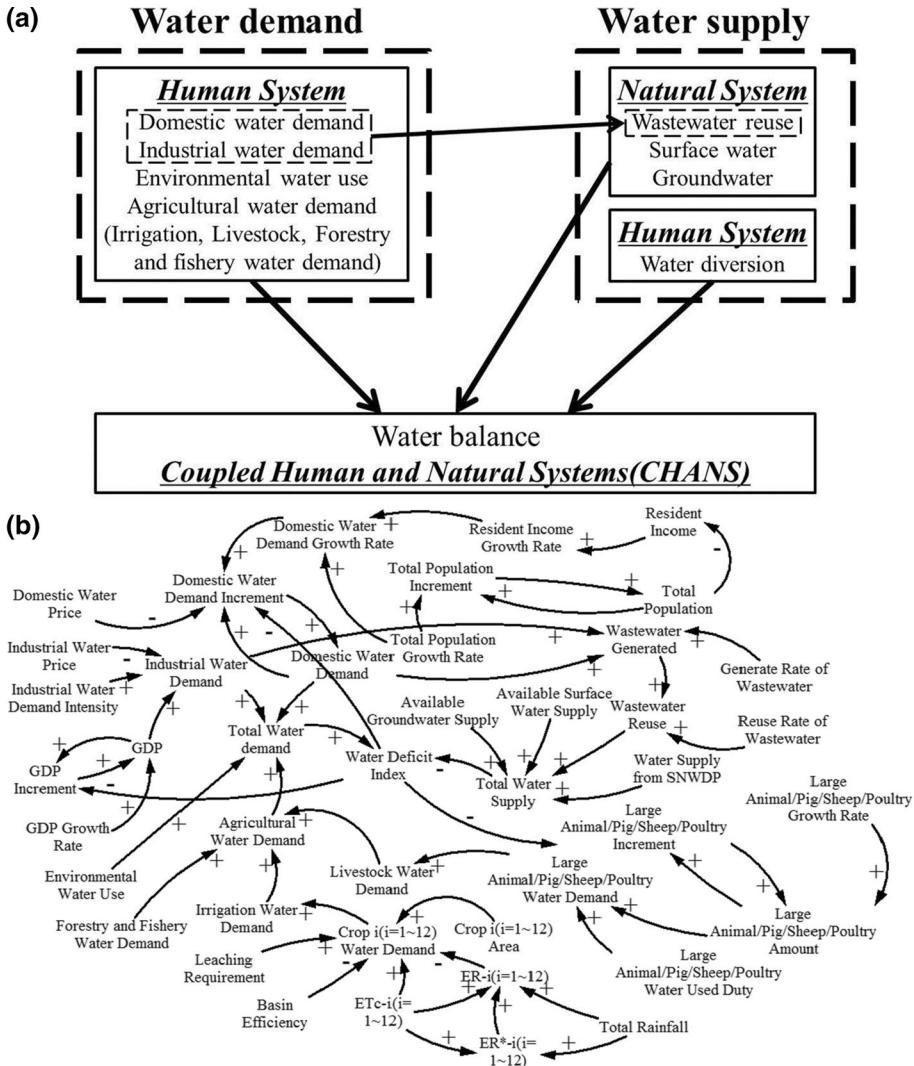


Fig. 2 **a** Conceptual model describing the water sustainability of Beijing, **b** CLD of the SD model for Beijing, where each arrow is a cause and effect relationship and the polarity on the link (\pm) represents the change in direction caused by a cause. “+” means the same direction while “-” means the reverse direction

$$S_Q(t) = \left| \frac{\Delta Q(t)/Q(t)}{\Delta X(t)/X(t)} \right| = \left| \frac{\Delta Q(t) \times X(t)}{Q(t) \times \Delta X(t)} \right| \quad (1)$$

In which $S_Q(t)$ is the sensitivity degree of output Q to parameter X ; $Q(t)$ refers to the output at time t ; $X(t)$ denotes the parameter at time t ; $\Delta Q(t)$ and $\Delta X(t)$ are changes in $Q(t)$ and $X(t)$.

For a simulation period, the sensitivity degree of Q to X is defined by Eq. (2):

$$S_i = \left[\sum_{t=1}^T S_Q(t) \right] / T \quad (2)$$

In which T is the total time steps, S_i is sensitivity degree of output i to parameter X over the period. The sensitivity degree of the model to parameter X can be calculated by Eq. (3):

$$S_X = \left(\sum_{i=1}^n S_i \right) / n \quad (3)$$

In which n is the number of outputs; S_x is the sensitivity degree of the model to X .

Impact analysis techniques are usually used to measure the expected impact of a change (Almasri et al., 2017). In this study, impact analysis is the activity of identifying what to modify to accomplish a change, or of identifying the potential consequences of a change (Arnold & Bohner, 1993). Impact analysis is a technique used in different domains such as business, engineering, and software development. The objective is mainly to study the consequences of a change in order to identify the risks and to better plan for the implementation of the change.

3 Study site and model setup

3.1 Study site

Beijing is located in the transition zone of the Mongolian plateau and the NCP and surrounded by Hebei Province and Tianjin municipality (Fig. 3). It spans from 39°28'N to 41°05'N and from 115° 45'E to 117°30'E with a total area of 1.68×10^4 km², including the Beijing plain area and the mountain areas. Beijing belongs to the warm temperate semi-humid continental monsoon climate. The multi-year (1996–2014) mean annual precipitation is 526 mm. The seasonal precipitation distribution is uneven, with about 60.0–80.0% occurring throughout the summer flood season from June to September. Beijing is China's political, economic, and cultural development center. In 2014, the total population was 21.5 million, with a density of 1.31×10^3 persons/km². The water resource per capita in Beijing is less than 300 m³/year, which is less than 1/8 of the national average and 1/30 of the world average. It is far below the international water shortage floor level (1000 m³/ (person × year)) (Qin et al., 2012).

3.2 Model setup

The simulation period is 1996–2014 with a time step of one year. A sensitivity analysis is implemented to adopt the most sensitive parameters. Further, analysis of the effects of the change in different factors on water demands will be carried out to exploit the driving forces that cause water demands change in Beijing. The input data include three types: table function, constant and initial value. Table 1 lists the calibrated constant values adopted from Qin et al. (2018), excluding the values of the crop coefficient (kc).

The variables in the model can be classified as endogenous ones and exogenous ones. The endogenous variables mainly refer to the state and auxiliary variables that are determined by the model, such as total population, domestic water demand, GDP and so on; while the exogenous variables refer to the parameters that are determined by external factors beyond the model, including the constant parameters and table function parameters.

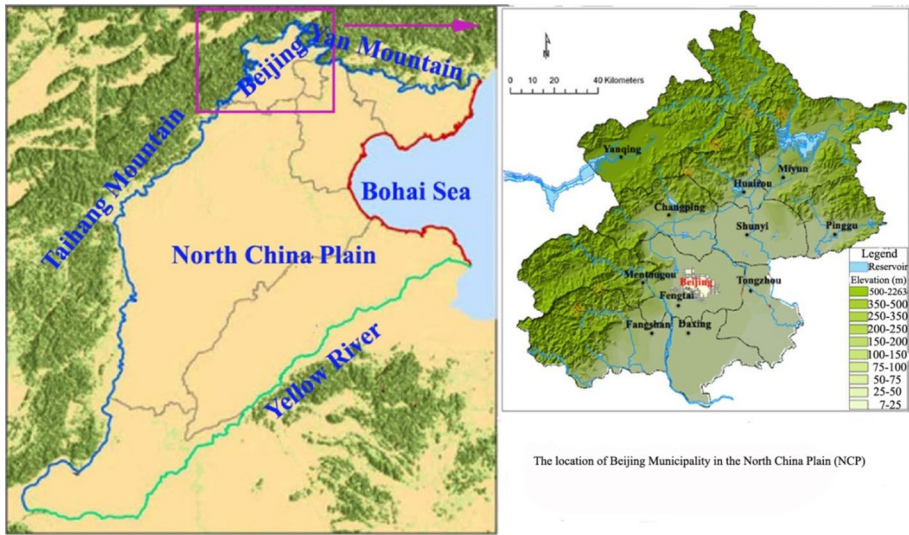


Fig. 3 The terrain elevation graph of Beijing and its location in the NCP. The districts and counties outside the main city zone are also shown in this figure

Table 1 Calibrated constant parameters used in the model

Parameter	Abbr	Unit	Value
Basin efficiency initial	BEI	–	0.568
Domestic wastewater fraction	DWF	–	0.850
Income coefficient	IncC	–	–0.00120
Investment coefficient	InvC	–	0.0235
Industrial wastewater fraction	IWF	–	0.900
Industrial water price elasticity	IWPE	–	–0.368
Large animal water used duty	LAWUD	m ³ /head/year	14.6
Lleaching requirement	LR	–	0.150
Pig water used duty	PWUD	m ³ /head/year	14.6
Poultry water used duty	PouWUD	m ³ /head/year	1.46
Sheep water used duty	SWUD	m ³ /head/year	2.92
Time coefficient	TC	–	–0.00960
WDI elasticity of DWD	WDIEDWD	–	–0.00600
WDI elasticity of IWD	WDIEIWD	–	–0.0762

Water deficit index (WDI), which is the ratio of water deficit to total water demand, is a quantitative indicator determined by the total water supply and demand. Positive value indicates that the water shortage problem exists and vice versa. Larger WDI values correspond to more serious water shortage problems.

There are several assumptions adopted by the SD model, including: (1) four kinds of livestock (large animal, pig, sheep and poultry) and twelve kinds of crops (wheat, corn, cotton, forage, rice, tuber, vegetable, oil-crop, melon and strawberry, soybean, drug and

flower) are considered in the model to calculate the livestock water demand and irrigation water demand, respectively; other livestock and crop contribute little to these water demands and are ignored in this model; (2) the quantitative relationships and related equations of the model are based on the literatures and the authors' research experience; (3) the model is divided into five sub-systems, including population, industry, agriculture, water reuse and water resources supply; (4) all the input data are collected from public materials released by the government of China.

The data adopted in this study and their sources include the following categories: (1) the socioeconomic data are collected from Water Resources Bulletin of Haihe River Basin (HRWCC-MWR 1996–2014) and Beijing Statistical Yearbook (BMBS 1997–2015); (2) the water resources data are collected from Beijing Water Resources Bulletin (BWA 1996–2014) and Huang et al. (2009); (3) the precipitation data are collected from Beijing Statistical Yearbook (BMBS 1997–2015) and Beijing Water Resources Bulletin (BWA 1996–2014), while the reference evapotranspiration data are adopted from Qin et al. (2013); (4) the crop coefficient is determined based on the data presented by Zhou (2005) according to the different growth cycles of different crop varieties; (5) parameters related to macroeconomic and price indices are determined according to the actual situation of the study area and the values from Cai and Rosegrant (2002) and Rosegrant and Cai (2002); (6) wastewater reuse data are collected from Beijing Water Resources Bulletin (BWA 1996–2014) and Beijing Statistical Yearbook (BMBS 1997–2015).

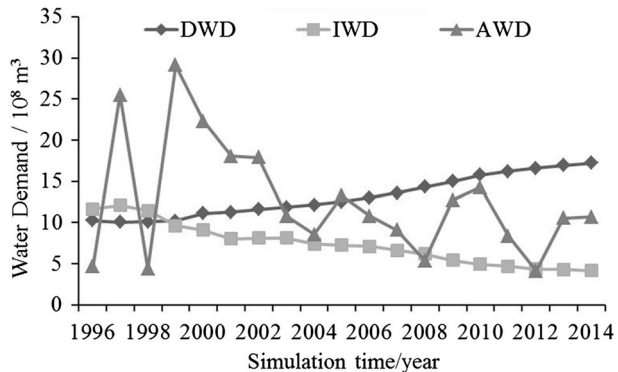
4 Results

4.1 Sectoral water demand simulations

DWD showed a rapidly increasing trend during the period: increased from 1.02 billion m³ in 1996 to 1.72 billion m³ in 2014 (Fig. 4). The average annual increase of DWD varies differently: 0.174, 0.450, 0.250 and 0.367 billion m³/year for 1996–2000, 2001–2010, 2011–2014 and 1996–2014, respectively. The population boom, living standards improvement, urbanization and rapid urban construction development are the main reasons contributing to the rapid increase in DWD (Zhao, 2015).

IWD indicated a rapidly decreasing trend during the period: decreased from 1.16 billion m³ in 1996 to 0.414 billion m³ in 2014 (Fig. 4). The average annual decrease of IWD varies

Fig. 4 Simulated water demand by sectors of Beijing for 1996–2014



differently: 0.510, 0.308, 0.133 and 0.394 billion m³/year for 1996–2000, 2001–2010, 2011–2014 and 1996–2014, respectively. The industrial structure upgrade, water conservation and reuse technologies progress, and environmental protection awareness enhancement are the main reasons for the rapid decrease in IWD (Che et al., 2015).

The agricultural water demand (AWD) includes IrriWD, LWD and forestry and fishery water demand (FFWD). FFWD and LWD account for small percentages of AWD (25.0% and 15.0% on average) compared to the percentage of IrriWD to AWD (60.0% on average). IrriWD is simulated according to crop species, meteorological conditions and agricultural investment. Generally speaking, the curved shape of IrriWD is the reverse of total rainfall: high rainfall means low IrriWD and vice versa. Therefore, IrriWD determined the curved shape of AWD (Fig. 4). The curve of AWD showed a fluctuating feature but a decreasing trend in general from a highest demand of 2.91 billion m³ in 1999 to 0.410 billion m³ in 2012. However, AWD here is a “natural” result of the crops and meteorological conditions. The farmers may use more water to irrigate the crops even when it is a wet year.

4.2 Sensitivity analysis results

Table 2 displays the sensitivity analysis results for 1996–2014, showing the sensitivity degree values of the outputs to the parameters, including 25 parameters and 7 outputs. The constant is increased by 10.0%, while the table function is increased by 10.0% for each year. Based on Eqs. (1 and 2), 19 sensitivity degree values can be obtained for each parameter-output pair and their mean value denotes the general sensitivity degree of the output to the parameter. Then, the sensitivity degree of the model to the parameters can be averaged based on Eq. (3).

17 parameters have a bigger effect on the system with a sensitivity degree over 0.0100 (up to 0.959), while other parameters have a smaller effect with a sensitivity degree less than 0.0100. The sensitivity analysis provides useful information on the effects of the parameters on the model’s behavior. As a further approach of the sensitivity analysis, a series impact analysis of various factor changes on the system’s behavior were carried out to obtain the water demand driving forces.

5 Discussions

5.1 Impacts of various factors

5.1.1 Water price

Beijing has conducted nine water price adjustments since 1992 and the price has risen between a minimum of 3.60 times and a maximum of 8.30 times for different industries (Shen et al., 2009). Beijing began to implement stepped water prices on May 1, 2014. The domestic water price has increased from 0.500 RMB/m³ in 1996 to 5.00 RMB/m³ in 2014 (RMB is China’s monetary unit), while the industrial water price has increased from 0.800 RMB/m³ in 1996 to 8.92 RMB/m³ in 2014. Beijing government announced that they will gradually promote an Increasing Block Rates for domestic purposes and will make reasonable adjustments for urban domestic water prices. In addition, Beijing will also strengthen the implementation of over planned progressive price increases for water in industry and service industries, and continue to implement differential water price policies more strictly

Table 2 Sensitivity degree of each parameter-output pair for 1996–2014, where *WDI*: water deficit index, representing the ratio of water deficit to total water demand; and *AVE* represents the sensitivity degree of each parameter to the model

Output								
Parameter	DWD	IWD	LWD	IrriWD	AWD	TWD	WDI	AVE
TR	0.00270	0.128	0.000900	2.824	1.36	0.406	1.99	0.959
GDPGR	0.00410	1.35	0.000400	0	0	0.236	0.827	0.346
BEI	0.00100	0.0489	0.000300	0.909	0.547	0.197	0.714	0.345
PWUD	0.000100	0.00490	0.601	0	0.0888	0.0238	0.100	0.117
IWPE	0.000300	0.442	0.000100	0	0	0.0802	0.271	0.113
TPGR	0.229	0.0108	0.000100	0	0	0.0979	0.402	0.106
DWF	0.000400	0.0191	0.000100	0	0	0.00290	0.616	0.0912
IWP	0.000200	0.333	0.000100	0	0	0.0725	0.203	0.0869
PouWUD	0.000100	0.00260	0.312	0	0.0462	0.0123	0.0537	0.0610
DWPE	0.00930	0.000400	0	0	0	0.0802	0.271	0.0516
LR	0.000100	0.00640	0.000100	0.130	0.0784	0.0283	0.101	0.0492
IWF	0.000200	0.00960	0.000100	0	0	0.00150	0.225	0.0338
TC	0	0.104	0	0	0	0.0164	0.0626	0.0262
PGR	0	0.000600	0.131	0	0.0185	0.00500	0.0281	0.0262
WDIEIWD	0.000200	0.0864	0	0	0	0.0142	0.0559	0.0224
InvC	0	0.00150	0	0.0429	0.0243	0.00770	0.0422	0.0169
PouGR	0	0.000500	0.0710	0	0.0105	0.00250	0.0158	0.0143
SWUD	0	0.000500	0.0459	0	0.00670	0.00190	0.00740	0.00890
LAWUD	0	0.000400	0.0413	0	0.00600	0.00160	0.00720	0.00810
SGR	0	0.000200	0.0272	0	0.00390	0.00130	0.00470	0.00530
DWP	0.00920	0.000400	0	0	0	0.00400	0.0168	0.00430
LAGR	0	0.000100	0.00960	0	0.00130	0.000500	0.00140	0.00190
IEDWD	0.00430	0.000300	0	0	0	0.00180	0.00700	0.00190
WDIEDWD	0.00150	0.000100	0	0	0	0.000700	0.00280	0.000700
IncC	0	0.00100	0	0	0	0.000100	0.000600	0.000200

for industries with high water consumption, so as to promote the adjustment of industrial structure and water structure (Xu, 2012).

This study assumes that the domestic and industrial water prices increase to constant values during the period. Specifically, the domestic water prices of two comparative cases are assumed to be 10.0 and 15.0 RMB/m³; the industrial water prices of other two comparative cases are assumed to be 15.0 and 20.0 RMB/m³. Figure 5 is the comparison results of the domestic and industrial water price changes on water demands and deficit.

Figure 5 shows that increasing domestic water price can reduce DWD and TWD but has a limited effect on reducing water demands. By 2014, DWDs under base price, 10.0 and 15.0 RMB/m³ are 1.72, 1.67 and 1.66 billion m³, respectively; TWDs of these prices are 3.93, 3.88 and 3.87 billion m³, respectively. In fact, increasing domestic water price has little effect on solving water shortage by the reduction of DWD and TWD. Due to the relatively low water price and the low proportion of water expenditure in residents' monthly income, urban residents are not sensitive to water price. Therefore, the adjustment of water price has little impact on the change of domestic water consumption, that is, increasing

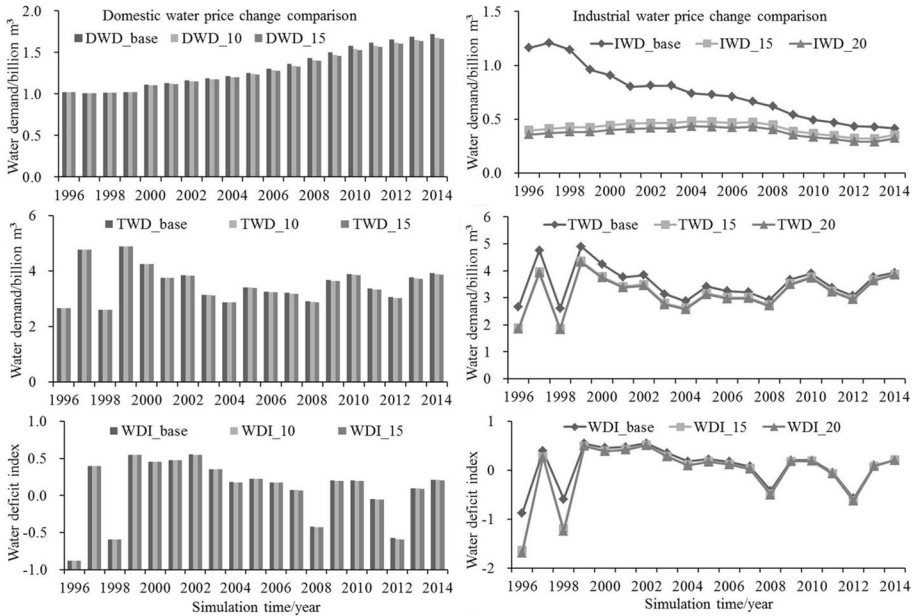


Fig. 5 Comparison of DWD, TWD and WDI under different domestic water price (left panel) and industrial water price (right panel). The suffix ‘_base’, ‘_10’, ‘_15’ and ‘_20’ denote base price, 10.0, 15.0 and 20.0 RMB/m³, respectively

water price will not lead to a large decline in domestic water consumption. Water is a necessary good for the residents. The water use habit will remain even if the price increases, in order to maintain the life quality. Price elasticity of water demand can be further defined as a measure of willingness to use more water when the price falls, or conversely, to reduce consumption when the price rises (Dhungel & Fiedler, 2014). An inverse relation is found between water pricing and consumption. Yoo et al. (2014) and Martínez-Españeira (2007) have synthesized some broad perspectives on the price elasticity of water demand in the USA and Europe, demonstrating that water demand is generally inelastic, but can be elastic to some extent, depending on different factors.

Increasing industrial water price has a greater effect on IWD and TWD (Fig. 5). IWD and TWD decreased due to the increase in industrial water price, especially for the beginning period. For 1996, IWDs of base price, 15.0 and 20.0 RMB/m³ are 1.16, 0.400 and 0.370 billion m³, respectively; TWDs of these prices are 2.65, 1.88 and 1.84 billion m³, respectively. The government has increased the water price for industrial consumers to encourage them to take water conservation measures in industrial production activities. The results show that increasing industrial water price can be an effective measure to reduce water demands.

5.1.2 Socioeconomic development

The population and GDP growth rates, which are assumed to increase 50.0% and decrease 50.0% for each year, respectively, are selected as the change factors to carry out a comparison analysis. Figure 6 is the comparison results of changes in population

and GDP growth rates on water demands. They showed that the changes of population and GDP growth rates have positive effects on water demands. For 2014, DWDs under population growth rates of basic value, 50.0% decrease and 50.0% increase are 1.72, 1.34 and 2.20 billion m³, respectively; TWDs under these rates are 3.93, 3.55 and 4.42 billion m³, respectively; IWDs under GDP growth rates of basic value, 50.0% decrease and 50.0% increase are 0.410, 0.120 and 1.31 billion m³, respectively; TWDs under these rates are 3.93, 3.62 and 4.83 billion m³, respectively. The effect of GDP growth rate is greater than that of population growth rate. However, decreases in both population and GDP growth rates can reduce water demands and can help alleviate the water deficit problem in Beijing.

5.1.3 Water use duty

The livestock water use duty has a high sensitivity on the system's behavior (Table 2). Here the large animal water use duty (LAWUD) is selected as an example. The large animal water use duties of two comparative cases are assumed to increase 50.0% and decrease 50.0%. LAWUD change has positive but little effect on LWD and TWD (Fig. 7). For 2014, LWDs under large animal water use duty of basic value, 50.0% decrease and 50.0% increase are 0.119, 0.117 and 0.122 billion m³, respectively; TWDs under these values are 3.93, 3.93 and 3.93 billion m³, respectively. It can be concluded from the water conservation aspect that a decrease in livestock water use duty has little impact on water demands.

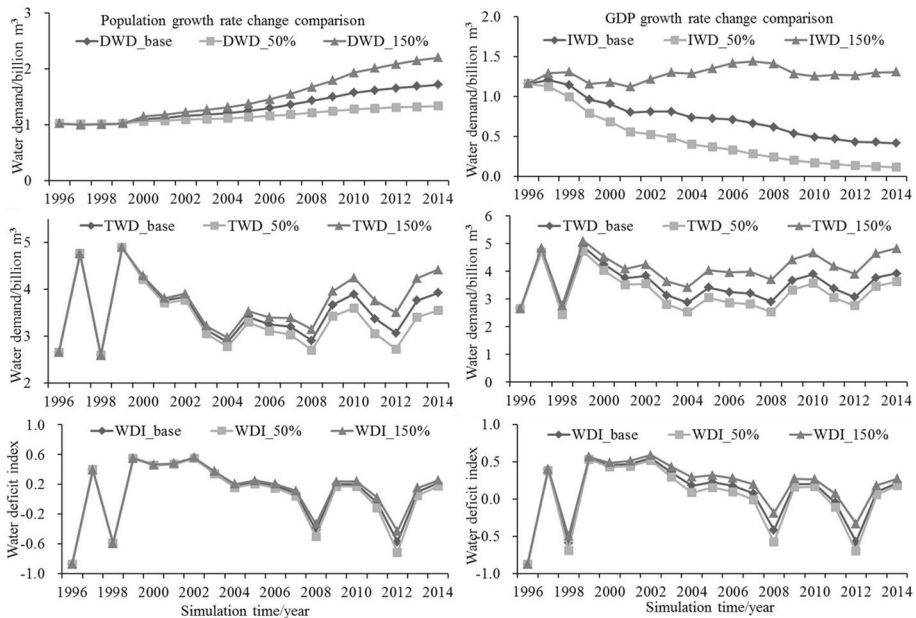


Fig. 6 Comparison of DWD, TWD and WDI under different population growth rate (left panel) and GDP growth rate (right panel). The suffix ‘_base’, ‘_50%’ and ‘_150%’ denote base rate, decrease 50.0% and increase 50.0%, respectively

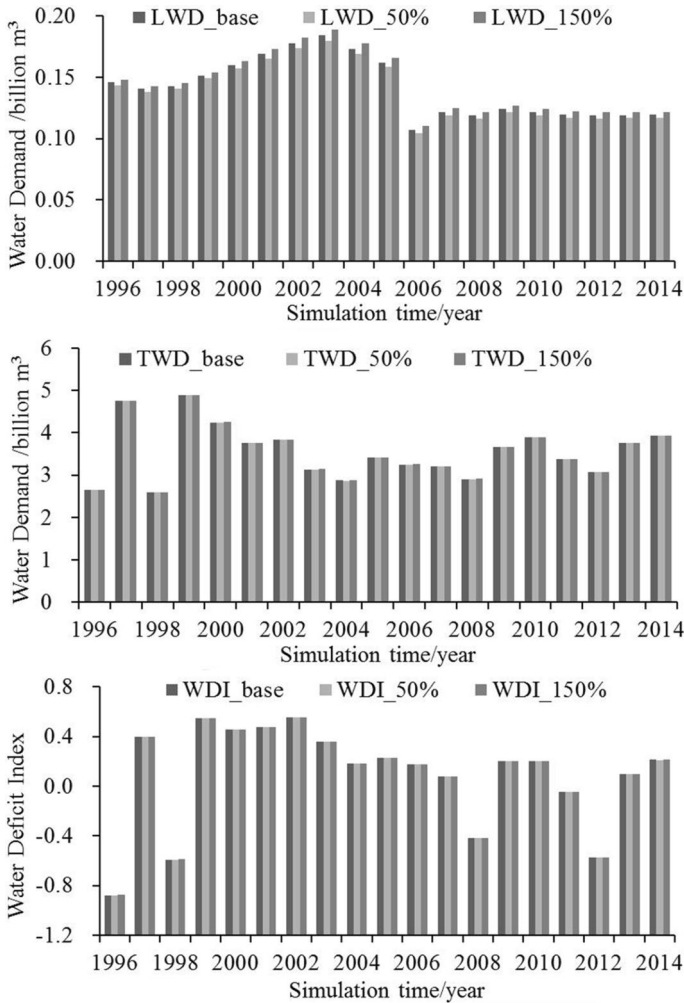


Fig. 7 Comparison of LWD, TWD and WDI under different large animal water use duties. The suffix ‘_base’, ‘_50%’ and ‘_150%’ denote basic value, decrease 50.0% and increase 50.0%, respectively

5.2 Water demand driving forces

5.2.1 DWD

DWD includes urban (household and public water use) and rural (peasant household water use) water demands. The population growth and resident income improvement are the main driving forces that spur the rapid DWD increase, which are supported by the sensitivity analysis results (Table 2).

The top panel in Fig. 8 indicates positive correlations between DWD and both total population and resident income. The total population has increased from 12.6 million in 1996 to 21.5 million in 2014 as the study area has a stable urbanization growth rate

and transient population growth. A higher population requires more water to support basic water needs. Previous studies indicate that DWD can vary with resident income (Dalhuisen et al., 2003; Daniel & Mazzega, 2018). However, countries with different national incomes are most likely to present distinct patterns of domestic water consumption (MIITPRC, 2013). The results of Daniel and Mazzega (2018) indicate that resident income has an effect over living standards and dwelling characteristics, where the higher the resident income, the bigger the built area, garden size and number of water consuming features. Furthermore, the results from the questionnaires and water audit inventories show that the quantity and quality of fixtures and appliances are also related to resident income, where the higher the resident income, the higher the quality and quantity of water fixtures and appliances was within dwellings (Daniel & Mazzega, 2018). The residents' living standards increase with the socioeconomic development. The resident income has increased from 1.42×10^4 RMB/capita in 1996 to 1.20×10^5 RMB/capita in 2014. DWD has increased from 1.02 billion m^3 in 1996 to 1.72 billion m^3 in 2014 due to these driving forces.

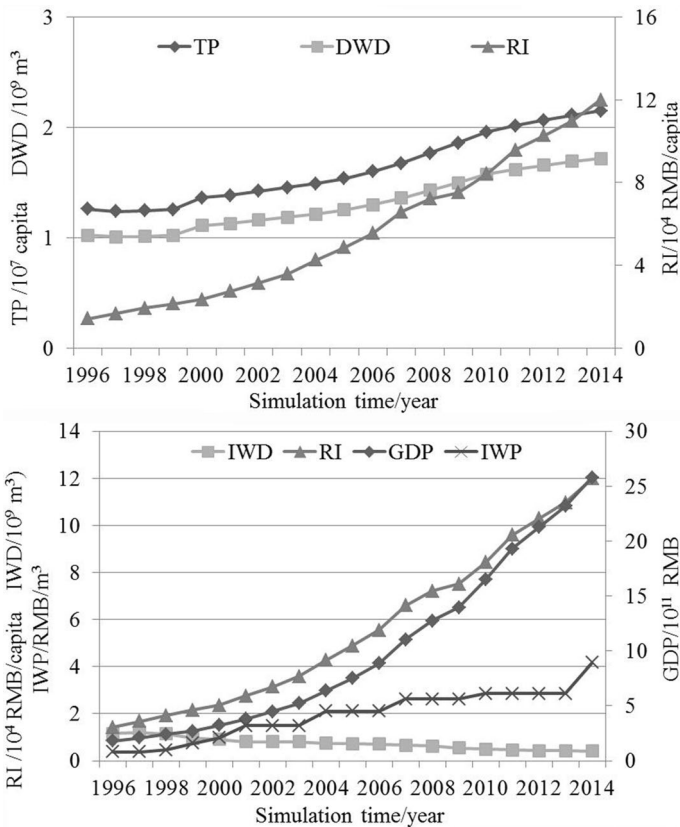


Fig. 8 The total population (TP), resident income (RI) and domestic water demand (DWD) (top panel) and resident income (RI), GDP, industrial water price (IWP) and industrial water demand (IWD) (bottom panel) of Beijing for the period 1996–2014

5.2.2 IWD

The main driving forces of IWD are GDP, industrial water price, technological change, the resident income, and upgrades in industrial structure (Liu et al., 2003; Che et al., 2015). The bottom panel in Fig. 8 indicates that IWD has a negative correlation with resident income, GDP and industrial water price. The resident income has increased from 1.42×10^4 RMB/capita in 1996 to 1.20×10^5 RMB/capita in 2014; GDP has increased from 179 billion RMB in 1996 to 2.58×10^3 billion RMB in 2014; IWP (industrial water price) has increased from 0.800 RMB/m³ in 1996 to 8.92 RMB/m³ in 2014. As a result, IWD has decreased from 1.16 billion m³ in 1996 to 0.414 billion m³ in 2014.

The industrial water price plays an active role in decreasing IWD through acting as the invisible hand behind the market that automatically adjusts the market's behavior. The industrial water use intensity decreases with the improvement in the society's technologies. The increase in technological advancements increases the effectiveness of water use, water reuse, and water conservation. Technological improvements can advance water conservation methods in the industrial sector.

The industrial structure upgrade is another important driving force (Liu et al., 2003; Che et al., 2015). First, this driving force has effect on the national economy as a whole. Namely, the proportions of primary and secondary industries declined while that of the tertiary industry increased. The three-sided industrial structure (refers to the share of primary industrial, secondary industry and tertiary industrial in a country's economic structure) of Beijing has changed from the structure where the secondary industry serves as an absolute advantage to another structure where the tertiary industry accounts for a majority proportion. The proportion ratio among the three-sided industries changed from 4.10%:39.0%:56.9% in 1996 to 0.700%:21.4%:77.9% in 2014. The second one is the evolution of the internal tertiary industrial structure. This means that within the tertiary industry, the labor- and capital-intensive industries (textile, metallurgy, petrochemical industry, etc.) have given way to emerging technology- and knowledge-intensive industries (electronics, new materials, etc.). This directly caused the decrease in high water consumption industries and then led to the decrease in IWD.

Beijing has also been paying more attention to environmental protection in recent years. Higher environmental standards require stricter restrictions on industrial wastewater discharge and clean water in industrial field, promoting the decrease of industrial water withdrawals. Meanwhile, the constant improvement in market mechanism through its internal regulation using economic levers, such as the increase of industrial water price and implementation of pollution discharge fees, has promoted the increase of industrial water utilization efficiency, which includes two indexes—water demand per 10⁴ RMB industrial added value and water reuse efficiency in industry (MIITPRC, 2013)—in the describing of this concept.

5.2.3 AWD

AWD showed a decreasing trend during the simulation period (Fig. 4). IrriWD is related to water conservation technology, irrigation area, and crop structure. In recent years, the effect of agricultural water conservation in Beijing is remarkable. The irrigation methods, such as flood irrigation and paddy field channeling irrigation, have been completely eliminated. The sprinkler irrigation method has been greatly adopted in Beijing. Water irrigation

has declined greatly from 2.53 billion m³ in 1999 (the highest) to 0.751 billion m³ in 2014. Although FFWD increased, AWD decreased due to the decrease of IrriWD.

The urbanization has effects on AWD in two aspects (Liu et al., 2003). First, the rural DWD increased rapidly due to the construction of satellite cities and towns as well as the increase in tourist resorts. The rural enterprises development has caused the increase in rural IWD. Therefore, the water supplied for agricultural purposes has turned into non-agricultural ones. Secondly, urban expansion and construction land increase have caused a decrease in farmlands and irrigation areas, which has contributions to the agricultural water use reduction. The agricultural water use has decreased from the highest of 2.91 billion m³ in 1999 to 1.07 billion m³ in 2014.

5.2.4 EWU

The environmental water use (EWU) refers to the water allocated by human measures for the replenishment of rivers, lakes, depressions and swamps as well as water used for greening and cleaning. The EWU in Beijing has a significant increase from “not available” in 1996 to 0.725 billion m³ in 2014. The driving force of EWU can be summarized as the whole society’s environmental protection consciousness improvement (Liu et al., 2003). The government has always allocated increasing water for environmental purposes in order to ensure the water needs for urban landscaping and other environmental purposes. The comprehensive planning of Beijing city (2004–2020) has been approved by the State Council of China on January 2005. There are two main aspects related to EWU, including the construction of a livable, tourist, and ecological city as well as an ecological environment and protection. As the implementation of this comprehensive planning advances step-by-step, it is sufficiently believed that the EWU will continue to increase for a certain period in future. The green park areas of Beijing have increased from 51.5 km² in 1996 to 288 km² in 2014, with the average area from 7.54 m²/capita in 1996 to 15.9 m²/capita in 2014. This is a powerful driving force that has reinforced and will continue to reinforce the increase of EWU.

5.3 Potential uncertainty

As the model simulation is an approximate estimation of the real world, the results of this study will inevitably have uncertainties. These uncertainties and deviations will not affect the correctness and applicability of the main conclusions of the study. In general, the uncertainty in this study is mainly caused by the following aspects. First, the SD model structure of water demand calculation cannot fully represent the water demand of Beijing under the real situation. Some actual factors affecting water demand in Beijing may not be quantified by SD model. Second, the socioeconomic and water resources data of the study area used in the SD model are mainly collected from the statistical yearbook and water resources bulletin of Beijing, which also has potential uncertainty and deviation. Thirdly, the integration algorithm and technology used in SD model calculation are provided by the software, and there are only a few choices. In this case, it may also bring some uncertainty to the simulation results. Finally, the modeler’s experience and operation (including the determination of variable causality, the input of model parameters and the analysis of simulation results) will also bring some possible uncertainties in the process of model simulation.

It is a pity that the work presented in this paper simulated CHANS till 2014. The work would be more significant if the recent years can be simulated. However, due to the

availability of data and the complexity of the SD model, the research period of this paper is set as 1996–2014, which is a typical simulation period for Beijing city. Considering that the main purpose of this paper is to study the variety characteristics and driving factors of water demands in Beijing, the length of research period has no substantive impact on this purpose. Meanwhile, the feedbacks, interactive relationships and model structure of the CHANS in Beijing can be fully understood through the integrated SD model adopted in this paper without being limited by the model simulation period. The experience of Beijing can be easily extended to other megacities with similar water resource utilization characteristics. In the future research work, if the additional data required by this model can be obtained, the author can expand the simulation period of the model to carry out more simulation and discussions.

6 Conclusions and implications

6.1 Conclusions

With an integrated SD model considering different social-economic and natural factors, the systematic structure of CHANS for Beijing megacity is analyzed. The driving forces of water demands and their quantitative effects are then obtained. The experiences from Beijing can be extended to other megacities with similar water shortage issues as Beijing.

The water demands of Beijing generally showed the following trends: total water demand was relative stable, ranging from 2.65 billion m³ in 1996 to 3.65 billion m³ in 2014; the quantities and proportions of industrial and agricultural water demands to total water demand decreased, ranging from 44.0% and 59.6% to 11.3% and 29.3%, respectively; domestic water demand rapidly increased, ranging from 1.02 billion m³ in 1996 to 1.72 billion m³ in 2014. There are different forces that drove the water demands of Beijing that faces severe water shortages. The driving forces of DWD are population growth and resident income improvement. The GDP, industrial water price, technological change, resident income, and industrial structure upgrades are the main driving forces of IWD. The driving forces of AWD are water conservation technology and urbanization. The driving forces of EWU are the whole society's environmental protection consciousness improvement.

6.2 Implications

The experiences of Beijing can be useful to other megacities with similar water shortage issues. Implications, such as adjusting the macroeconomic structure, keeping population growth stable, promoting the application of new and advanced technologies in the water use field, and encouraging the use of economic lever measures, are all valuable lessons that should be taken by other megacities with similar water shortage issues. The governments of these megacities should be more proactive in promoting all these implications and measures through various ways such as propagandas on radio and television, education programs, legislation, economic tools and so on. The public should be guided through the propagandas and education programs by the government to form good water conservation habits. The enterprises should be incentivized via economic tools such as higher prices or rebate programs and restrictions/rationing from the government to take the positive measures to reduce the water used in the product production processes. Only if they work

together effectively will the water shortage issue be solved in the future in such megacity as Beijing.

First implication, the macroeconomic structure should be changed from a structure where the secondary industry serves as an absolute advantage to the one where the tertiary industry accounts for the majority proportion. As the secondary industrial water demand has decreased throughout the historical period, the adjustment of the macroeconomic structure can further maintain this trend and can reduce the total water demand of Beijing in future.

The second implication is that megacities should maintain the population growth at a relatively constant level. With the population growth and the improvement in residents' living standards, the water required for domestic purposes continues to increase. However, it is hard to reduce the water required for this purpose because that would reduce the quality and standards of the residents. Therefore, the government should keep the domestic water demand relatively constant from year to year by keeping the total population growth rate at a very low and constant level. The policies, such as "late marriage, late childbirth, good birth, good breeding" policy, effectively improving the national social insurance, old-age pension and medical systems, expanding the scope of employment for women and so on, are the ones that can be taken by the policy makers. Good water use habits, such as using a shower instead of a bathtub, using concentrated laundry instead of decentralized laundry, and having multiple uses for the same water, can make great contributions to domestic water conservation, as much of the water that is wasted in the usage process can be saved and reused at a later time.

The most important measure to completely solve the water shortage in megacities is water conservation, including water use efficiency improvement and wastewater reuse. The advancement levels of science and technology in society guarantee the development of water use, reuse and conservation technologies. The government should encourage and promote the technologies adopted by the water use sectors. One of the reasons that cause water shortages includes low water use efficiency. Therefore, new and advanced technologies in water use field are important and should be encouraged and adopted by all sectors.

The market mechanism improvement in megacities can enhance the effects of its internal regulation through economic levers. To reduce the water required by the industrial sector, increasing the industrial water price is a good choice for the policy maker. These economic levers can promote the increase of industrial water utilization rate. Although the effect of water price on domestic water demand is small, megacities should adopt and promote progressive surcharges for overruns in the domestic sector. This will allow the continuation of strict implementation of different water price policies on high water consumption industries and will promote the industrial and water use structures adjustments.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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