Proc. IAHS, 376, 51–55, 2018
https://doi.org/10.5194/piahs-376-51-2018

Forecasting domestic water demand in the Haihe river basin under changing environment

Xiao-Jun Wang[1,2,3], Jian-Yun Zhang[1,2], Shamsuddin Shahid[4], Yu-Xuan Xie[5], and Xu Zhang[1,2]

[1]State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Nanjing Hydraulic Research Institute, 210029 Nanjing, China
[2]Research Center for Climate Change, Ministry of Water Resources, 210029 Nanjing, China
[3]State Key Laboratory of Water Environment Simulation, School of Environment, Beijing Normal University, 100875 Beijing, China
[4]Faculty of Civil Engineering, Universiti Teknologi Malaysia (UTM), 81310 Johor Bahru, Malaysia
[5]Haihe River Water Conservancy Commission, 300170 Tianjin, China

Correspondence: Xiao-Jun Wang (xjwang@nhri.cn)

Received: 8 June 2017 – Accepted: 25 July 2017 – Published: 1 February 2018

Abstract. A statistical model has been developed for forecasting domestic water demand in Haihe river basin of China due to population growth, technological advances and climate change. Historical records of domestic water use, climate, population and urbanization are used for the development of model. An ensemble of seven general circulation models (GCMs) namely, BCC-CSM1-1, BNU-ESM, CNRM-CM5, GISS-E2-R, MIROC-ESM, PI-ESM-LR, MRI-CGCM3 were used for the projection of climate and the changes in water demand in the Haihe River basin under Representative Concentration Pathways (RCPs) 4.5. The results showed that domestic water demand in different sub-basins of the Haihe river basin will gradually increase due to continuous increase of population and rise in temperature. It is projected to increase maximum $136.22 \times 10^8\,m^3$ by GCM BNU-ESM and the minimum $107.25 \times 10^8\,m^3$ by CNRM-CM5 in 2030. In spite of uncertainty in projection, it can be remarked that climate change and population growth would cause increase in water demand and consequently, reduce the gap between water supply and demand, which eventually aggravate the condition of existing water stress in the basin. Water demand management should be emphasized for adaptation to ever increasing water demand and mitigation of the impacts of environmental changes.

1 Introduction

Residential water demand is defined as the amount of water withdrawal for residential purposes such as in-house water use for drinking, food preparing, bathing, clothes and dishes washing, toilet flushing, etc. as well as outdoor water needs for gardening, lawn watering, etc. (Blokker et al., 2010; Wang et al., 2017a). Water demand is different from water consumption which indicates the portion of total water use that is not returned to the original water source. Generally, residential water withdrawal or demand are measured in household or regional levels and forecasted. The domestic water demand depends on number of factors including population growth, socio-economic development, climate change, urbanization, water saving technological advances, water tariff, etc. (Sebri, 2014; Wang et al., 2016). A number of recent studies assessed the impacts of those factors on domestic water demand in different regions (Dursun, 2010; Zachariadis, 2010; Protopapas et al., 2010; Karamouz et al., 2011; Jakimavičius and Kriaučiūnienė, 2013; Browne et al., 2013; Wang et al., 2014, 2017b; Babel et al., 2014; Price et al., 2014; Walker et al., 2016; Froelich and Magiera, 2016). The studies revealed that the World will face a growing challenge to maintain safe and adequate water supplies due to continuous growth of population and changes in climate. Residential water demand shares a major portion of total water demand in urbanized catchment. Therefore, understanding possible changes in residential water demand due to environmental changes is important for water resources planning and man-

Published by Copernicus Publications on behalf of the International Association of Hydrological Sciences.

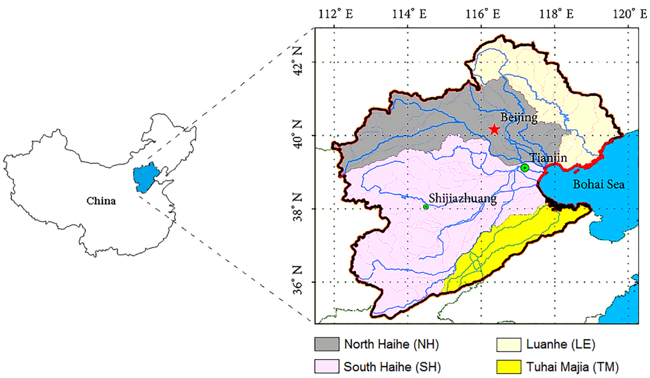

Figure 1. Location of Haihe River basin in the map of China. The sub-basins of the river and the location of major cities in the basin are also shown.

agement and adaptation to environment changes (Shahid et al., 2016).

The objective of this study is to develop a statistical model for forecasting domestic water demand due to climate change, population growth and technological advances. The proposed model is developed through the analysis of the effects of climate variables on domestic water use, and then applied in Haihe River basin of China for forecasting water demand. The Haihe River (112–120° E and 35–43° N), flows through the major cities like Beijing and Tianjin (Fig. 1) plays a major role in national, economic, and social development of China. The Haihe River basin covers 8 % of total area of China (318 000 km^2), but about 10 % of total population reside in the basin and about 13 % of total GDP comes from the basin. About 45 % area of the basin is urbanized. High population density, rapid urbanization and socio-economic development have caused a sharp increase in water demand, particularly residential water demand. This has made the basin one of the most water stressed region of China. However, water security in the basin has extreme importance in China's economic development and societal safety (Liu and Speed, 2009; Wang et al., 2015). Therefore, forecasting residential water demand is very important for the basin.

2 Materials and methods

2.1 Data and sources

The population, domestic water use and urbanization rate data for the period 1980–2012 were collected from Chinese Water Resources Bulletins (MWR, 2000–2012). The recent data of domestic water use in four sub-basins of Haihe River basin, namely, the Luanhe River and Coastal areas in Eastern Hebei (LE), Northern Haihe (NH), Sorthern Haihe Region (SH), Tuhai Majiahe Region (TM) as well as for the entire Haihe River basin (HR) were collected from the Haihe River Water Resources Bulletins (HRCC, 2001–2012).

The bias corrected daily temperature data of the basin for the period of 1961–2012 were obtained from National Climate Center of China (NCCC). The bias corrected future projections of daily average temperature by an ensemble of 7 GCMs namely BCC-CSM1-1, BNU-ESM, BNU-ESM, CNRM-CM5, GISS-E2-R, MIROC-ESM, PI-ESM-LR, and MRI-CGCM3 under the Representative Concentration Pathways (RCPs) 4.5 were also collected from NCCC.

2.2 Modeling domestic water demand

According to the water resources planning technical specifications in China, domestic water demand is forecasted by multiplying the projected population (10^4 P) with the projected per capita water consumption (L^{-1} p^{-1} day^{-1}; Zhang, 2005; Wang et al., 2017b). The advances in water saving technologies, water pricing, possible changes in people's lifestyles, etc. are considered in projection of per capita water consumption. However, it does not consider the influence of climate change in water demand. We attempted to improve the exiting method of water demand forecasting by incorporating climate change factor.

The most common approach for considering the effect of climatic conditions on water demand is to include temperature and precipitation variables in the regression equations as there is a common conception that higher temperature and less rainfall make people consume more residential water. However, the influence of rainfall on domestic water consumption is often found negligible (Slavíková et al., 2013; Zhou, 2016). Zhou (2016) found the residential water demand elasticity of rainfall is insignificant for China, while it is significantly positive (0.4299) in case of daily average temperature. Slavíkoná et al. (2013) also reported no impact of rainfall on residential water demand in Czech Republic. Therefore, only the impact of temperature rise due to climate change is considered to modify the existing equation of residential water demand forecasting. The changes in residential water demand $\Delta \mathrm{LW}^t$ can be expressed as:

$$\Delta \mathrm{LW}^t = d_T \cdot \Delta T \cdot \mathrm{LW}^t \quad (1)$$

Where, LW^t is the residential water demand (10^4 m^3) forecasted using existing method; ΔT is the change in temperature (°C) due to climate change; d_T is the temperature elasticity of domestic water demand, which is defined as,

$$d_T = \frac{\Delta \mathrm{LW}}{\Delta T} \quad (2)$$

Where, ΔLW is the changes in residential water demand in 10^4 m^3 due to changes in temperature (ΔT) in °C.

In this paper, a linear regression model was developed with domestic water use data as independent and temperature as dependent variable in order to estimate the temperature elasticity of domestic water demand. The regression model was developed separately for each sub-basin for the estimation of d_T of each sub-basin.

Table 1. Daily average temperature projected by different GCMs in the Haihe River basin.

	BCC-CSM1-1	BNU-ESM	CNRM-CM5	GISS-E2-R	MIROC-ESM	MPI-ESM-LR	MRI-CGCM3
Base year (1961–2000)	9.36	9.38	9.65	9.54	9.44	9.17	9.33
2020	11.26	10.63	10.16	9.85	11.08	10.04	10.64
2030	10.53	11.59	10.27	10.86	10.57	10.64	9.98

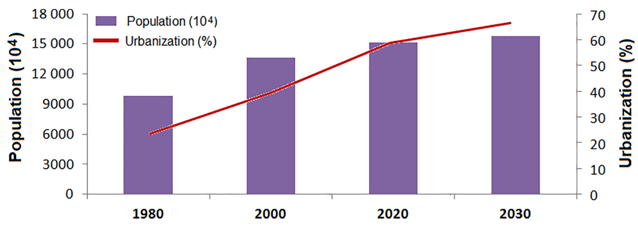

Figure 2. The historical changes and future projections of population and urbanization in the Haihe River basin.

3 Projection of domestic water demand in Haihe River basin

3.1 Projections of population and urbanization

With rapid urbanization, the population in Haihe River basin has grown rapidly in last four decades. The historical changes and future projections of population and urbanization in Haihe River basin is shown in Fig. 2. The basin had a population of 9721×10^4 and only 23.6 % of the basin was urbanized in 1980. The population reached to $13\,606 \times 10^4$ and 42.4 % of the basin became urbanized in 2006. The growing population caused a rapid increase in domestic water demand. For example, the domestic water demand in the basin increased from $1.92 \times 10^8\,m^3$ in 1980 to $5.93 \times 10^8\,m^3$ in 2012. According to the future plan of the river basin, the total population will reach to $15\,117 \times 10^4$ and the urbanized area will reach to 58.6 % in 2020. In 2030, the total population will reach to $15\,752 \times 10^4$ and the urbanized area will reach to 66.4 %.

3.2 Temperature projections

The simulated daily average temperature for the base period (1961–1990) and for the years 2020 and 2030 by 7 GCMs in Haihe River basin are shown in Table 1. The table shows increase in temperature by 0.31 to 1.9 °C in year 2020 and by 0.65 to 2.19 °C in year 2030 in the basin. The highest increase was projected by BCC-CSM1-1 in 2020 and BNU-ESM1 in 2030, while the lowest by GISS-E2-R in 2020 and CNRM-CM5 in 2030.

3.3 Projection of domestic water demand

The water resources planning technical specifications in China estimated per capita water consumption considering the advances in water saving technologies, water tariff, changes in socio-economic condition, etc. Urbanization (shown in Fig. 2) is considered as proxy for socio-economic condition. The per capita water consumptions projected for year 2020 and 2030 were multiplied with projected population (shown in Fig. 2) to estimate the amount of residential water demand due to population growth, water saving technological advances and socio-economic development. The temperature elasticity of water demand and temperature rises projected by different GCMs were then used to estimate the domestic water demand using Eq. (1) in order to incorporate climate change factor in water demand. The water demand projected by different GCMs for different sub-catchments as well as the whole Haihe River basin for years 2020 and 2030 are presented in Fig. 3.

The figure shows that domestic water demand in Haihe River basin will continuously increase due to population growth and temperature rise. The results were found to vary for different GCMs. The BCC-CSM1-1 projected the highest increase in residential water demand in the basin ($110.37 \times 10^8\,m^3$) in 2020, while the GISS-E2-R projected the lowest increase ($85.82 \times 10^8\,m^3$). In 2030, the BNU-ESM projected the highest increase in domestic water demand ($136.22 \times 10^8\,m^3$), while the CNRM-CM5 projected the lowest increase ($107.25 \times 10^8\,m^3$). The results indicate large uncertainty in projection of domestic water demand in the Haihe River basin under projected scenarios.

The changes in water demand were also found to vary for different sub-basins. The highest increase was projected in the SH sub-basin, followed by NH. The SH and NH are the most populated regions of the Haihe River basin. Therefore, it can be anticipated that increased water demand will accelerate the condition of growing water stress in the basin.

4 Discussion and conclusion

A model has been developed for forecasting domestic water demand in the context of climate change, population growth and technological development. The model is applied in the Haihe River basin of China which is considered as one of the most economically and politically impor-

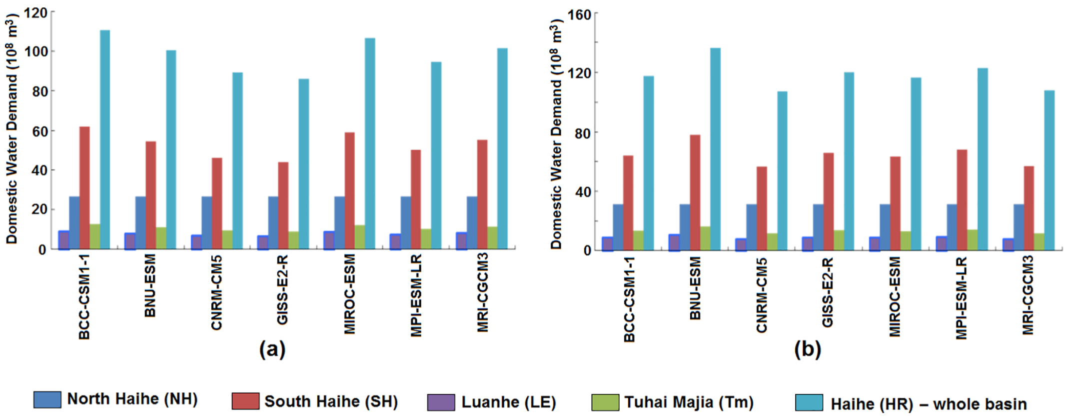

Figure 3. Projection of domestic water demand in different sub-basins of the Haihe River in years **(a)** 2020; and **(b)** 2030.

tant but worst water stress region of the country. The results show considerable variations in domestic water demand with space, time and scenarios. Overall, all the GCMs reveal increase in water demand with time, mainly due to increase in population and rise in temperature. The domestic water demand in the Haihe River basin is projected in the range of 85.82×10^8 to 110.37×10^8 m^3 in 2020, and 107.25×10^8 to 136.22×10^8 m^3 in 2030. Considerable variations in projections of domestic water demand by different GCMs indicate large uncertainty in projections. A large variation in water demand among different sub-basins indicates heterogeneous change in water demand. The higher increase in water demand might be in the South and North sub-basins, which are already under water stress due to high population density and rapid urbanization. Large increase in domestic water demand in those regions would aggravate the condition of existing water stress. The study indicates prudent management of water resources in the Haihe River basin is very important for mitigation of the impacts of environmental changes. It is expected that the knowledge generated in this paper on possible future changes in domestic water demand would help in water resources planning and management of the basin. The method proposed in this article will help in rapid assessment of water demand in the context of changing scenarios. However, it should be noted that the method presented in this paper is only one of a new innovation in the field of forecasting domestic water demand under changing environment, which need further attention to improve. The domestic water demand is influenced by many factors which can be considered in future research for better projection of water demand. It is also required to quantify the uncertainty in water demand due to population growth and socio-economic development.

Data availability. Data are available in the Chinese Water Resources Bulletins (2000–2012) and the Haihe River Water Resources Bulletins (1998–2012).

Competing interests. The authors declare that they have no conflict of interest.

Special issue statement. This article is part of the special issue "Water security and the food–water–energy nexus: drivers, responses and feedbacks at local to global scales". It is a result of the IAHS Scientific Assembly 2017, Port Elizabeth, South Africa, 10–14 July 2017.

Acknowledgements. We are grateful to the National Key R&D Program of China (NO: 2017YFC0403506), National Natural Science Foundation of China (No. 51309155), Strategic Consulting Projects of Chinese Academy of Engineering (NO: 2016-ZD-08-05-02), China Water Resource Conservation and Protection Project (No. 126302001000150001) and Open Research Fund of State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin China Institute of Water Resources and Hydropower Research) (NO: IWHR-SKL-201515) for providing financial support for this research. We are also thankful to reviewers (Mykhaylo Romashchenko and another anonymous referee) and the editor Barry Croke for their helpful comments and suggestions.

Edited by: Barry Croke
Reviewed by: Mykhaylo Romashchenko
and one anonymous referee

References

Babel, M. S., Maporn, N., and Shinde, V. R.: Incorporating Future Climatic and Socioeconomic Variables in Water Demand Forecasting: A Case Study in Bangkok, Water Resour. Manage., 28, 2049–2062, 2014.

Blokker, E. J. M., Vreeburg, J. H. G., and van Dijk, J. C.: Simulating residential water demand with a stochastic end-use model, J. Water Res. Pl.-ASCE, 136, 19–26, 2010.

Browne, A. L., Medd, W., and Anderson, B: Developing Novel Approaches to Tracking Domestic Water Demand Under Uncertainty – A Reflection on the "Up Scaling" of Social Science Approaches in the United Kingdom, Water Resour. Manage., 27, 1013, https://doi.org/10.1007/s11269-012-0117-y, 2013.

Dursun, S.: Effect of Global Climate Change on Water Balance of Beyşehir Lake (Konya – Turkey), BALWOIS 2010, Ohrid, Republic of Macedonia, 25–29 May 2010.

Froelich, W. and Magiera, E.: Forecasting Domestic Water Consumption Using Bayesian Model, Intelligent Decision Technologies 2016, 337–346, 2016.

HRCC: Haihe River water resources bulletin, Haihe River Conservancy Commission, Tianjin, 2001–2012.

Jakimavičius, D. and Kriaučiūnienė, J.: The climate change impact on the water balance of the Curonian Lagoon, Water Resour., 40, 120–132, 2013.

Karamouz, M., Yazdi, M. S. S., Ahmadi, B., and Zahraie, B.: A system dynamics approach to economic assessment of water supply and demand strategies. Paper presented at the World Environmental and Water Resources Congress 2011: Bearing Knowledge for Sustainability, Proceedings of the 2011 World Environmental and Water Resources Congress, 1194–1203, 2011.

Liu, B. and Speed, R.: Water resources management in the People's Republic of China, Int. J. Water Resour. Dev., 25, 193–208, 2009.

MWR: China Water Resources Bulletin, Ministry of Water Resources (MWR), Beijing, 2000–2012.

Price, J. I., Chermak, J. M., and Felardo, J.: Low-flow appliances and household water demand: an evaluation of demand-side management policy in Albuquerque, New Mexico, J. Environ. Manage., 133, 37–44, 2014.

Protopapas, A. L., Katchamart, S., and Platonova, A.: Weather effects on daily water use in New York City, J. Hydrol. Eng., 5, 332–338, 2000.

Sebri, M.: A meta-analysis of residential water demand studies, Environ. Dev. Sustain., 16, 499–520, 2014.

Shahid, S., Wang, X.-J., Harun, S. B., Shamsudin, S. B., Ismail, T., and Minhans, A.: Climate variability and changes in the major cities of Bangladesh: observations, possible impacts and adaptation, Reg. Environ. Change, 16, 459–471, 2016.

Slavíková, L., Malý, V., Rost, M., Petružela, L., and Vojáček, O.: Impacts of Climate Variables on Residential Water Consumption in the Czech Republic, Water Resour. Manage., 27, 365–379, 2013.

Walker, D., Creaco, E., Vamvakeridou-Lyroudia, L., Farmani, R., Kapelan, Z., and Savic, D.: Forecasting Domestic Water Consumption from Smart Meter Readings Using Statistical Methods and Artificial Neural Networks, Procedia Engineering, 119, 1419–1428, 2016.

Wang, X.-J., Zhang, J.-Y., Wang, J.-H., He, R.-M., ElMahdi, A., Liu, J.-H., Wang, X.-G., King, D., and Shahid, S.: Climate change and water resources management in Tuwei river basin of Northwest China, Mitigation and adaptation strategies for global change, 19, 107–120, 2014.

Wang, X.-J., Zhang, J.-Y., Yang, Z., Shahid, S., He, R.-M., Xia, X.-H., and Liu, J.-H.: Historic water consumptions and future management strategies for Haihe River basin of Northern China, Mitigation and adaptation strategies for global change, 20, 371–387, 2015.

Wang, X.-J., Zhang, J.-Y., Shahid, S., Guan, E., Wu, Y., Gao, J., and He, R.-M.: Adaptation to climate change impacts on water demand. Mitigation and Adaptation Strategies for Global Change, 21, 81–99, 2016.

Wang, X.-J., Zhang, J.-Y., Shahid, S., Xie, W., Du, C.-Y., Shang, X.-C., and Zhang, X.: Modeling domestic water demand in Huaihe River Basin of China under climate change and population dynamics, Environment, Development and Sustainability, online first, 1–14, https://doi.org/10.1007/s10668-017-9919-7, 2017a.

Wang, X.-J., Zhang, J.-Y., Shahid, S., Oyang, R.-L., Guan, T.-S., Xue, J.-G., and Zhang, X.: Impacts of climate variability and changes on domestic water use in the Yellow River Basin of China, Mitigation and Adaptation Strategies for Global Change, 22, 595–608, 2017b.

Zachariadis, T.: Residential water scarcity in Cyprus: impact of climate change and policy options, Water, 2, 788–814, 2010.

Zhang, H.: Strategic study for water management in China, Southeast University Press, Nanjing, 2005.

Zhou, M.: Residential Water Demand in China: Applications of Double-Log Model and EDM System, The Southern Agricultural Economics Association's 2016 Annual Meeting, San Antonio, Texas, 6–9 February 2016.