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Domestic water demand forecasting in the Yellow River basin under changing environment

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Abstract

Purpose – The purpose of this paper is to develop a statistical-based model to forecast future domestic water demand in the context of climate change, population growth and technological development in Yellow River.

Design/methodology/approach – The model is developed through the analysis of the effects of climate variables and population on domestic water use in eight sub-basins of the Yellow River. The model is then used to forecast water demand under different environment change scenarios.

Findings – The model projected an increase in domestic water demand in the Yellow River basin in the range of 67.85×10^8 to 62.20×10^8 m³ in year 2020 and between 73.32×10^8 and 89.27×10^8 m³ in year 2030. The general circulation model Beijing Normal University-Earth System Model (BNU-ESM) predicted the highest increase in water demand in both 2020 and 2030, while Centre National de Recherches Meteorologiques Climate Model v.5 (CNRM-CM5) and Model for Interdisciplinary Research on Climate- Earth System (MIROC-ESM) projected the lowest increase in demand in 2020 and 2030, respectively. The fastest growth in water demand is found in the region where water demand is already very high, which may cause serious water shortage and conflicts among water users.

Originality/value – The simple regression-based domestic water demand model proposed in the study can be used for rapid evaluation of possible changes in domestic water demand due to environmental changes to aid in adaptation and mitigation planning.

Keywords Climate change, Statistical model, Water demand forecasting, Water resources management, Yellow river

Paper type Research paper

1. Introduction

Climate change, rapid social economic development and population growth have imposed significant challenges to sustainable development all around the world (Nigel and Ben, 2014, Wang *et al.*, 2014a, 2014b; Shahid *et al.*, 2014, 2016). As a unique and increasingly scarce commodity, water is among the most significantly affected resources by these changes. Ensuring continuous and adequate water supply to growing population and developing economy is one of



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the major concerns for policy makers and scientists (Butler and Memon, 2006; Kim *et al.*, 2014). It is much more challenging in arid and semi-arid river basins in Australia, Middle East, Africa and Northern China due to limited availability of water resources (Howe *et al.*, 2005; Butler and Memon, 2006; Wang *et al.*, 2012a). Understanding possible future changes in water demand is essential for the development of effective climate change adaptation policies (Shahid *et al.*, 2017).

Water demand is influenced by various factors such as population growth, technological development, climate change, social-economic (Wang *et al.*, 2016a). The complex interactions of different influential factors have made the forecasting of water demand a difficult task (Vörösmarty *et al.*, 2000; Downing *et al.*, 2003; Alvisi *et al.*, 2003; Babel *et al.*, 2007; Khatri and Vairavamorthy, 2009; Wang *et al.*, 2015). A number of studies have been carried out to predict water demand (Combalicer *et al.*, 2010; Dursun, 2010; Jakimavičius and Kriauciūnienė, 2013; Wang *et al.*, 2016b). The approaches generally used for forecasting water demand can be classified into three broad classes, namely, time series, econometric and end-use forecasting (Zhou *et al.*, 2000; Alvisi *et al.*, 2003; Altukaynak *et al.*, 2005; Bougadis *et al.*, 2005; Khatri and Vairavamorthy, 2009; Caiado, 2010; Wang *et al.*, 2017). Besides that, artificial neural network, support vector regression, etc. have been used in a few cases (Ghiassi *et al.*, 2008; Adamowski, 2008). Unfortunately, yet only a few of the traditional forecasting models can adequately manage the dynamics of a water supply system because of the limitations in modeling structures. Potential challenges also arise, as these traditional methods require long-term, continuous historical records of water demand and other variables (Simonovic, 2002; Qi and Chang, 2011).

The impact of climate change on water demand is a major issue in recent years. Most of the recent studies on climate change impacts on water demand are based on the historical relationship between water demand and climate variables such as rainfall, air temperature, sunshine duration, relative humidity and wind speed (Protopapas *et al.*, 2000; Downing *et al.*, 2003; Karamouz *et al.*, 2011). It is widely accepted that water demand will increase due to the increased evapotranspiration caused by higher temperature. However, how to take consideration of climate variables and population growth together for forecasting future domestic water demand is still a challenge.

The Yellow River, originated in the Qinghai-Tibetan plateau of Qinghai province, flows across eight other provinces and autonomous regions of China before it ends into the Bohai Sea (Liu and Zhang, 2002; Wang *et al.*, 2012b). The river plays a key role not only in the country's economic development, but also in the historic and cultural identity of the Chinese people. With approximately 9 per cent of China's population and 17 per cent of its agricultural area depending on the Yellow River basin, it is designated as "the cradle of Chinese Civilization" (Liu and Zhang, 2002; Giordano *et al.*, 2004). Population and economy of the River Basin have grown rapidly in the recent years. This has caused a significant increase in water demand for agriculture, industry and households in the Basin. Consequently, the gap between water supply and demand has widened in recent years (Giordano *et al.*, 2004; Barnett *et al.*, 2006; Gonçalves *et al.*, 2007). Some of the main tributaries of the Yellow River, such as Kuye River and Tuwei River, showed a decreasing trend of runoff, even drying up (Wang *et al.*, 2014b). Increase in demand of water for domestic use due to climate change and population growth may aggravate the existing situation of water shortage in the Basin. Forecasting possible changes in residential water demand is very important for planning and management of water resources of the Basin.

The objective of the present paper is to develop a statistical model to forecast domestic water demand in the context of climate change, population growth and technological development. The proposed model is developed through the analysis of the effects of climate and population on domestic water use and then applied in the Yellow River basin to forecast water demand under different environment change scenarios.

2. Materials and methods

2.1 Data and sources

2.1.1 Water consumption and population growth data. Population growth, domestic water use and economic development data of the Yellow River basin for the period 1980-2012 were collected from China Water Resources Bulletins (MWR, 2000-2012). The recent data of domestic water use in eight sub-basins of the Yellow River, namely, Uperstream of Longyangxia (UL), Longyangxia-Lanzhou (LL), Lanzhou-Hekouzhen (LH), Hekouzhen-Longmen (HL), Longmen-Sanmenxia (LS), Sanmenxia-Huayuankou (SH), Downstream of Huayuankou (DH) and Interior Area (IA), were collected from the Yellow River Water Resources Bulletins (YRCC, 1998-2012). Table I summarizes the basic statistics of collected data for different sub-basins of the Yellow River.

2.1.2 Meteorological data. Daily temperature data of 61 stations for the period 1961-2012 were obtained from National Climate Center of China (NCCC). Climate projections by a suit of seven general circulation models (GCMs), namely, Beijing Climate Center-Climate System Model version 1 (BCC-CSM1-1), BNU-ESM, CNRM-CM5, Goddard Institute for Space Studies Model E version 2 with Russell ocean model (GISS-E2-R), MIROC-ESM, Max Planck Institute-Earth System Model-Low Resolution (MPI-ESM-LR) and Meteorological Research Institute-Coupled Global Climate Model version 3 (MRI-CGCM3), under Representative Concentration Pathways (RCPs) scenario RCP4.5 were also collected from NCCC.

2.2 Domestic water demand forecast modeling

Domestic water demand includes water needs for all residential purposes such as in-house water use for drinking, preparing food, bathing, washing clothes and dishes and flushing toilets, etc. as well as outdoor water needs for gardening, lawn watering, etc. (Alvisi *et al.*, 2003; Garcia *et al.*, 2004; Blokker *et al.*, 2010; Wang *et al.*, 2017). According to the water resources planning technical specifications of China, domestic water demand and population growth can be linked through the following equations:

$$\begin{aligned}
 LW^l &= LuW^l + LrW^l \\
 &= Pu^l \times LQu^l \times \frac{365}{1000} + Pr^l \times LQr^l \times \frac{365}{1000}
 \end{aligned}
 \tag{1}$$

Sub-basin	Area (10 ⁴ km ²)	Precipitation (mm) (1956-2000)	Population (10 ⁴ p) in 2010		Urbanization rate (%) in 2010	Population density (P/km ²) in 2010
			Urban	Rural		
Yellow River	79.5	445.8	4543.27	6824.96	40.0	143
UL	13.1	478.3	14.28	50.95	21.9	5
LL	9.1	478.9	327.12	590.29	35.7	101
LH	16.3	261.9	850.36	755.62	52.9	99
HL	11.2	433.5	265.02	605.98	30.4	78
LS	19.2	540.6	2066.34	3053.14	40.4	268
SH	4.2	659.5	529.66	810.61	39.5	319
DH	2.2	647.8	463.68	928.22	33.3	633
IA	4.2	271.9	26.81	30.15	47.1	14

Table I.
Climate and
population of
different sub-basins
of the Yellow River

where LW^t is the domestic water demand (10^4 m^3), which can be estimated by multiplying the projected population (10^4 p) with the projected per capita water consumption (l/p.d). The urban water demand, LuW^t is estimated by multiplying the urban population, Pu^t (10^4 p), with the per capita water consumption by urban population, LQu^t (l/p.d); the rural water demand, LrW^t , is estimated by multiplying the rural population, Pr^t (10^4 p), with the per capita water consumption by rural population, LQr^t (l/p.d) (Wang et al., 2011).

Equation (1) does not consider climate change for forecasting water demand. Therefore, the equation is modified in this study to incorporate the impact of climate change on water demand, ΔLW^t , as follows:

$$\Delta LW^t = d_T \cdot \Delta T \cdot LW^t \tag{2}$$

where:

$$d_T = \frac{\Delta LW}{\Delta T} \tag{3}$$

where d_T is the climatic elasticity of domestic water demand; ΔLW is the change in domestic water demand (10^4 m^3); and ΔT is the change in temperature ($^{\circ}\text{C}$).

3. Domestic water demand under changing environment

3.1 Population growth and domestic water use

The historical changes and future projection of population in different sub-basins of the Yellow River basin are shown in Figure 1. The highest population in the Yellow River basin is in LS sub-basin, while the lowest population in UL sub-basin. Figure 1 shows that the population in all the sub-basins has increased rapidly over the past years. Population in the Yellow River basin was $8,177 \times 10^4$ in 1980 and the urbanization rate was only 17.8 per cent. The highest rate of urbanization was in LH (33.5 per cent). According to the future plan of River Basin management authority, the total population and urbanization in the Basin will reach $12,658 \times 10^4$ and 50.4 per cent, respectively, in 2020 and $13,094 \times 10^4$ and 58.8 per cent, respectively, in 2030.

The growing population has caused a drastic increase in domestic water demand in the Basin. The domestic water consumption in the Yellow River basin has increased from $11.72 \times 10^8 \text{ m}^3$ in 1980 to $22.66 \times 10^8 \text{ m}^3$ in 2000. The per capita water demand has also increased due to urbanization and changes in socioeconomic condition of the people. The changes in per capita domestic water demand in different sub-basins are shown in Figure 2. The figure shows

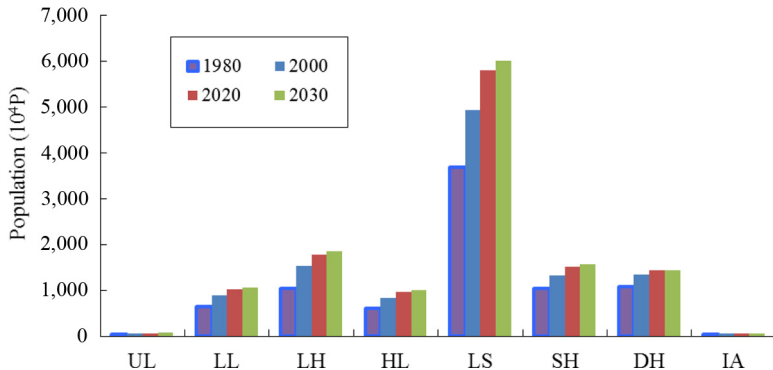


Figure 1.
Historical and projected change in population in different sub-basins of the Yellow River

that the average per capita water consumption in the Basin has increased from only 73 l/p.d in 1980 to 103 l/p.d in 2000. It has been projected that per capita water demand will continue to increase in the Basin and will reach 115 l/p.d and 123.7 l/p.d in 2020 and 2030, respectively.

3.2 Projection of temperature

The climate models projected increase in temperature, but no significant change in rainfall in the Yellow River basin. The projections of temperature by GCMs BCC-CSM1-1, BNU-ESM, CNRM-CM5, GISS-E2-R, MIROC-ESM, PI-ESM-LR, MRI-CGCM3 in the Yellow River basin are shown in Figure 3. The figure shows a increase in temperature before 2030. As there is no change in rainfall, only temperature was considered to assess the impact of climate change on water demand in the Basin.

3.3 Domestic water demand due to climate change

The ensemble mean of the projected temperatures by different GCMs was used to estimate future changes in water demand in the Yellow River basin due to climate change. The changes in residential water demand in different sub-basins due to climate change for the years 2020 and 2030 are shown in Figures 4 and 5, respectively. The figures show increase in water demand in all

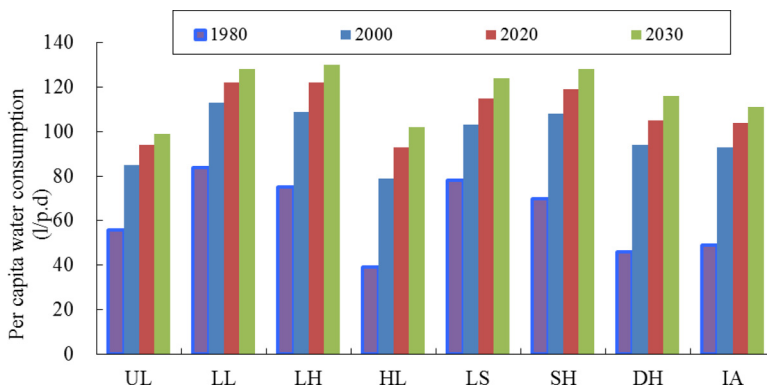


Figure 2. Changes in per capita water consumption in the Yellow River basin

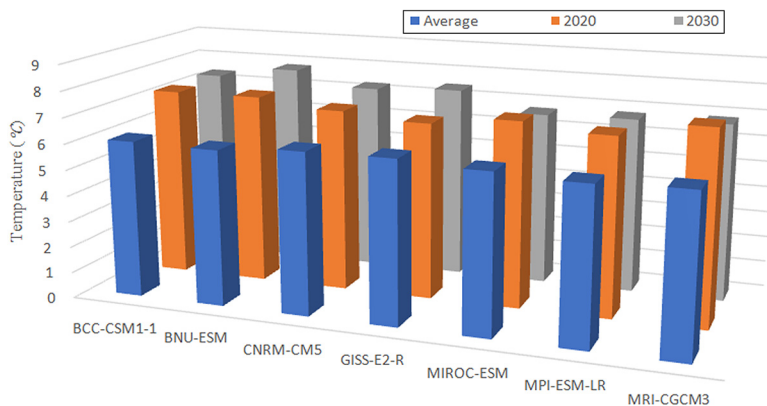


Figure 3. Temperature projections by different GCMs in the Yellow River basin under RCP4.5 in 2020 and 2030

the regions of the Yellow River basin. The highest increase was observed in LS, followed by DH. Domestic water demand in LS is already very high due to large population. Faster increase in water demand due to climate change may aggregate the condition of water scarcity and conflict among water users in the region.

3.4 Domestic water demand under changing environment

The projected growth in population and the advancement in water-saving technologies were also considered along with climate change to forecast domestic water demand in the Yellow River basin. Equation (1) was used to estimate the impact of population growth and urbanization on domestic water demand. Reduction of water demand through the advancement of water-saving technologies as planned by the Yellow River basin authority was then incorporated to estimate the net changes in water demand. Figures 6 and 7 show the projected change in domestic water demand in 2020 and 2030, respectively, due to climate change, population growth and technological advancement together.

Figure 6 shows that domestic water demand will increase in the range of 67.85×10^8 to $62.20 \times 10^8 \text{ m}^3$ in 2020. The GCM BNU-ESM projected the highest increase, while CNRM-CM5 the lowest. The water demand was projected to increase in the range of 89.27×10^8 to $73.32 \times 10^8 \text{ m}^3$ in 2030. The highest increase was projected by BNU-ESM and the lowest by MIROC-ESM. Among the Sub-Basins, the highest increase in water demand was projected in LS and the lowest in UL.

4. Conclusion

A statistical model was developed in this paper to forecast domestic water demand due to changes in climate, population and water-saving technologies. Results showed that

Figure 4. Projected domestic water demand in year 2020 under RCP4.5

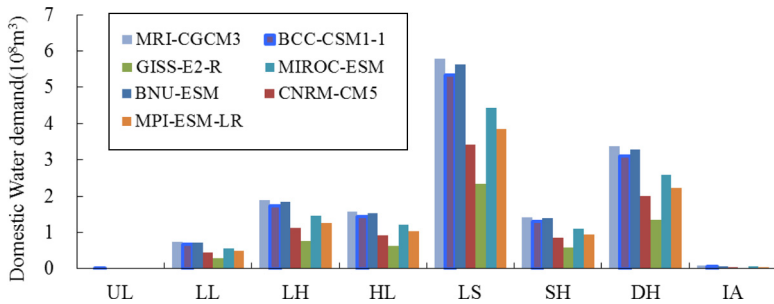
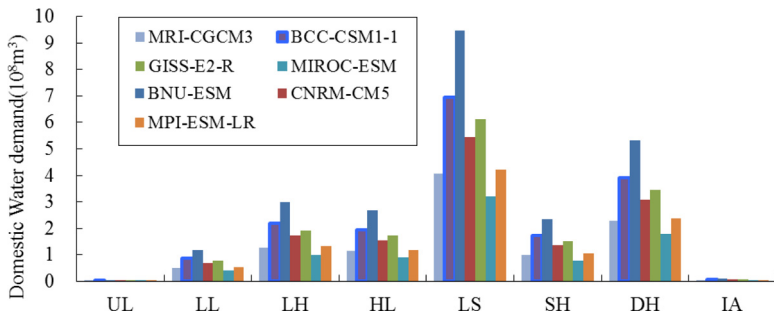


Figure 5. Projected domestic water demand in year 2030 under RCP4.5



domestic water demand in the Basin will increase in the range of 67.85×10^8 to $62.20 \times 10^8 \text{ m}^3$ in 2020 and 89.27×10^8 to $73.32 \times 10^8 \text{ m}^3$ in 2030. The highest increase will be in the LS and the lowest in UL. The LS is the most populated region of the Basin. High water demand due to large population has already made water in the Sub-Basin scarce. It can be anticipated that the rapid increase in water demand due to climate change and population growth will aggravate the situation in the future. It will also increase the competition among water users and, therefore, more conflicts.

The method proposed in the study can be used for rapid evaluation of possible changes in domestic water demand in the context of environmental changes. However, more attention is required for improvement of the method. Following points should be considered for future improvement of the model:

- domestic water demand for different in-house and outdoor activities are different and therefore, impacts of environmental changes on each activity should be evaluated for better projection of water demand;
- only the average temperature was considered to estimate the impacts of climate change on domestic water demand in this study and other climatic variables such as maximum and minimum temperature and humidity can be considered for the improvement of model accuracy; and
- furthermore, future study is required to assess uncertainties in water demand projection for better planning and management of water resources.

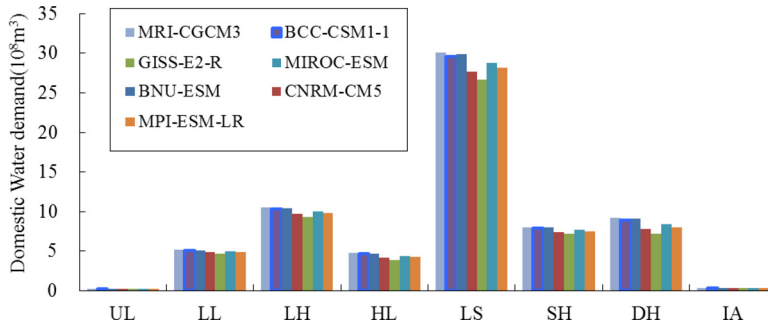


Figure 6. Changes in domestic water demand in year 2020 due to environmental changes

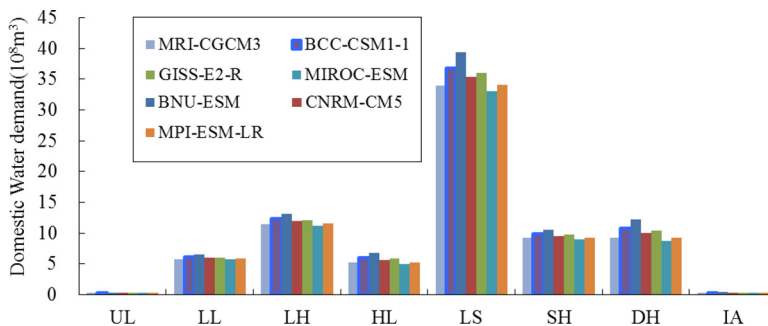


Figure 7. Changes in domestic water demand in year 2030 due to environmental changes

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