Peak water: future long-term changes driven by socio-economic development in China

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Abstract

Population and economic growth cause an increase in water demand leading to ever-increasing water shortage and water crisis. The paper presents China’s future long-term changes in water demand driven by socio-economic development based on the construction of a water demand model. At the national and state or provincial level, the water demand model was calibrated and validated with historical data involving developed countries and developing countries, respectively, which exemplifies the feasibility and applicability of the model. Through analyzing the historical data and predicting the future water demand, the following conclusions are obtained. First, total water use in 2013 is not peak water. Second, total water demand is projected to continue increasing to an extent, which would not surge for the next few decades. Third, peak water of around 630 billion m$^3$ may appear in 2026 or 2027. Fourth, the peak water will not be beyond 700 billion m$^3$ issued by the National Comprehensive Water Resources Plan from China, even at the possible peak of population. In general, the water demand model can inform early intervention to prepare for times of scarcity and help track the effectiveness of water policy and management activities.

Keywords Socio-economic driving factors · Water security · Future water demand · Peak water

Introduction

Water resources have a crucial role among other natural resources, which is the fundamental for sustaining a high quality of life and economic and social development (Shiklomanov 2000). World Water Scenarios point out that the major focus is the future of water availability (Gilberto 2011; D’Odorico et al. 2020). Water availability (how much water is available) denotes water security. Water security refers to the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development (UN-water 2013). Water use has been increasing worldwide by about 1% per year since the 1980s, driven by a combination of population growth and socio-economic development (World Water Assessment Programme (WWAP) 2015). Global water demand is expected to continue increasing at a similar rate until 2050 (World Water Assessment Programme (WWAP) 2019). Much of this increase will be in developing countries experiencing rapid industrial development (World Water Assessment Programme (WWAP) 2019). In particular, from 2010, demand for water in developing countries witnessing fast and sustainable growth would be increasing by 85% by 2030 (Cosgrove and Cosgrove 2012). Over 40% of world countries would be experiencing a severe freshwater scarcity of 74% by 2030 (Cosgrove and Cosgrove 2012). Although the population facing water shortages will likely decrease after the 2050s, it is widely believed that Asian countries (South Asia and China) will continue to face severe water scarcity (Shen et al. 2014; Zhou et al. 2020). According to national statistics, the total water use across China presented a downward trend since 2013, seemingly moving to economic growth without water demand growth in the past several years (MWR 2000–Ministry of Water Resources of China (MWR) 2019). Meanwhile, the “National Comprehensive
Water Resources Plan” issued in 2011 and the “National Water Conservation Action Plan” released in 2019 forecast China’s maximum water use to be 700 billion m³ by 2030 or 2035 (Jiao 2011). As such, the paper chooses China, where future water demand-peak water was explored. All water or water resources mentioned in this paper refer to freshwater. Ultimately, we aim to answer four main research questions about water security: (1) In China, is there a downward trend in water demand for human use based on the historical trend of populations and economies growth? (2) Has total water use already passed the point of peak water? (3) When will it reach peak water, and what is the range of peak water? (4) Will the peak water exceed the limit of 700 billion m³ issued by National Comprehensive Water Resources Plan (Jiao 2011)?

Before going further, it is vital to understand predominant driving factors of water use and previous water demand prediction to obtain relatively accurate projections as far as possible.

Literature review

Driving factors of water use

Making sustainable water management decisions in an increasing uncertainty requires an improved understanding of driving factors of human water use. Cosgrove and Cosgrove (2012) summarized 10 drivers including agriculture, climate change and variability, demography, economy and security, ethics society and culture, governance and institutions, infrastructure, politics, technology, and water resources. They have varying influences and impacts in different regions of the world. In the process of water use, water demand is either met (abundant water resources) or not (water scarcity) based on a confluence of factors. Water use change largely depends on the socio-economic scenarios, which many researchers agree with despite many factors influencing water demand. For instance, Yoo (2007) reported that regional economic growth results in a higher proportion of water consumption. Population and socio-economic development are the major drivers causing the water scarcity situation to become more severe (Shen et al. 2014). Veldkamp et al. (2015) believed that hydro-climatic variability contributes to the variation in water scarcity in the short term, whereas socio-economic drivers become more critical after 6 to 10 years. Fant et al. (2016) found that socio-economic drivers are more important than the climate in the future of water scarcity. The water demand estimates are sensitive to the underlying assumptions regarding socio-economic drivers such as economic growth (Wad et al. 2016). Alcamo et al. (2007) reported that a better representation of all socio-economic processes is needed in global water studies. Distefano and Kelly (2017) concluded that future water scarcity is the most critical driver of economic growth. To cope with water crises, water resources research should consider directing more attention to the underlying and dominant drivers of demand (Srinivasan et al. 2012).

Combined the above driving factors of human water use, the analysis of China’s water use driving forces is carried out. In China, the population slowly increases (Zhou et al. 2020; National Bureau of Statistics of China (NBS) 2003–National Bureau of Statistics of China (NBS) 2020). The National Population Development Planning predicted that a peak population of 1.45 billion would be reached by 2030 (Council and (SC) 2016). The economy presents an exponential growth trend over the past decades, so it will be in the future (World Bank, Development Research Center of the State Council (DRCSC) 2013; World Bank 2020). To date, China has a great improvement on water supply infrastructures. Water supply through infrastructures had already basically met the human activities demand for water, while the water supply from 2008 to 2019 was almost stable (Jia and Zhu 2020). Additionally, in response to ever-increasing ecological environment deterioration induced by water shortage, Chinese government enacted “the Most Stringent Water Resources Management System” in 2013 (General Office of the State Council (GOSC) 2013). Subsequently, a series of policies were issued including “the Action Plan to Control the Total and Intensity of Water Resources Consumption during the 13th Five-Year Plan period” in 2016 and the “National Action Plan for Water Conservation” in 2019. In summary, in terms of long-term water demand, socio-economic development has larger impacts on the future water demand/supply situation than the other factors in China.

Water demand prediction

Exploring future potential changes in water use, water demand forecasting is a reliable and commonly used mean or tool through a better understanding of the dominant affecting factor for water utilization (Wegelinschuringa 2002; Wong et al. 2010). Many excellent studies have developed various models and methods to project future water demand at a different time and space scales in past decades. Some literature on water demand modeling focuses on the daily or monthly demand as an explanatory variable applying conventional nonlinear iterative models or emerging artificial intelligence techniques to predict urban water demand (K. Tiwari M, and Adamowski J 2015; Ghiassi et al. 2016; Gharabaghi et al. 2019; Capt et al. 2021). Alcamo et al. (2007) set different scenarios including variables of population, per capita gross domestic product (GDP), area of irrigated land and assumed rate of improvement in water use efficiency, etc., to explore
future long-term changes in global water resources. Shen et al. (2008) investigated water withdrawal projections under the Special Report on Emissions Scenarios on the basis of population, energy consumption, water stress index represented economic development, and so on. Zubaidi et al. (2018) selected meteorological data as explanatory variables to predict the water demand of the Yarra River catchment. Pandey et al. (2020) adopted hybrid models and a time series variable of hourly water consumption to predict the short-term water demand. In other studies building on economic and climatic data set coupled with scenario analysis, Sanchez et al. (2020) predicted water demand under future land and climate change scenarios using geographically weighted regression.

To sum up, among existing researches, time series models based on historical data are widely used for water demand forecasting purposes, while daily or monthly water demand usually applies to short-term urban water demand predictions. Water demand predictions integrating meteorological and economic data do not incorporate water use efficiency connecting economic growth with water resource utilization. Commonly, water use efficiency rising was identified as the main driving force to deceleration of human water use (Distefano and Kelly 2017). Nevertheless, few water demand predictions involved potential variations on water use efficiency from the economic perspective of water resource utilization. Moreover, as stated in driving factors of water use, compared to other factors, human economic activities significantly impact water resource utilization. As such, the water demand prediction model was also applied to the other developed countries and regions to examine model rationality.

**Methodology and materials**

As described above, future water demands for all sectors were based on population growth, economic growth, and projected changes in water use efficiency. The basic procedure of the analysis is as follows. First, a water demand forecasting model was built on socio-economic development scenario. Second, per capita GDP and water use efficiency models were simulated by time and per capita GDP in previous years. Third, we selected several traditional criteria and indicators to explore constructed models’ applicability and feasibility. Finally, water demand changes for 2021–2050 were computed. Overall, the future scenario is supposed business as usual. That is, it assumes population and economic trends keep growing. In addition, the water demand model was also applied to the other developed countries and regions to examine model rationality.

**Water demand prediction model**

In general, total water use is divided into domestic water use containing tertiary industry water use, production water use consisting of water for agriculture, and water for industry (Ministry of Water Resources of China (MWR) 2003–2020), coupled with ecological water use according to water resource utilization. As such, the water demand prediction model was developed on the basis of water use classification. The expression is as follows.

\[
TWD = W_D + W_P + W_E
\]  

where \( TWD \) is total water demand, \( W_D, W_P, \) and \( W_E \) represent domestic water demand, productive water demand (agricultural and industrial water demand), and ecological water demand, respectively, at the provincial level.

\[
W_D = P \times Y_a \times Q_U + P \times (1 - Y_a) \times Q_R
\]

where \( P \) denotes population, \( Y_a \) is urbanization degree, namely urban population proportion relative to the total population, \( Q_U \) and \( Q_R \) express the domestic water use per capita in urban and rural areas correspondingly.

\[
W_P = P \times Y_a \times Q_{GDP}
\]

In Eq. (3), \( Y_a \) is per capita GDP, \( Q_{GDP} \) is defined as water use per CNY10,000 of GDP, which represents water use efficiency. Here, it needs to note that water use per CNY10,000 of GDP is different from official statistics, which is measured through the ratio of total water use to GDP. In Eq. (3), \( Q_{GDP} \) is calculated as annual total water use involving industrial water and agricultural water use, not embodying domestic water use and ecological water use. That is attributed to non-productive water demand making no contribution to GDP.
Owing to data availability limitations, the tertiary industry with a small percentage of 2% relative to total water use volume is embodied in domestic water use for urban areas (MWR 2003–2020), not consider.

**Per capita GDP forecasting model**

The experiences of developed countries and developing countries in their development process show that economic growth is not always high-speed but gradually slows down (World Bank and Council 2013; IMF 2019) (see SI). Consequently, the per capita GDP level for each province is projected as a sigmoid-like function of time, depicting features of an S-shape curve the per capita GDP initially grows faster, and the growth rate slows at the middle stage until it finally almost no growth (see Fig. 1a). Per capita GDP growth function over time is as follows.

\[
y = a/[b \cdot \exp(x) + c]
\]  

(4)

Here, \(y\) is per capita GDP at 2019 constant price level, \(x\) represents time with year as a unit. The coefficients \(a\), \(b\), and \(c\) are constants estimated by using 2003–2020 original data; the rest \(\exp\) approximately equals 2.71828. Then, the annual per capita GDP of 2021–2050 were predicted through Eq. (4).

**Water use efficiency forecasting model**

The soft path for water strives to improve the productivity of water use rather than seek endless sources of new supply for the twenty-first century (Gleick 2003). Based on the existent literature on water use and economic growth (Cazcarro et al. 2013; Zhao et al. 2017; Hao et al. 2019), a nonlinear relation involving the Kuznets curve was simulated between gross domestic product and water use within different countries or regions. Analogously, through the historical time series data set (MWR 2003–2020), we find that water use efficiency (water use per CNY10,000 of GDP) changes show an inverted S-shaped curve with the changes of per capita GDP (see Fig. 1b). That curve characteristics show a rapid decrease to a gradual stabilization in water use per CNY10,000 of GDP. The dynamic changes in water use efficiency along with the per capita GDP matter. And then, the fitting function between per capita GDP and water use efficiency can be expressed below.

\[
z = d/[m \cdot \ln y + n \cdot (\ln y)^2 + p \cdot (\ln y)^3 + q]
\]  

(5)

where \(z\) denotes water use per CNY10,000 of GDP, \(y\) is per capita GDP at 2019 constant price, and the coefficients \(d\), \(m\), \(n\), \(p\), and \(q\) are constants estimated by using the 2003–2019 original data. Then, the annual water use efficiency of 2021–2050 was predicted through Eq. (5) combined with Eq. (4), respectively.

**Technical validation**

In order to make the analysis robust and scientific, along with verifying the accuracy of the above models, some traditionally tested criteria, including mean absolute percentage error (MAPE), coefficient of determination of \(R^2\), and symmetric mean absolute percentage error (SMAPE), have been adopted as follows. Independent-samples \(t\)-test was also used.
to analyze the significant difference between estimated and actual values.

\[
MAPE = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{\hat{y}_i - y_i}{y_i} \right|
\]

(6)

\[
R^2 = 1 - \frac{\sum_{i=1}^{n} (\hat{y}_i - y_i)^2}{\sum_{i=1}^{n} (\bar{y}_i - y_i)^2}
\]

(7)

\[
SMAPE = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{\hat{y}_i - y_i}{(\hat{y}_i + |y_i|)/2} \right|
\]

(8)

where \(y_i\) represents measured value, namely actual data, \(\hat{y}_i\) is their fitted value, \(n\) denotes sample size, and \(\bar{y}_i\) indicates mean of actual values. Among the above statistical measures, when \(MAPE = 0\), the constructed model indicates a fully perfect model; when \(MAPE > 1\), it represents an inferior model, the same to \(SMAPE\). The range of \(R^2\) is \([0, 1]\), the bigger, the better, conversely \(MAPE\) and \(SMAPE\) the smaller, the better. In addition, the \(t\)-test was performed at the significance level of 5%.

### Materials and data processing

Water demand, for the scope of this paper, also refers to water use, which means they are equal numerically but different from water consumption, which is the difference between water use and return. These are consistent with official statistics (MWR 2000–2020). There is a water consumption rate between water use and water consumption. Namely, the water consumption rate equals water consumption divided by water use, which cannot be ignored. To avoid underestimating water demand, we employed water demand instead of water consumption, which has more true meaning and guiding reference significance to cope with water shortage and to meet socio-economic, ecologically sustainable development needs for water.

2021–2050 population data and urbanization of each province were collected from Chen et al. (2020) predictions. What needs illustration is that water demand estimation at the provincial level does not contain Hong Kong, Macao, and Taiwan in China due to lack of data availability. The \(Q_U\) and \(Q_K\) were determined by time series data from the China Water Resources Bulletin (MWR 2003–2020). Specifically, the Mann–Kendall method (Hamed 2008) was used to judge the trend of time series data from 2003 to 2020. When existing prominently downward or rise trend, the predicted value by the artificial neural network backpropagation autoregressive method was adopted (Al-Zahrani and Abo-Monasar 2015). If there was no obvious trend, the mean value was selected. Annual per capita GDP and water use per CNY 10,000 of GDP estimations of 2021–2050 were computed by the above Eqs. (4) and (5), taking 2019 as the base year as well as per capita GDP standardized at 2019 constant prices. Among the rest, historical time series data used in this study comes from the China Statistical Yearbook (NBS 2001–2021). Reference to the past patterns and rules, ecological water demand in the coming decades will not be beyond 30 billion \(m^3\) projected by relevant scholars (IGSNRR 2020; Zhao et al. 2021). As a result, in this analysis, ecological water 30 billion \(m^3\) was seen as a constant. That accounts for a lower proportion of total water demand in accord with historical trend characteristics, which has little impact on the future water availability.

### Results

#### Models performance and accuracy

Through the water demand model, we employed relevant variables obtaining 2003–2020 estimated water demand. Compared to the actual value and estimated value by the tested parameters of the 3.4 part, the models’ applicability and rationality were tested at the provincial level. Of these parameters, the ranges of \(MAPE\) and \(SMAPE\) are \([0.37%, 3.8\%]\) and \([0.36%, 3.55\%]\) correspondingly, and the coefficient of determination of \(R^2\) is all greater than 0.9 in each province. At the significance level of 5%, all provincial estimates passed the test. These signify that water demand model has good performance.

Per capita GDP and water use efficiency fitted models were verified by actual values and fitted values through several traditional test statistical standards in 3.4 part. On the ground of water demand estimation at the provincial level, each provincial fitting model was tested one by one. The ranges of \(R^2\), \(MAPE\), and \(SMAPE\) of per capita GDP fitted model are \([0.9918, 0.9999]\), \([0.31%, 3.58\%]\), and \([0.31%, 3.62\%]\), respectively. The ranges of \(R^2\), \(MAPE\), and \(SMAPE\) of per capita GDP fitted model are \([0.9475, 0.9997]\), \([0.93%, 10.08\%]\), and \([0.93%, 9.91\%]\), respectively. According to their standards of judgment, the value of \(R^2\) is close to 1 and big enough, which points toward the better goodness of fit of the model. Similarly, the values of \(MAPE\) and \(SMAPE\) are slightly higher than 0, which means a perfect fitted model. Analogously, at the 5% significance level, the values of probability \(p\) for the per capita GDP model and water use efficiency model are above 0.9, far greater than 0.05 by a \(t\)-test that illustrates the fitted models are reasonable and practicable. These figures make the models more convincing and confidential.
Water demand forecasting

The total water demand was obtained by integrating the separate estimations of productive, domestic, and ecological demands for every province and taking into account urbanization, per capita GDP, water use efficiency, and how much water the urban and rural residents need. These made the predictions more accurate and reliable. Figure 2 shows potential changes in future total water demand, domestic water demand, industrial water demand, and agricultural water demand. In order to facilitate comparison with historical trends and find peak points, the actual water use from 2002 to 2020 and the projected water demand from 2021 to 2050 were exhibited in Fig. 2.

![Water use of 2003–2020 and water demand prediction from 2021 to 2050.](image)

(c) Total water demand from 2003 to 2050  (d) Domestic water demand from 2003 to 2050

(e) Agricultural water demand from 2003 to 2050  (f) Industrial water demand from 2003 to 2050

**Fig. 2** Water use of 2003–2020 and water demand prediction from 2021 to 2050. c Total water demand from 2003 to 2050. d Domestic water demand from 2003 to 2050. e Agricultural water demand from 2003 to 2050. f Industrial water demand from 2003 to 2050
Total water demand

Figure 2c illustrates the historical transmutation of water use and future potential total demand changes from 2021 to 2050. The existing peak point in 2013 is not yet real peak water. It is expected to reach around 630 billion m$^3$ of peak water in 2026 or 2027 with a high probability, far below 700 billion m$^3$ limited by the “National Comprehensive Water Resources Plan” issued in 2011 and the “National Water Conservation Action Plan” in 2019. Afterward, as the population declines and rising water use efficiency, demand for water shows a decreased tendency that just what we expected, remaining around 610 billion m$^3$ by 2050. Although there is a large gap between the previous forecast of 700 billion m$^3$ under water security and projected peak water in this analysis, the mindful awareness to respond to water security cannot be let down because of the uncertainty of future scenarios, including natural calamities, emergencies, economic stability, and technological innovation speed. By comparison with developed countries, China considered decades’ lags behind developed countries in peak water. Such as in the 1980s, peak water had been reached in the USA (Gleick and Palaniappan 2010) and in France and Germany in the 1990s (Zhang 2013; IGSNRR 2020).

Domestic water demand

Domestic water demand must take precedence over agricultural and industrial water demand, which is the basic to meet human drinking water service. Hence, it was determined predominantly exactly by population and per capita water use, in more detail, through per capita water use for urban and rural areas representing per capita welfare level and well-being. On the whole, domestic water use shows an upward trend (see Fig. 2d), but it is not increasing all the time. In summary, future potential changes in domestic water demand presented a slow upward consistent with the historical time series, expected totaling about 100 billion m$^3$ of peak domestic water demand. From the perspective of water use structure, the domestic water percentage rose from 11.26% in 2002 to 14.8% in 2020, on average, rising 0.18% every year. In California, 17.6% of water consumption is for residential, commercial, and industrial use (Wilson et al. 2016); the rest is for the agricultural sector. In comparison, future domestic water demand will reach approximately 16% of total water demand, which can meet human use.

Productive water demand

Advance in water use efficiency results in less productive water use. As shown in Fig. 3, productive water demand displayed a decreased trend. Of productive water demand, it contains only agricultural water demand and industrial water demand. On the basis of statistics for the past few decades, agricultural water use accounts for a considerably large proportion of 70–76% of productive water demand (Ministry of Water Resources of China (MWR) 2002-2019). In light of this, agriculture water demand was separated by a proportion of 75% according to the proximity principle and for meeting irrigation demand to ensure food security at the same time. Thus, the potential changes in agricultural water demand and industrial water demand, as shown in Fig. 2e–f, have a downturn. On the one hand, in terms of agricultural water demand, in spite of the existing decreased trend, before 2045, the projected are higher than actual water use in 2019. Furthermore, the “National Comprehensive Water Resources Plan” emphasized that on the basis of vigorously improving agricultural water use efficiency and rational allocation of water resources, irrigation water supply will be maintained at 350–380 billion m$^3$ to ensure food security. It can be seen from Fig. 2e that the forecast by 2050 is still greater than 350 billion m$^3$ in the context of the decreased situation. Consequently, agricultural water demand estimations from 2021 to 2050 are reasonable that can satisfy irrigation water need under continuous popularization of water-saving technology measures and increasing water use efficiency. On the other hand, as far as industrial water demand is concerned, before 2047 the forecasts are more excellent than 2019’s industrial water use 121.74 billion m$^3$ (MWR 2019), and the minimum in 2050 is only slightly lower than the current 121.74 billion m$^3$ (see Fig. 2f). While comparing with water use per CNY10,000 of GDP, water use per CNY10,000 industrial added value is falling faster (National Office of Water Conservation (NOWC) 2019), mainly due to industrial water reuse; usually official industrial water use only consists of new freshwater withdrawal and not contains reuse water. Especially in developed countries, the rate of water reuse has reached a high proportion. For instance, nearly 80% of water used in the industrial sector is recycled in Japan (Oki and Kanae 2006). With continuous improvement in technology, more industrial water reuse will reduce new freshwater withdrawal. Hence, separated industrial water quantity is able to meet the future need for water.

As can be seen from Figs. 2 to 3, there is a difference between 2020 and 2021. On the one hand, there is an error in water demand estimates for different purposes in each province, which leads to the increase of the error in the estimation of national water demand. On the other hand, as the population grows, domestic water demand is incremental; and continuous improvement in the ecological environment requires more water. Moreover, in 2020, owing to the outbreak of COVID-19, the economic development stagnated, and production water use was decreased. However, on the whole, under normal economic growth with no major shock, the demand forecast is not false high within a reasonable error range and can satisfy certain development needs.
The model applies to the other regions

In order to increase the credibility of the water demand model, the water demand model is also applied to developed countries at both state and national levels, including New South Wales, Victoria, and Queensland of three states in Australia; together with California, Florida, New York, Texas, and Pennsylvania of five states in the USA; and Spain and Hungary as verification samples. To be more specific, the calculation of productive water demand in all regions is consistent with Eq. (3). Regarding domestic water use estimation, as a result of statistics difference between China and those regions, the domestic water demand estimates differ slightly from China without deviating from the same principle of quota calculation as Eq. (2). In Australia, domestic water use calculations were obtained by estimated household water use times per household every year from 2015 through to 2019 correspondingly. In the USA, total domestic water use was estimated by total population and domestic per capita use. In Spain, per capita domestic water use is multiplied by total population equals annual total domestic water from 2012 to 2016. In Hungary, water abstraction for public water supply equals water abstraction by public water supply per capita is multiplied by the total population. See supplementary information (SI) for detailed data. Moreover, we also did a significant difference test between the actual values and estimations in developed countries by traditional metrics in the “Technical validation” section. As shown in Table 1, favorable rationality of the water demand model has been proved.

To sum up, the water demand model presented in this paper is not confined to a specific region or country that is widely available in different areas. It has relatively accurate characteristics to future water demand estimations.

### Discussion

Any long-run study comes with a set of difficulties that consist of intrinsic unpredictable events. We considered a business-as-usual scenario that maintains historical development features as our assumption. Hence, the predictions...
based on socio-economic progress have some limitations and uncertainty as well.

**Technical uncertainty**

A considerable number of water technologies, such as water conservation technologies, sewage treatment technologies, greywater recycling, reclamation techniques, and desalination of seawater technologies, hold the prospect of increasing the amount of water for human use or of all. It is expected that desalination could produce 25% of the drinking water for cities by the end of the 2040s, but it could produce 5% of water used for agriculture by mid-century worldwide (Cosgrove and Cosgrove 2012). In China, water supply from unconventional water source projects embodying desalination, rainwater harvesting, and sewage treatment have taken shape on a certain scale. Presently, of these projects, there are nearly 4,000 sewage treatment plants (DMSPE 2017), 142 seawater desalination projects (Department of Marine Strategic Planning and Economics (DMSPE) 2018), and the rate of urban sewage reuse has reached 15% (Yan 2018). So far, their totaling water supply accounts for around 2% (MWR 2000-2020), indicating that freshwater resources abstraction is still a source of water supply. Furthermore, as stated earlier, there is still a lot of room for advancement in water use efficiency by comparison with other developed countries. With continuing technological improvements, extension, and expansion, these can significantly reduce water stress and increase water available volumes. Technical progress and innovation are difficult to quantify with uncertainty, as a consequence, neither no consideration of technical progress separately nor unconventional water resources scale in the coming decades. As a rule, there is a nonlinear relationship between economic growth (per capita GDP) and water use efficiency as described above. And future water use efficiency is inferred by possible economic size in the future.

**Water-related policy uncertainty**

Up to the present, since “the Most Stringent Water Resources Management System” was enacted, in which the total water use volume of each province has been ruled. There is an examination of implementation every year, whose assessment result shows a fine performance to water use reduction due to water resources management policy (MWR 2019). In the USA, the implementation of the Clean Water Act led to reductions in industrial water use and physical and economic constraints on access to new supplies (Gleick and Palaniappan 2010). Additionally, increasing water price of reform measures dramatically expands the potential for demand management to make water savings of 30–40% readily (Brooks and Brandes 2011). For example, in Los Angeles, water price increase, as well as mandatory conservation measures, resulted in a 22% reduction in water demand between 2007 and 2015 (Ashoori et al. 2017). Water resources management of hard infrastructure for water supply has turned into water government of soft path. Water soft path requires a broader institutional approach to water resources management, including various policy and economic tools couple with social forces (Gleick 2003; Brooks and Brandes 2011; Yang 2013; Cao 2020). Water resources management requires a more institutionalized approach to balance the relationship between ecological sustainability of water use and social sustainability over a long period of time (Yang 2013). Hence, soft paths are a long-term approach to water management for the twenty-first century (Gleick 2003; Brooks and Brandes 2011). Future policy formulation affecting water demand relies on unknown scenarios change. How much soft path is responsible for water availability, yet there remains uncertainty to direction and effectiveness for designing programs and policies to varying degrees.

**Population prediction uncertainty**

In spite of the population prediction considering many contributing factors of the fertility rate, population mobility, education degree, population structure, and so on, as depicted by Chen et al. (2020), there are some still uncertainties, particularly policy uncertainties which will influence the projection and distribution for the population. Such as in the metropolis of Beijing and Shanghai, their upper limitation for accommodating population is 23 million (Zhang 2015) and 25 million (Luo 2017) respectively released by local government, in order to relieve “urban disease” of natural resources shortages and the like (Chen et al. 2020). Concerns on water supply and demand are all the time in tight balance in mega-cities (People's Government of Beijing Municipality (PGBM) 2016). Other relevant policies also can encourage or restrict population migration between regions. Moreover, the current fertility rate of population policy does not seem to be having a good effect (Chen and Miao 2020), inducing not optimistic future population increase. The projections used in this analysis do not consider the above impacts. At the same time, in light of the above definition for urbanization, there are also more or less deviation on the number of urban residents and rural residents. Further, the accuracy of water demand prediction is challenged. But in general, the population projections selected in this paper have high precision than the similar publications because of numerous considerations involving age, sex, educational levels, etc.
Uncertainty about the future economic environment

Water use efficiency plays a critical role in water use change, determined by per capita GDP through Eq. (5). However, per capita GDP variation is susceptible to the economic environment. The exponential growth of per capita GDP is predicted on the absence of major economic fluctuations. On the other hand, globally, emerging economies are on the rise who need more robust demand for everything than advanced economies (Cosgrove and Cosgrove 2012; IMF 2019). That will aggravate global competition between countries, leading to greater uncertainty for the global economic environment. On the other hand, emergent events could swiftly take society in a completely different direction, such as the global economy is experiencing one of the sharpest recessions on record due to the COVID-19 pandemic spread widely. By water itself, the growth of international trade has aggravated water stress in some countries (World Water Assessment Programme (WWAP) 2009). Over 40% of intra-state wars are linked to the exploitation of natural resources (World Water Assessment Programme (WWAP) 2009).

Regarding the Chinese domestic economy, the GDP growth with a positive growth trend since the second quarter of 2020 (NBS 2020) will be expected to rebound in 2021 (World Bank 2020). As a result, we predicted optimistically that the future economy still shows slow and exponential growth. To sum up, economic environment shock will cause a change in water demand. As stated earlier, socio-economic development is the major factor for water. Sudden economic expansion or economic depression will escalate or decrease water demand directly and indirectly (Makki et al. 2015).

Despite all kinds of uncertainties, the predictions through annual calculations at the provincial level have the characteristics of higher accuracy. As a result, water demand in the coming decades will not increase substantially with a high probability. At a certain point, long-run forecasting is mandatory for planning and designing of water resources management. As we move into a future where water security events are projected to be more frequent and intense, it is reasonable to assume that demand-side researches will become ever more strategic (Maggioni 2015).

Conclusion

Accurate and realistic water demand prediction to reconcile sustainable water resource utilization with meeting economic and environmental demands is still challenging. In the long run, the main driving factor of water resource utilization is socio-economic development, according to the previous research achievements. This study presents a synoptic view of water demand during 2021–2050 across business-as-usual scenarios with a socio-economic perspective. In short, long-term changes in water demand for all sectors were based on population, economic development, and projected variation in water use efficiency.

We hope to heighten the awareness of how to be better prepared for potential changes in water resources through such projections. The objective of presenting these predictions is to understand the possible range of future outcomes and the magnitude of the challenges to build more robustness in decision-making and lower system failure risks through demand management measures. The projected work can offer more information on future water demand. The results may serve as an informational tool for the stakeholders. The key conclusions of this study can be summarized as follows. First, water use efficiency is identified by economic growth; in other words, water use per CNY10,000 of GDP is determined mainly by per capita GDP. Second, total water demand is projected to continue increasing to an extent, which would not surge for the next few decades. Peak water of around 630 billion m$^3$ (see Fig. 2c) appeared in 2026 or 2027 possibly will not be beyond 700 billion m$^3$ rather than an inflection point for peak water of 2013. Third, domestic water demand shows a slowly rising tendency integrally from 2021 to 2050 but existing certain dynamic changes. It can be seen from Fig. 2d that the peak of domestic water is 100 billion m$^3$ approximately. Fourth, owing to water use efficiency continuous enhancement, total productive water demand will present a decreased trend with no considerable amplitude of variation. As Alcamo et al. (2007) predicted, in the 2050s, productive water demand, especially the agriculture sector, continues to have the largest volume of water withdrawals but does not undergo substantial increases. By comparison, domestic water experiences some dynamic changes.

Since myriad drivers determine the future situation, it is rarely possible to consider all of them simultaneously. Scenario prediction based on historical trends is still of practical significance to assess their combined influence on the variables of interest that characterize the future. Peak water can help water managers, policymakers, and the public understand and manage water systems more effectively and sustainably. Water demand prediction by province by year can help shift the way freshwater resources are managed toward more productive, equitable, efficient, and sustainable use.

Moreover, the input variables in the same scenario are more accurate for the prediction, but at the same time, there is a lack of qualified continuous and scientific data for many years, so the business-as-usual scenario is more close to the actual situation. As a result, we considered a business-as-usual scenario that maintains historical development features as our assumption. Then, we selected Chen et al. (2020) predictions about urbanization and population under the business-as-usual scenario. A single scenario is a shortcoming in this study; next, we will explore more scientific scenarios.
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Declarations

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Consent for publication  Not applicable.

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