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Will China's water resources be safe in 2030?

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Abstract

This paper is distinct from existing studies on water resources carrying capacity which usually use dimensionless data to represent trend and status of water resources carrying capacity. Here, on the grounds of the most stringent water resource management system and following the principles of water determining population, water determining city scale, water determining production and so on, water resources carrying capacity prediction model was established. The water resources carrying capacity was represented by population, which can directly reflect the status of water resources. Under the rigid constraints of water use quantity and water use efficiency, six scenarios were set to predict China's maximum population in 2030. The results demonstrated that the maximum population in each scenario is close to 1.45 billion of National Population Development Plan. It means water resources rigid constraints can support population and economic growth at the socio-economic development current pace and path. Total water use quantity will not break through the limit of 800–900 billion m^3 when achieving the expected goals of social and economic development, not even more than 700 billion m^3. Meanwhile, in order to relieve water resources stress, to improve water resources carrying capacity, and to accelerate construction of a water-saving society, some suggestions were put forward.

Keywords: Rigid constraints; Maximum population; Water resources carrying capacity

Highlights

- Constructed water resource carrying capacity model with population as objective function is used to evaluate future water security.
- The maximum population is estimated under 700 billion cubic meters of total water use control line.
- By 2030, total water use quantity will never come to its limit, not even more than 700 billion cubic meters.

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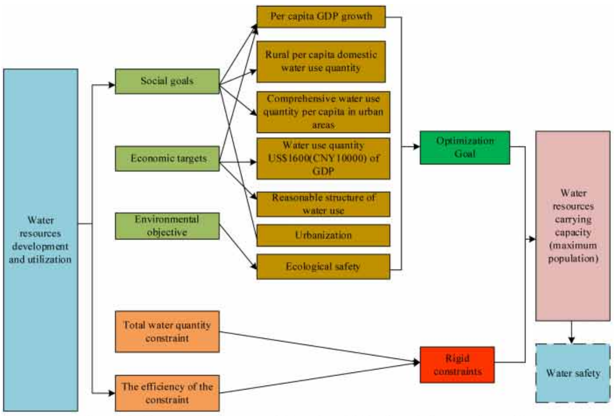
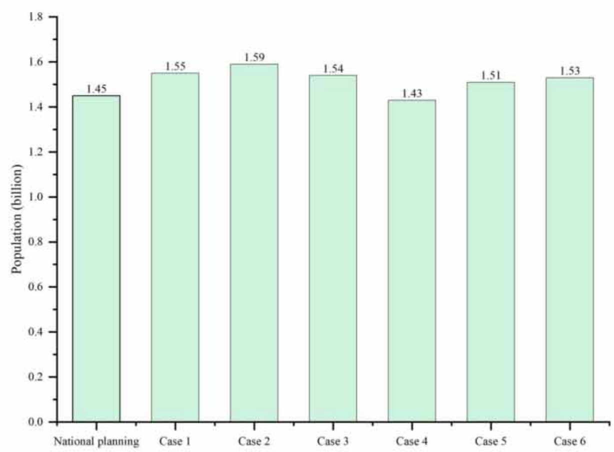
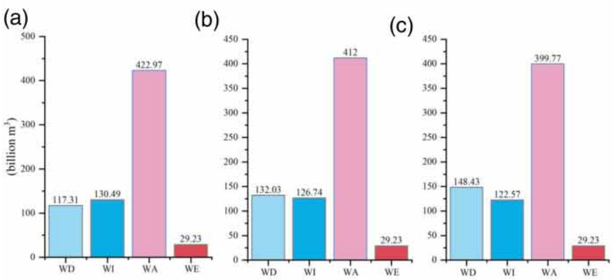
Graphical Abstract



Research ideas and framework based on China's existing water policy



National planning predicted population and the maximum population under six scenarios



Introduction

Water is the basic foundation for the survival of mankind and socio-economic development. From ensuring food production and energy security to maintaining human and environmental health, water has contributed to improve the quality of human life, with water demand growing at twice the rate of population growth over the past few decades (WWAP, 2015; Chen, 2020). The scarcity of available freshwater in the world becomes more serious year by year, and the frequency and severity of drought in many river basins have also changed dramatically. In the world, it is estimated that 500 million people live in areas that consume more water than they can generate locally, and 50% of those facing water shortages live in China and India (WWAP, 2017). Global water use has increased six times over the past 100 years and continues to grow steadily at a rate of about 1% per year as a result of increasing population, economic development, and shifting consumption patterns (WWAP, 2020). The increasing frequency and intensity of extreme events such as floods and droughts will aggravate the situation of countries facing water stress (WWAP, 2020). Therefore, the water resources management mode must keep pace with the times. From 2011, the Central Document No. 1 of 'Decision of the Communist Party of China Central Committee and the State Council on Accelerating the Reform and Development of Water Conservancy' and the Central Water Conservancy Work Conference has explicitly called for the most stringent water resource management system. Since then, the central government and relevant departments have formulated and promulgated a series of policies and regulations concerning the most stringent water resource management system. The General Office of the State Council (2013) issued 'the assessment method for the implementation of the most stringent water resource management system', at the provincial level, including total water use quantity control, water use efficiency control, water resources management responsibility control and assessment system, and the like. In 2015, the central government clearly put forward implementing the most stringent water resource management system, adhering to the principles of water determining population, water determining city scale, and constructing a water-saving society (Communist Party of China Central Government, 2015). In 2016, the total water use quantity and water use intensity for 2020 was strictly stipulated (Ministry of Water Resources & National Development and Reform Commission, 2016). In 2019, the government once again emphasized the dual control of total water use quantity and water use efficiency, and strengthening rigid constraints on the water resources carrying capacity (National Development and Reform Commission & Ministry of Water Resources, 2019).

Water resources carrying capacity was proposed by Chinese scholars (Shi & Qu, 1992; Li & Gan, 2000; Liu, 2000; Wang, 2001; Xia & Zhu, 2002; Wang *et al.*, 2004), and after continuous enrichment and improvement, the concept of water resources carrying capacity were adopted as follows: under the principles of sustainable development, certain level of technology, and certain standard of living welfare, the maximum population size that can be supported by the available freshwater resources in an area (Jia *et al.*, 2004). Here, the principles of sustainable development mean that the development and utilization of water resources must be sustainable, neither the non-renewable water resources can be used nor the ecological water can be occupied to destroy the integrity of the ecosystem. Certain level of technology refers to a specific industrial structure and water efficiency level. Certain standard of living welfare means that in a specific stage, the public can accept the per capita GDP, per capita domestic water use quantity, and other living standard requirements (Jia *et al.*, 2004).

China has the potential to become a modern, harmonious, and creative high-income country by 2030 (World Bank & Development Research Center of the State Council, 2010). The national population development plan predicts 1.45 billion population by 2030 (State Council, 2016), with an urbanization rate of 70% (State Council, 2016). According to the current development speed and progress path: can the 'dual control' rigid constraints support the future regional development? When the expected development goals are achieved, whether total water use quantity will break the water resources' development and utilization limit of 800 to 900 billion m^3 (Jiao, 2011)? This paper builds a mathematical model based on the concept of water resources carrying capacity and 'dual control' rigid constraints to answer the above questions.

Materials and methods

Here, water use quantity represents the direct supply or withdrawal of freshwater instead of water consumption. It is greater than water consumption, which is more meaningful to meet the needs of water resources and ensure water security. This is in line with China's official statistics that total water use quantity includes domestic water use, industrial water use, agriculture water use, and ecology water use. Domestic water use quantity comprises the comprehensive water use quantity for urban residents and water use quantity for rural residents. Comprehensive water use quantity for urban residents is composed of the water used by residents, and the water used for public use (including the water used for tertiary industry and the construction industry). Water use quantity for rural residents refers to the water used by residents. Industrial water use quantity refers to the water used by industry and mining enterprises in the production process for manufacturing, processing, cooling, air conditioning, purification, washing, and other aspects, excluding the internal water reuse. Agricultural water includes irrigation water for farmland, irrigation water for forest and fruit fields, irrigation water for grassland, irrigation water for fish ponds, and water for livestock and poultry. Ecological water use quantity only includes urban environmental water supplied by human measures, and some river and lake wetlands' replenishment, but does not include the water quantity naturally satisfied by precipitation and runoff (http://www.stats.gov.cn/tjsj/zbjs/).

Water resources carrying capacity prediction model

Based on the above water resources carrying capacity concept, with taking efficiency level, per capita welfare standard, water use structure into consideration comprehensively, the prediction model of water resources carrying capacity embodying the principles of water determining population size, water determining city scale, water determining production was constructed with the province. The prediction model is as follows.

Objective function:

$$\max P = [\min(P_1, P_2)] \tag{1}$$

in which, P is the maximum population that can be carried in the future.

Constraints:

$$TW_i \geq WD_i + WI_i + WA_i + WE_i \tag{2}$$

where subscript $i = (1, 2, 3, \ldots, 31)$ denotes 31 provinces and regions except Hong Kong, Macao, and Taiwan in China. TW_i is total water use quantity red line that comes from 'the Action Plan for the

Dual Control of Total Water Use Quantity and Water Use Intensity'. *WD* represents domestic water use quantity. *WI* is the actual industrial water use quantity, *WA* is the actual agricultural water use quantity. *WE* denotes ecological water use quantity.

$$WD_i = P_i \times ur_i \times Q_{c,i} + P_i \times (1 - ur_i) \times Q_{r,i} \tag{3}$$

Q_c and Q_r represent, respectively, domestic water use quantity per capita for urban residents and rural residents. *ur* is a proportion of urban population (urbanization).

$$(WI_i + WA_i) = Y_{P_i,i} \times Q_{GDP,i} \times (1 - dp_i) \tag{4}$$

Q_{GDP} denotes the actual water use quantity per US$1,600 (CNY10,000) of gross domestic product (GDP), Y_{P_i} represents GDP under the largest population, *dp* represents water use quantity per US $1,600 (CNY10,000) of GDP decreased proportion.

$$Q_{GDP,i} = (WI_i + WA_i)/Y_{1,i} \tag{5}$$

Y_1 is the actual GDP.

$$Y_{P_i,i} = P_i \times Y_{a,i} \times (1 + gr_i)^{15} \tag{6}$$

Y_a is the actual GDP per capita. *gr* represents GDP per capita annual growth rate.

$$WD_i = TW_i \times dwr \tag{7}$$

dwr denotes domestic water use proportion.

It was deduced from the formulas (2)–(7):

$$P_1 = WD_i/[ur_i \times Q_{c,i} + (1 - ur_i) \times Q_{r,i}] \tag{8}$$

$$P_2 = (WI_i + WA_i)/[Y_{a,i} \times (1 + gr_i)^{15} \times Q_{GDP,i} \times (1 - dp_i)] \tag{9}$$

Water use structure model

Given water resources allocation, domestic water use, ecological water use, industrial water use, and agricultural water use are separated on the grounds of the following formulas. Among them, in accordance with the 'National Comprehensive Plan for Water Resources', industrial water and ecological water are separated by average annual growth rate, 0.9% (Jiao, 2011) and 40% (Jiao, 2011) by the new water supply. Domestic water shall be withdrawn according to the set proportion. Given the availability of data and the accuracy of the results, take the industrial water structure in 2018 as the base year. The mathematical expression is as follows:

$$WD_i = TW_i \times dwr \tag{10}$$

$$WE_i = (TW_i - ATW_i) \times 40\% \tag{11}$$

$$WI_i = iwr \times (1 + 0.9\%)^{12} \times TW_i \tag{12}$$

$$WA_i = TW_i - WI_i - WD_i - WE_i \tag{13}$$

where, iwr denotes industrial water proportion in 2018, ATW_i is total water use red line of the ith province in 2015. The other parameters have the same meaning as the formulas (2)–(7).

Data source and processing

In 2030, the urbanization of each province or region was extracted from 'Population Planning or Town Planning' of each province or region. China's per capita GDP is expected to be US$16,000 by 2030 (World Bank & Development Research Center of the State Council, 2010). Thereby, according to the change rate of 6.46 (http://www.stats.gov.cn/) in 2010 and per capita GDP in 2015, when per capita GDP reaches US$16,000 by 2030, an average annual growth rate of GDP per capita is set at 5%. The National Comprehensive Plan for Water Resources reported water use quantity per US$1,600 (CNY10,000) of GDP will decrease by 40% from 2020 to 2030 (Jiao, 2011). Thus, taking 2015 as the base year, the water use quantity per US$1,600 (CNY10,000) of GDP in 2020 is calculated in the light of the decreasing proportion from 'the Action Plan for the Dual Control of Total Water Use Quantity and Water Use Intensity' (Ministry of Water Resources and National Development and Reform Commission, 2016) and then calculating the 2030s.

According to the 'National Comprehensive Plan for Water Resources', the annual growth rate of urban comprehensive domestic water use quantity can reach 2.9% (Jiao, 2011); however, from 2013 to 2018, the average annual growth rate of total domestic water use quantity is 2.54%, which was compiled by official statistics (Ministry of Water Resources of the People's Republic of China, 2013–2018). Thus, picking up the integer as the nearest whole number, the maximum increase ratio of domestic water is set to 3%. Calculated by official data of China Water Resources Bulletin, from 2013 to 2018, the annual growth rate of comprehensive domestic water use quantity per capita for urban residents and domestic water use quantity per capita for rural residents is 1.2% and 2.1% or so (Ministry of Water Resources, 2013–2018). Hence, the annual growth rate of domestic water use quantity per capita is set at 1 and 2%. Domestic water for residents is a priority, but does not have infinite growth. In this paper, we set the upper limit of 165 L per day of domestic water use quantity per capita for rural residents (Luna *et al.*, 1992; Howard & Bartram, 2003; Naimi Ait-Aoudia & Berezowska-Azzag, 2016), and we chose 2:1 for the ratio of the comprehensive domestic water use quantity per capita in urban areas to that for rural residents (Zhang *et al.*, 2010), and the maximum is 330 L per day for urban residents. When the value of domestic water use quantity per capita for rural residents is greater than 165 L per day, the value is 165 L per day, and when it is lower than 165 L per day, the set value is taken. The same applies to comprehensive domestic water use quantity per capita for urban residents.

Supposing that the water use quantity per US$1,600 (CNY10,000) of GDP can be achieved, we set the following six scenarios (Table 1). It should be stated that the percentage of water use structure is based on 2018, and except for the urbanization rate the other data are based on 2015.

Table 1. Scenario description.

Case	Annual growth rate of GDP per capita	Proportion of domestic water use quantity	Annual growth rate of domestic water use quantity per capita
Case 1	5%	1%	1%
Case 2	5%	2%	1%
Case 3	5%	3%	1%
Case 4	5%	1%	2%.
Case 5	5%	2%	2%.
Case 6	5%	3%	2%.

Results

Water resources carrying capacity (maximum population) in 2030

Under the water use quantity red line of 700 billion m^3, when expected targets of urbanization of 70% and water efficiency (water use quantity per US$1,600 (CNY10,000) of GDP) decrease by 40% from 2020 to 2030 is achieved, the maximum population is 1.55 billion, 1.59 billion, 1.54 billion, 1.43 billion, 1.51 billion, 1.53 billion, respectively, from Case 1 to Case 6 (see Figure 1). Only Case 4, with a population of 1.43 billion, is slightly lower than 1.45 billion from the national planning.

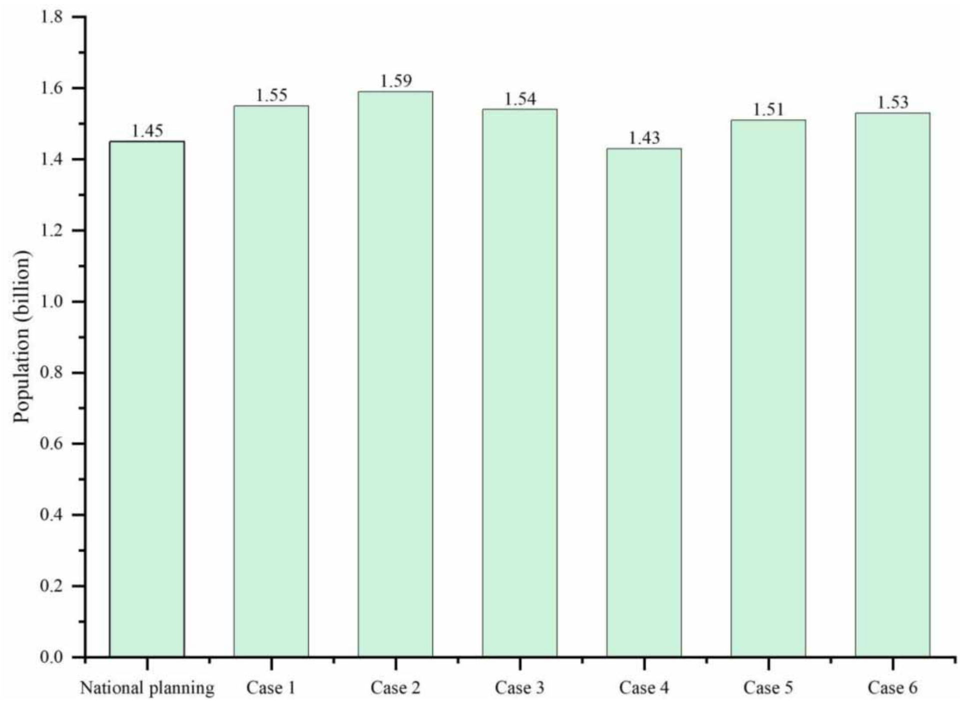


Fig. 1. National planning predicted population and the maximum population under six scenarios.

Water use structure separation

Various water use and water use percentage under different scenarios are shown in Figures 2 and 3. It can be seen from Figures 2 and 3 that agricultural water use is still the largest user. Domestic water use will exceed industrial water use, becoming the second largest user. The proportion of industrial water use will be between 17 and 18%, and the proportion of agriculture water use between 57 and 60% in 2030 (see Figure 3).

At present, in terms of industrial and agricultural water use, during the period of 2013–2018, industrial water use proportion fell from 22.74% to 20.97%, and agricultural water use fell from 63.42% to 61.39%**,** both of which show a downward trend (see Figure 4). Hence, the water use proportion structure under the six cases is reasonable according to historical trend and can meet demand of water for human activities.

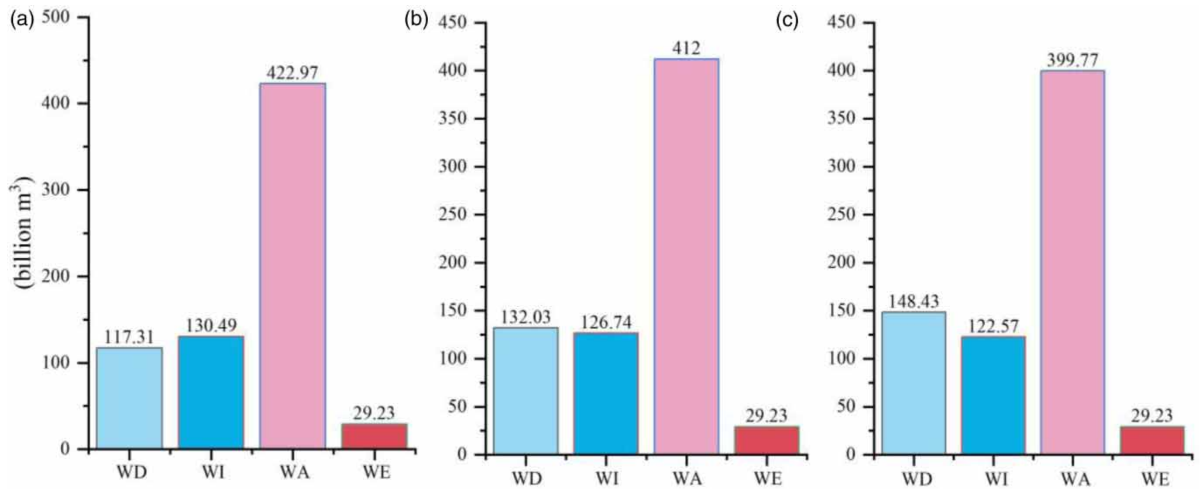


Fig. 2. Different water use quantity under six scenarios of 2030: (a) indicates the same amount of water use for both Case 1 and Case 4; similarly, (b) is for Case 2 and Case 5; and, (c) is for Case 3 and Case 6.

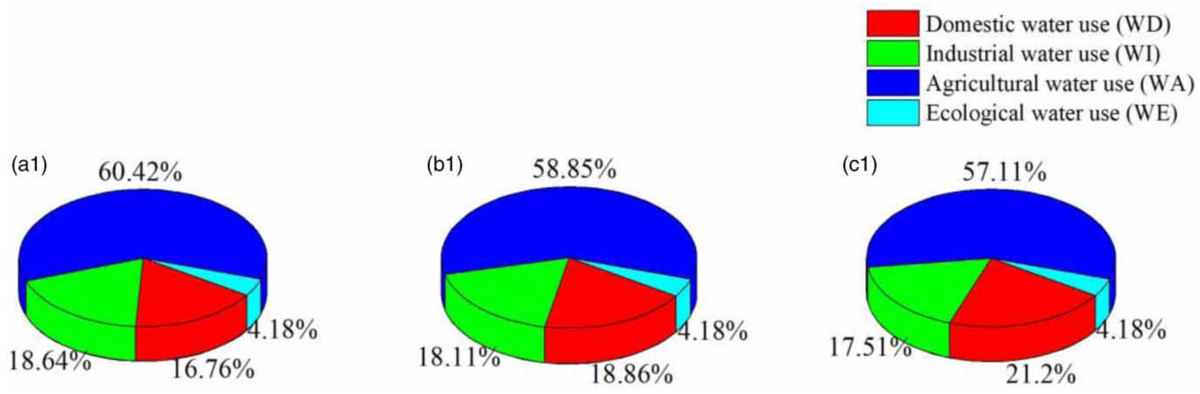


Fig. 3. Different water use proportion under six scenarios of 2030: (a1) indicates the same proportion of water use in both Case 1 and Case 4; similarly, (b1) is for Case 2 and Case 5; and (c1) is for Case 3 and Case 6.

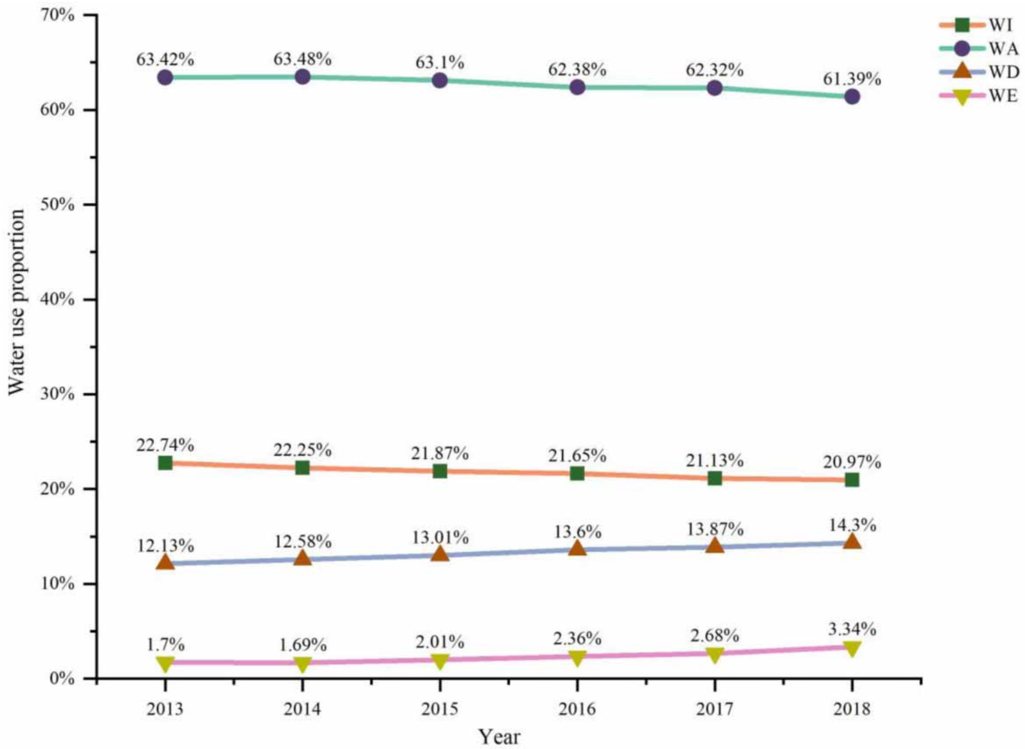


Fig. 4. Water use trend from 2013 to 2018.

Discussion

Comprehensive domestic water use quantity per capita is high and ideal

From Figure 1, compared to the National Population Development Plan, only the scenario of Case 4 is less than 1.45 billion, resulting from the low proportion of domestic water use, while the proportion of per capita increase of domestic water is set high. Lu *et al*. (2014) described that from 2010 to 2014, the growth trend of per capita domestic water use quantity has slowed down significantly, and the total domestic water use quantity has shown a slow growth. After 2015, both will enter the stage of micro growth or even zero growth in the north of China. Hence, generally speaking, a growth rate of 2% per capita domestic water use quantity for urban and rural areas is high and ideal, not merely in Case 4. Moreover, the upper limit of 330 L per day of comprehensive domestic water use quantity per capita in urban areas is relatively high. In fact, water use quantity per capita for urban residents has presented a downward trend or no obvious trend in developed countries and some cities of China (see Supplementary material, Tables S1 and S2). For example, per capita domestic water use quantity in Berlin, Germany fell from 220 L per day to 115 L per day (Naimi Ait-Aoudia & Berezowska-Azzag, 2016); in Luxembourg, domestic water use quantity per person dropped from 242.8 L per day in 2010 to 200.5 L per day in 2017, a decrease of more than 17% since 2010 (Grand Duchy of Luxembourg Statistics, 2019); and, in Anhui, China, comprehensive domestic water use quantity per capita in urban areas dropped from 213 L per day in 2012 to 200 L per day in 2018 (Ministry of Water Resources of the People's Republic of China, 2012–2018).

Rationality of water structure

Comparing with water use proportion of developed countries. Compared to the current situation of some developed countries, there is a considerable gap between Chinese water use structure and that of developed countries. We calculated industrial water use proportion and agricultural water use proportion of developed countries from 2015 to 2016 (see Table 2). On the whole, the average value of industrial and agricultural water use proportion is below 12 and 27%, respectively, and there is still a downward trend in some countries. Among the above scenarios, in 2030, industrial water use minimum percentage of 17.51% and agricultural water use minimum percentage of 57.11% are lower than the average levels of developed countries in 2015 and 2016. Thus, from the point of view of catch-up speed, the scenarios' proportions are reasonable.

Agricultural water use and ecological water use security. According to the National Comprehensive Plan for Water Resources, total agricultural water use quantity should reach 407.8 billion m^3 to ensure food security (Jiao, 2011). However, agricultural water use quantity proportion under six scenarios (see Figure 3), in this study, can meet water consumption for food, which is between 399.77 billion and 422.97 billion m^3. In fact, owing to reform and opening up policy, China has achieved a great leap from basic food and clothing to a moderately prosperous society in all respects over the past few

Table 2. Industrial and agricultural water use proportion of developed countries from 2015 to 2016.

	Industrial water use proportion		Agricultural water use proportion	
Country	2015	2016	2015	2016
Australia	1.50%	1.62%	23.85%	26.90%
Belgium	23.85%	–	1.14%	–
Canada	9.25%	–	8.57%	–
Czech Republic	14.14%	13.30%	3.37%	2.90%
Germany	–	17.95%	–	1.23%
Denmark	4.27%	4.44%	55.24%	52.07%
Spain	1.29%	1.23%	65.67%	65.15%
France	8.19%	7.88%	11.43%	11.73%
Greece	1.27%	1.85%	82.72%	79.99%
Japan	13.90%	12.1%	67.59%	67.53%
Korea	10.90%	10.97%	53.18%	52.84%
Lithuania	7.45%	8.89%	14.96%	17.45%
Luxembourg	4.17%	2.78%	1.51%	0.66%
Latvia	10.77%	17.53%	27.97%	31.43%
Netherlands	26.46%	31.80%	1.26%	0.96%
Poland	4.25%	4.40%	8.94%	9.35%
Singapore	3.76%	3.16%	–	–
Slovak Republic	31.35%	31.59%	5.32%	3.75%
Slovenia	4.57%	4.59%	0.41%	0.37%
Sweden	50.65%	–	3.16%	–
United States	5.00%	–	45.59%	–
Average	11.85%	10.36%	25.36%	26.52%

Note: Original data come from https://stats.oecd.org/; '–' denotes lack of data.

decades. Now in China, society's principal contradiction has been shifted from the contradiction between the growing material, cultural needs of the people at the primary stage and the backward social production to the contradiction between the people's growing needs for a better life and unbalanced, inadequate development (http://www.gov.cn/zhuanti/2017-11/14/content_5239477.htm). In short, China's current focus has shifted from basic food security and material needs to regional unbalanced development. Compared to the ecological water quantity of 20.1 billion m^3 in 2018 (Ministry of Water Resources of the People's Republic of China, 2018), the proportion increase of ecological water can also satisfy the restoration and protection of the ecological environment, which is not only the actual environmental needs but also the most stringent water resources management needs.

Rationality of water use efficiency

The trend of water use efficiency. In this paper, water use efficiency, that is, the calculated value of water use quantity per US$1,600 (CNY10,000) of GDP is lower than the actual value, because tertiary industrial water use quantity is not considered, only industrial water and agricultural water. However, if official water use quantity per US$1,600 (CNY10,000) of GDP is adopted, the water use efficiency is overestimated, because both ecological water and domestic water are taken into account in the official calculation, and actually, domestic water and ecological water do not belong to production water use and contribute nothing to GDP. By calculation, in recent years, both ecological water and domestic water account for more than 10% (Bureau of Statistics of the People's Republic of China, 2014–2019), and the water use for tertiary industry, construction industry, and urban public life has been about 7% or so (Bureau of Statistics of the People's Republic of China, 2014–2019), among which, urban public life water has no contribution to GDP. Furthermore, the proportion of water used by tertiary industry and the construction industry is less than 7%, which is ignored. Hence, the water use quantity per US$1,600 (CNY10,000) of GDP is slightly biased. According to 'the Action Plan for the Dual Control of Total Water Use Quantity and Water Use Intensity' and 'National comprehensive plan for water resources' in 2020, water use quantity per US$1,600 (CNY10,000) of GDP will decline by 23% (Ministry of Water Resources and National Development and Reform Commission, 2016) from 2015 and will reduce by 40% (Jiao, 2011) by 2030 from 2020. At national level, water use quantity per US$1,600 (CNY10,000) of GDP will fall to 41.58 m^3 for 2030 from 90 m^3 in 2015 (Ministry of Water Resources of the People's Republic of China, 2015). In this paper, on the basis of the calculation method of the province as a unit, in 2030, the national average water use quantity US$1,600 (CNY10,000) of GDP is 45.72 m^3 more than the 41.58 m^3 above. On the other hand, water use quantity per US$1,600 (CNY10,000) of GDP has dropped by 18.9% during the period of 2015–2018 (http://qgjsb.mwr.gov.cn/zwxw/jsyw/201908/t20190814_1353270.html). Hence, by 2020, water use quantity per US$1,600 (CNY10,000) of GDP reductions by 23% than in 2015 will be achieved. From 2020 to 2030, a decreased proportion of 40% in water use quantity per US$1,600 (CNY10,000) of GDP will be achieved.

Comparing with water use efficiency of developed countries. Compared to the current situation of some developed countries, water use per US$1,600 (CNY10,000) of GDP of 25 developed countries from 2015 to 2016 was calculated (see Table 3). The average value of water use per US$1,600 (CNY10,000) of GDP is 23.53 m^3 and 22.47 m^3, respectively, in 2015 and 2016. In terms of 2015 and 2016, average decrease ratio reached 8.98% from 25 developed countries. Based on past experience, the decrease ratio of water

Table 3. Water use quantity per US$1,600 (CNY10,000) of GDP for developed countries in 2015 and 2016 (unit: m^3).

Country code	2015	2016	Decrease ratio (%)
Australia	23.47	19.37	17.45%
Belgium	13.94	–	–
Canada	33.07	–	–
Czech Republic	13.84	12.70	8.21%
Germany	–	10.68	
Denmark	4.33	3.60	16.80%
Spain	42.59	38.44	9.73%
France	18.60	16.27	12.54%
Greece	81.29	87.24	−7.32%
Hungary	52.19	47.04	9.87%
Japan	29.34	–	–
Korea	31.15	28.25	9.30%
Lithuania	16.00	11.98	25.11%
Luxembourg	1.27	1.12	11.23%
Latvia	10.52	12.26	−16.62%
Netherlands	17.73	15.45	12.86%
Poland	37.47	35.80	4.45%
Singapore	2.53	2.29	9.42%
Slovak Republic	10.46	9.39	10.26%
Slovenia	33.50	30.03	10.36%
Sweden	7.61	–	–
United States	34.28	–	–
Australia	23.47	19.37	17.45%
Average	24.53	22.47	8.98%

Note: Original data come from https://stats.oecd.org/; '–' denotes lack of data.

use per US$1,600 (CNY10,000) of GDP will slow down. Thus, two assumptions are set. First, depending on the assumption of an average decrease ratio of 5%, the average value of water use quantity per US$1,600 (CNY10,000) of GDP for developed countries in 2030 is about 11.4 m^3. Second, according to the assumption of an average decrease ratio of 2%, the average value of water use quantity per US$1,600 (CNY10,000) of GDP for developed countries in 2030 is about 17.43 m^3. In the rationality of the above water use efficiency, neither 47.58 m^3 nor 41.23 m^3 are lower than those of developed countries except Greece and Hungary. There is still a vast difference to developed countries.

To sum up, no matter the development trend of China itself or catch-up speed with the developed countries, water use proportion and water use efficiency have their own reasonability.

Conclusions

It can be known from the above calculation results, under the above six scenarios and the quantity-efficiency constraint, all the results of maximum population are close to 1.45 billion of the National Population Development Plan to achieve the urbanization goal of 70% (State Council, 2016). In other words, by 2030, following the current path and development speed, water resources rigid constraints basically can support population and economic growth. Total water use quantity will not exceed the limit of 800 to 900 billion m^3 (Jiao, 2011), which is enough to achieve the expected goals of social and economic development. In part of the discussion, about water use structure and water use efficiency, we further expound that the scenarios' setting conforms to China's own development trend, and from the perspective of catch-up, the development speed of water use structure changes and water use quantity per US$1,600 (CNY10,000) of GDP will not exceed that of developed countries. There are significant differences between China and developed countries. Therefore, in order to relieve water resources stress, to improve the water resources carrying capacity, and to accelerate the construction of a water-saving society, some suggestions are put forward. First of all, we should further strengthen the propaganda regarding China's water resources situation and education of the people's consciousness and public awareness for saving water. At the same time, we should implement the policy of water price reform by the State Council, using the economic lever water price, to promote saving water in various industries, and to establish a water-saving economy and society. Second, the construction of water-saving irrigation projects and the spread of water-saving irrigation technologies should be accelerated. In particular, in areas where water resources are scarce and where large-scale crops are cultivated, micro-irrigation and drip irrigation and other high-efficiency water-saving irrigation technologies should be actively promoted to improve the agricultural water utilization efficiency. Third, water-saving measures of biotechnology and rationally arranging crop planting structure should be actively popularized. Fourth, the renovation of urban water supply pipes to reduce leakage and waste for improving water efficiency should be promoted. Fifth, the wide use of water-saving utensils and equipment should be promoted. Sixth, adjusting the structure of high-water consuming industries, strictly implementing water quota management, and rationally allocating a water quota for industrial enterprises should be carried out. Seventh, importance should be attached to the use of unconventional water resources, such as construction of rainwater harvesting projects, innovation of seawater desalination technology, and so on.

This study is based upon the rigid constraints of total water quantity and water use efficiency enacted by national policy, taking the regional development level (urbanization) and the welfare level per capita (GDP per capita, domestic water use quantity per capita for urban and rural areas) as the target conditions, and representing the carrying capacity of water resources by population. The premise of the established model is to give priority to domestic water use, followed by ecological water use and production water use, which is consistent with the notion of the most stringent water resources management system and the principles of determining people scale by water, city scale by water, and production by water. The prediction model in this paper can serve as a new way of thinking for the rational allocation of water resources, and can be employed in countries and regions with similar conditions.

Data availability statement

All relevant data are included in the paper or its Supplementary Information.

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