Author/s:
Li, M;Finlayson, B;Webber, M;Barnett, J;Webber, S;Rogers, S;Chen, Z;Wei, T;Chen, J;Wu, X;Wang, M

Title:
Estimating urban water demand under conditions of rapid growth: the case of Shanghai

Date:
2017-04-01

Citation:
Li, M., Finlayson, B., Webber, M., Barnett, J., Webber, S., Rogers, S., Chen, Z., Wei, T., Chen, J., Wu, X. & Wang, M. (2017). Estimating urban water demand under conditions of rapid growth: the case of Shanghai. Regional Environmental Change, 17 (4), pp.1153-1161. https://doi.org/10.1007/s10113-016-1100-6.

Persistent Link:
https://hdl.handle.net/11343/283079

Estimating Urban Water Demand Under Conditions of Rapid Growth: The Case of Shanghai

Maotian LI[1]
mtli@sklec.ecnu.edu.cn
Brian FINLAYSON[2*]
brianlf@unimelb.edu.au
Michael WEBBER[2]
mjwebber@unimelb.edu.au
Jon BARNETT[2]
jbarn@unimelb.edu.au
Sophie WEBBER[4]
srwebber@ucla.edu
Sarah ROGERS[2]
rogerssm@unimelb.edu.au
Zhongyuan CHEN[1]
z.chen@sklec.ecnu.edu.cn
Taoyuan WEI[1]
weit235@163.com
Jing CHEN[1]
jchen@geo.ecnu.edu.cn
Xiaodan WU[3]
xiaodan.83@163.com
Mark WANG[2]
myw@unimelb.edu.au

[1] State Key Laboratory of Estuarine and Coastal Research, East China Normal University, Shanghai 200062, China
[2] School of Geography, The University of Melbourne, Victoria 3010, Australia
[3] Department of Geography, East China Normal University, Shanghai 200062, China
[*]Corresponding Author. Email: brianlf@unimelb.edu.au; Phone:- +61408391573; Fax:- +61 3 9349 4218
[4] Department of Geography, University of California at Los Angeles, Los Angeles CA 90095, USA

Abstract

Many of the world's major cities are expected to face significant water shortages in coming decades, largely due to increased demand arising from economic and population growth. In this paper we estimate the effects of economic and population growth on future public water needs in Shanghai, one of the world's megacities. Despite significant investment in a new reservoir and associated supply systems, and its location at the estuary of one the world's major rivers (the Yangtze), it is widely believed that Shanghai is vulnerable to water shortages, though the causes of this have hitherto not been systematically examined. Our method of estimating future water needs involves extrapolation from past trends and Principle Component Analysis regression, and from the experience of comparable cities around the world, to construct three scenarios of future GDP and population growth and associated water needs. Our analysis shows that under various scenarios, by 2050 the difference between demand and present supply capacity will range between 1.6 and 6 million m^3/day, and that the critical constraint to meeting future demand is treatment capacity, which will need to increase by between 35 and 83 per cent beyond present levels. We discuss four options for managing the estimated deficit between future water demand and supply in Shanghai.

Keywords: urban water supply, urban water demand, water demand prediction, Shanghai.

Number of words:

Text (excluding references): 4700

Figures: 5 @ 300 ea = 1500

Total words: 6200

1. Introduction

As cities grow their water needs increase, and on present trends, up to 1 billion people may be living in water stressed cities by the year 2050 (McDonald et al. 2011a), requiring some $500 billion of annual global investment in water infrastructure (Stevens et al. 2006). A number of studies show that in the next few decades it will be increased demand more than water availability that will be the principal driver of these future urban water shortages (McDonald et al. 2011b; Padowski and Gorelick 2014; Vörösmarty et al. 2000).

The ability of water managers to forecast aggregate urban water demand and thus to estimate water supply capacity needs is therefore critical to the sustainability of cities (Candelieri and Archetti 2014; Lundqvist et al. 2005; Milly et al. 2008; Ouda 2014; Seckler et al. 1998). Most analyses of urban water demand use regression, time series or dynamic models (Candelieri and Archetti 2014). Regression models forecast water demand by quantifying the effects of such variables as population, income, climate and public water policies on demand and then projecting the values of those determinants into the future (Babel et al. 2007 is typical). Time series models use trends and more complex functions of time to project demand (Zhou et al. 2000). Dynamic models include Artificial Neural Networks, fuzzy logic and agent based models, all of which are mathematically simulated models suited to replicating complex systems (Qi and Chang 2011; Vijayalaksmi and Babu 2015). These models can produce sophisticated results, but they require data about (among other things): variations in demand at district, residential and household scales; daily and monthly variations in demand; and household decision making, water use, attitudes and norms (House-Peters and Chang 2011). However, in most cities in developing countries – including Shanghai – such data are not available. Thus we seek here to estimate aggregate demand for public water supply in Shanghai using a method of extrapolation and Principal Component Analysis regression that requires only basic data, and which most urban water managers in developing countries could replicate.

2. Data and Methods

While there are many procedures described in the literature for predicting future water use, we here follow the proposals of Xu et al. (2002), whereby public water demand is forecast by projecting the growth in population and GDP (see also Zhu et al. 2004; and Liu 2007). In this paper we estimate future water demand on the basis of projected population increases to 2050 and projected GDP growth to 2050. We assume that the demands for water per unit of population and GDP will continue to change at their historically-observed rates of change – that is, increasing use of water per person, decreasing use of water per unit of GDP. Three scenarios based on projections of population and GDP are developed. In Shanghai, population and GDP are highly correlated, so they cannot both be used in a simple linear regression. Instead, we estimate a principal components transformation of the two variables and use the component scores as independent variables in the regression model for water demand. Then, projected population and GDP levels are fed back through the component loadings to calculate component scores that generate projected demand through the regression equation.

We begin by examining Shanghai's current water supply system. Data for the year 2013 on the water use of municipal raw water intake plants, municipal public water plants, and private water plants were extracted from government documents and web-pages sourced from the Shanghai Water Authority (SWA), and the online database of the Office of Shanghai Local Chronicles (OSLC 2012; SWA, 2012, 2013). Data on the annual raw water intake volumes from the Huangpu River (1978-2013), the Chenghang Reservoir (1996-2013) and the Qingcaosha Reservoir (2010-2013), as well as the number of public water treatment plants in each year were collected from the electronic bulletins of SWA (SWA 1998-2013).

We then examine the relationship between population and water use, and GDP and water use in Shanghai between 1978 and 2013. 1978 is a significant year in the history of Chinese economic development, marking the end of a period of centrally controlled markets, and the beginning of an economic system in which market forces have come to increasingly determine exchanges. Data on annual public water consumption between 1978-2013 were collected from the Compilation Committee of Shanghai Water Conservancy Chronicles (CCSWCC 1997) and the electronic bulletins of the Shanghai Water Authority (SWA, 1998-2014). Data on population and GDP (current) for 1978-2013 were collected from the electronic bulletins of the Shanghai Statistical Yearbook (SMSB 2014). All data on GDP (current) was converted to GDP (2010) using implicit price indices for GDP published by the National Bureau of Statistics.

We use the United Nations Department of Economic and Social Affairs, Population Division 2014 population projections (UNDESA 2015). This provides national and total urban population projections by country. Various projections of future growth of GDP in China are available in the literature. Perkins and Rawski (2008) estimate that from 2016 to 2025 GDP growth will be in the range 5-7 per cent per year with less than 6 per cent being more likely. This is consistent with the estimates of Garnaut et al. (2008) of 6.8 per cent per year for the period 2015-2025, while Garnaut (2011) gives growth projections of 8 per cent per year on average for the period 2005-2030. This overall concensus that there will be sustained but slightly slower growth rates is also supported by Li et al. (2011) who, for the period 2016 to 2030, give a range of 4.3 to 5.9 per cent per year.

Based on these scenarios of the population and GDP of Shanghai, as well as time series regressions of past public water consumption in relation to population and GDP in Shanghai, three scenarios of annual public water consumption in relation to population and GDP are calculated. In order to make provision for losses in the distribution system, it is assumed that the maximum daily water supply capacity needs to be 20 per cent larger than the daily water consumption. So, predicted annual public water consumption (Q_a) requires a maximum daily water supply capacity (Q_{md}) of: $Q_{md} = 1.2 (Q_a/365)$.

3. Results

3.1. Shanghai's urban water system and trends in urban water consumption

Shanghai is a large and wealthy city: it has a population of 24.3 million, GDP per capita in 2013 was ¥80,000 (~US$ 13,000), and it produces over 4 per cent of China’s GDP. Given the trend of high rates of population and GDP growth in Shanghai over the past 30 years (Jiang, 2009; SMG, 2010), many scholars infer that these will be the primary drivers of increases in public water consumption over the next 50 years (NBSC 2006; Oki and Kanae 2006).

Shanghai no longer uses significant quantities of groundwater, because it caused land subsidence. Average subsidence rates of 40 mm a^{-1} occurred in central Shanghai between 1920 and the mid-1960s due to heavy extraction of underground water (Chai et al. 2004; Wei et al. 2010). However, reduced pumping and increased groundwater recharge have cut the subsidence rate to ca. 2 mm a^{-1} since the mid-1960s. Thus, Shanghai needs to use surface water, which historically has been drawn from the Huangpu, a river that flows from Tai Lake, which in turn is supplied in part from the Yangtze River, and in part from its own catchment. Due to heavy pollution of both Tai Lake and the Huangpu, Shanghai has progressively shifted to the Yangtze as its primary source of water. The Yangtze’s water remains relatively clean when compared to the Huangpu because of its very large discharge (approximately 900 10^9 m^3 a^{-1}).

Since 2010 the major freshwater intake for Shanghai has been the Qingcaosha Reservoir, which is a shallow reservoir located on an island in the mouth of the Yangtze, and which now supplies 54 per cent of Shanghai’s raw water. Despite this new infrastructure, many researchers have expressed concerns regarding future freshwater supply to Shanghai, primarily due to the rapid increase in water demand, but in the context of poor water management (Cheng et al. 2009; Jiang 2009; McDonald et al. 2011a; Varis and Vakkilainen 2001). Because Shanghai has access to adequate water due to the large and reliable annual flow of the Yangtze River, it is the infrastructure necessary to supply potable water to consumers that is the primary barrier to meeting Shanghai’s future public water needs, and this problem of water delivery is identified by McDonald et al. (2011b) as being the major constraint to urban water provision worldwide.

Water use in Shanghai can be divided into power station cooling, agriculture, industry, residential, and public open spaces (Finlayson et al. 2013). According to SMSB (2000-2015), water used by power stations and agriculture is self supplied, with the public system supplying industry (using 33.6 per cent of public treated water output), domestic users (34.9 per cent), and public open spaces (31.5 per cent). Thus the three principal uses of public water in Shanghai are residential, public open space and industrial. We observe that residential water use in Shanghai is nearly all indoors, with little garden watering, so climate is not an important determinant of residential water use. Thus, population, average income and government controls (such as price and demand management) are the main controls over residential water use.

Although future climate may affect the use of water in public open spaces, there is insufficient data on the variability in water demand of this kind, and great uncertainty about the effects of climate change on urban Shanghai, so we are unable to make meaningful estimates of the effect of climate on the demand for water for public open spaces. Instead, we assume that this demand will increase in parallel with the growth of residential water use.

Industrial water demand depends principally on price and other government determined variables (which influence the efficiency with which water is used), aggregate output (GDP) and the sectoral composition of output (Strzepek and Boehlert 2010; Zhang 2010). In Shanghai, growth of GDP is highly correlated with a long term shift from secondary industry to the tertiary sector, with GDP from primary industry remaining static; the demand for water from both these sectors is principally affected by their size (GDP), price and other government determined variables.

Shanghai's water management over the past several decades has been characterised by no restrictions on water demand, no water recycling, unclear water rights, low prices, and a fragmented water governance structure (Blanke et al. 2007; Zhang et al. 2007). Such a system of water management has led to unconstrained increases in water demand, and without changes in the water management regime this rate of increase is likely to continue. We assume there will be no changes in this water management system, and treat improved management as an *ex ante* variable, which we discuss later.

In 2013 there were eight municipal raw water intake pumps in operation in Shanghai, with a combined capacity of 41 10^9 m^3 a^{-1}. These are located in remote and rural areas: four (Songpu, Jinshan Xietang and Taipuhe – accounting for 39 per cent of total capacity) are located in the upper Huangpu River, and the others

(Dongfengxisha, Huating, Chenghang and Qingcaosha – accounting for 61 per cent of total capacity) are located on the Yangzte River Estuary. Since 2010 the Yangtze's waters have significantly substituted for the more polluted waters from the Huangpu. There is unused capacity to extract raw water from the Huangpu if need be, if only this water could be cleaned to a standard that allows treatment to potable standard at reasonable cost.

Shanghai's 36 public water treatment plants, which supplied 31.2 10^9 m^3 a^{-1} in 2013, and which are mostly located in the urban area along the lower Huangpu River, are supplied by eight raw water pumping stations. Those eight stations also supply 12 clusters of private industrial water treatment plants, which have a combined treatment capacity of 2.1 10^9 m^3 a^{-1}.

Historical data for annual public water consumption and the maximum capacity raw water supply in Shanghai over the period 1978 to 2013 is plotted in Figure 1A and B respectively. The population, consisting of the migrant population and the registered population, and the annual GDP, consisting of primary, secondary and tertiary industry, over the same period are plotted in Figures 2A and B respectively. Figures 1 and 2 show that in Shanghai public water consumption, population and GDP all increased rapidly in the period 1978-2013. Water consumption in the public system in the period 1978-2013 increased from 9.7 10^9 m^3 a^{-1} to 31 $10^9 m^3$ a^{-1}; of this, the water for residential and public open space increased from 3.6 $10^9 m^3$ a^{-1} to 19.7 $10^9 m^3$ a^{-1}, a five-fold increase and therefore a rate obviously greater than that of industrial water (6.2 to 11.5 $10^9 m^3$ a^{-1} over the same period) (Figure 1A). Thus, the major cause of increased public water consumption was growth in water for domestic use and public space uses. To meet this growth, the capacity of public raw water pumping grew from 11.7 10^9 m^3 a^{-1} in 1978, to 41.0 $10^9 m^3$ a^{-1} in 2013 (Figure 1B).

Between 1978-2013 Shanghai's population increased from 11.0 to 24.2 million. Of this, the registered population slowly rose from 11 to 14.3 million, while the non-registered migrant population increased from 50 000 in 1978 to nearly 10 million by 2013. Shanghai has experienced remarkable annual influxes of migrants – peaking at 990,000 new arrivals in in 2007, but many years since 2004 witnessed over 500,000 new arrivals. Remarkably, the extra demand for water created by these large increases in population did not result in significant water shortages.

Over this period from 1978-2013 the rate of increase in Shanghai's GDP far exceeded the rate of population growth, and the rate of increase in water consumption. GDP grew from ¥145.94 billion in 1978 to ¥1931.72 billion in 2013 (in 2010 prices). There has been virtually no change in the value of primary production, secondary sector GDP has increased by a factor of 11.1, and tertiary industry GDP has increased by a factor of 31.2. Annual rates of GDP growth in Shanghai have been very high for a very long period, reflecting (though exceeding) the high rates of growth in China overall over this period.

There are positive correlations between the logarithm of annual public water consumption and annual population and annual GDP over the period 1978-2013; the correlation coefficients (R^2) are 0.86 and 0.95 respectively and the regression coefficients are 1.762 and -0.400, respectively (all correlation and regression coefficients are significant at p<.001). GDP is more strongly correlated with water consumption than is population.

3.2 Projecting Shanghai's future population and GDP

China's population is forecast to peak in 2030 at 1.45 billion and decline thereafter (Figure 3A). The projection of the urban population to 2050 shows a continued rapid increase to around 2030 after which it begins to plateau (Figure 3B). This means that despite the projected decline in the total population of China by 2050, the population of urban areas will continue to rise, and Shanghai, as one of the major cities, will very likely experience that ongoing population rise. In 2013, Shanghai's population was 3.3 per cent of China's total urban population and if it retains this share then by 2050 its population will be 34.7 million, an average annual increase over that period of 285 000. We have therefore chosen an annual increase of 300 000 as the medium projected level of increase of Shanghai's population from 2014 to 2050 in our scenarios.

However, during this time China's economy will continue to grow, and, as is the case in OECD economies, where the share of the population in the largest city increases with growth, so too may Shanghai's population growth exceed that of national population growth. To estimate this, we use data from the United Nations Population Division (UNPD 2014) to correlate the population of 138 countries with populations greater than 1 million with the population of their largest city in 2013 (Figure 4A). There is a positive correlation between the population of a country's largest city and the population of that country; the correlation coefficient (R) is 0.92

($p < .001$; Figure 4A). It is notable that the populations of first world metropolitan cities such as Tokyo, Seoul, and New York are all far greater than would be expected on the basis of their national populations, whereas the populations of metropolitan cities in developing economies such as Shanghai and Bombay are all lower than their national populations would predict. This relationship implies that Shanghai's population may move up towards the regression line and even above it as China's economy develops. We use an annual population increase 400 000 in our scenario building to provide an estimate of this outcome. We also use an annual increase in population of 200 000 as a reasonable lower limit of population growth.

In Section 2 we discussed possible future rates of growth of China's GDP based on sources in the literature. On the basis of those estimates we assume the most likely rate of GDP growth for China over the period to 2050 is around 5 per cent per year, with an upper limit of 7 per cent and a lower limit of 3 per cent. As a major city and growth centre, the GDP of Shanghai will likely grow at a similar rate to the national economy. To investigate further the relation between the GDP of Shanghai and the GDP of China we use a similar comparative method as used above for population. The GDP of 60 countries whose GDP exceeds US$ 120 billion, and the 2012 GDP of the largest city in those countries were compiled from data provided by the International Monetary Fund and the Brookings Institute, respectively (Parilla et al. 2015; International Monetary Fund, 2013). The correlation between the GDP of a country's largest city and of that country are positive with $R = 0.81$ ($p < .001$; Figure 4B). As in the case of population (Figure 4A), most first world metropolitan cities such as Tokyo, London, Paris, and Seoul are also positioned far above the regression line, whereas third world metropolitan cities such as Shanghai are below the regression line. In other words, there is the potential for the GDP of Shanghai to rise to or above the regression line in the future, which in turn implies a corresponding significant rise in GDP. This reasoning supports the assumptions we have made in setting upper growth rates in the scenarios.

Based on these projected rates of growth of Shanghai's population and GDP, low, medium and high scenarios of population and GDP growth are shown in Figure 5. In the most conservative scenario (scenario 1), Shanghai’s population is estimated to grow from 24.2 million in 2014 to 31.5 million in 2050, and its GDP is estimated grow from ¥1931.73 billion to ¥5766.64 billion by this time. In the middle range scenario (scenario 2) Shanghai’s population is estimated to grow to 35.3 million by 2050, and GDP is estimated grow to ¥11747.60 billion. In the high growth scenario (scenario 3), Shanghai’s population is estimated to grow to 39 million by 2050, and GDP to ¥23612.66 billion. In all scenarios the rate of increase of GDP exceeds that of population, particularly in scenario 3.

3.3 Estimating Shanghai’s aggregate municipal water demand

Based on the population and GDP growth scenarios the annual demand for water from public treatment plants in Shanghai in 2050 is estimated to be between 42 billion m^3 (scenario 1) and 57 billion m^3 (scenario 3), representing increases of between 35 per cent and 83 per cent above 2013 levels (Figure 5). The annual public water treatment capacity (set at 120 per cent of demand to account for leakage, as explained in section 2) will need to increase to between 49.9 and 68.4 10^9 m^3. Particularly when growth of GDP and population follows the high growth scenario (3), substantially larger supplies of water will be needed from Shanghai's public water system. It is worth noting that this scenario is not unlikely: historically Shanghai’s GDP growth has exceeded that of China’s overall, and this high growth scenario assumes annual growth rates of 7 per cent per annum, which are consistent with estimates of rates of growth in China overall until the year 2030 (Li et al. 2011).

This analysis suggests that under the low growth scenario, the present raw water intake capacity (41.0 10^9 m^3 a^{-1}) will be adequate to meet Shanghai’s future needs in 2050. Indeed, given the underutilised capacity to increase raw water supply from the Huangpu (noting that this assumes water from the Huangpu can be treated to a suitable standard), investment in increasing water supply does not seem to be necessary to meet future demand under the low growth scenario. That is, if the growth in demand is relatively slow (because of slow growth in population and GDP or because of effective demand management) treatment plant capacity will be the major constraint on future supply. However, if growth in demand for water is higher (because population and GDP are both growing at moderate levels) then a 40 per cent increase in intake capacity would be required in order to meet future demand, as well as increases in treatment capacity, and these are significant investments.

4. Discussion: the challenge of maintaining municipal water supply to Shanghai

Even leaving aside the risks to Shanghai's raw water supply arising from water pollution and saline incursions (which are not insignificant – see Finlayson et al. 2013 and Li et al. 2014), under even the most optimistic scenarios, future growth in GDP and population pose major challenges to water supply in Shanghai. The above analysis shows that under all scenarios a significant constraint arises from water treatment capacity. Under the most sedate of the growth scenarios two large water treatment plants will be required: Shanghai's two largest water treatment plants (the Yangshupu and Changqiao plants) each have the capacity to treat 1.5 million m^3 d^{-1}, meaning that more than one such plant is required to meet the minimum of anticipated future increases in demand. This is also a challenge for Shanghai given the tensions over land use and rapid population and economic growth in a small area (Mao et al. 2000; Chen et al. 2001; Chen et al. 2003; Shen et al. 2003). Under the highest demand scenarios five such plants would be required as well as substantial increases in intake capacity.

There are, however, four other options. First, Shanghai's private water plants could be upgraded to provide higher quality water, and this water could be supplied to public uses. This implies a trade-off between industrial and public uses, which might be justified were it not the case that 31.5 per cent of Shanghai's public water use is for open spaces. Trading off water used by industries that employ people for water used to wash streets and irrigate parks does not make economic or political sense. It might make economic sense to the operators of these water plants if the price of the water they sold enabled them greater profits than their existing uses of water, but given State control of water prices and obvious political disincentives to raise them, this also seems unlikely.

A second option is to focus on reducing demand for water. Demand side measures, such as pricing, have increasingly been implemented around the world, although there is little experience of this in Chinese cities (Arbués, et al. 2003). The effectiveness of such measures is hotly contested. The extent to which demand for water is price inelastic is debated given the lack of substitutes, with mixed findings in the literature (see Arbues et al. 2003; De Mouche et al. 2011; Worthington and Hoffman 2008). It appears too that water demanded for necessary purposes (such as for drinking and cooking) is less elastic to price than water used for more luxury purposes (such as for swimming pools, or watering lawns) (De Mouche et al. 2011) Just how much of the domestic water use in Shanghai is for luxury uses is uncertain, but certainly few houses in Shanghai have gardens, and domestic swimming pools would appear to be very rare. At the domestic level there may therefore be little price elasticity in water consumption. In any event, the government has shown significant reluctance to raise prices for fear of public ire.

Third, water recycling is another means of coping with water shortages in urban areas as has been done with great success in Singapore (Tortajada 2006). However, as we explain earlier, the problem in Shanghai is not shortage of water but limited capacity for the treatment of water. Recycling would require the same or greater investment in water treatment capacity as would the treatment of more raw water from the Yangtze.

The final, and perhaps most practicable option, is to separate out the water supplied for human consumption from the water used for some industry and for public open spaces, and to source the latter water from the underutilised Huangpu sources (after treating this to the minimum standard necessary). This would mean that only water from the cleaner Yangtze sources is used for household consumption, and would likely significantly reduce the need for new treatment plants. In this strategy much depends on the costs of separating the systems required for supplying water for household and public open spaces uses, as well as the costs of treating water for industrial and public open spaces uses so that its application does not pose risks to public health.

5. Conclusions

This study estimates future demand for public water supply in Shanghai, and finds that in the absence of any further measures, Shanghai's existing water system is incapable of meeting future demand. Shanghai arguably has sufficient raw water sources, and pumping capacity, to meet future demand under slow growth scenarios. The critical constraint to future growth in public supply is treatment capacity – which we estimate will need to increase by between 35 and 83 per cent by the year 2050. Simply adding additional treatment plants may no longer be an adequate strategy, and we suggest disaggregating the public water supply system into distinct systems for supplying water for personal consumption and tertiary enterprises and for use in public open spaces.

Acknowledgements

This research is supported by the Australian Research Council (Grant No: P110103381) and the National Natural Science Foundation of China (Grant No. 41271520).

References

Arbués F, García-Valiñas M, Martínez-Espiñeira R (2003) Estimation of residential water demand: a state-of-the-art review. J Socio Econ 32:81-102. doi:10.1016/S1053-5357(03)00005-2

Blanke A, Rozelle S, Lohmar B, Wang J, Huang J (2007) Water saving technology and saving water in China. Agric Water Manag 87:139-150. doi:10.1016/j.agwat.2006.06.025

Babel MS, Das Gupta A, Predhan P (2007) A multivariate econometric approach for domestic water demand modeling: an application to Kathmandu, Nepal. Water Resour Manag 21:573-589. doi:10.1007/s11269-006-9030-6

Candelieri A, Archetti F (2014) Identifying typical urban water demand patterns for a reliable short-term forecasting – the Icewater Project approach. Procedia Eng 89:1004-1012. doi:10.1016/j.proeng.2014.11.218

CCSWCC (Compilation Committee of Shanghai Water Conservancy Chronicles). (1997) Shanghai Water Conservancy Chronicles. The Shanghai Academy of Social Sciences Press, Shanghai, pp 626.

Chai JC, Shen SL, Zhu HH, Zhang XL (2004) Land subsidence due to groundwater drawdown in Shanghai. Géotechnique 54:143–147. doi:10.1680/geot.2004.54.2.143

Chen X, Zong Y, Zhang E, Xu J, Li S (2001) Human impacts on the Changjiang (Yangtze) River basin, China, with special reference to the impacts on the dry season water discharges into the sea. Geomorphology (Amst) 41:111-123. doi:10.1016/S0169-555X(01)00109-X

Chen Y, Fan C, Teubner K, Dokulil M (2003) Changes of nutrients and phytoplankton chlorophyll-a in a large shallow lake, Taihu, China: an 8-year investigation. Hydrobiologia 506-509:273-279. doi: http://dx.doi.org.ezp.lib.unimelb.edu.au/10.1023/B:HYDR.0000008604.09751.01

Cheng H, Hu Y, Zhao J (2009) Meeting China's water shortage crisis: current practices and challenges. Environ Sci Technol 43:240-244. doi: 10.1021/es801934a

De Mouche L, Landfair S, Ward F (2011) Water right prices in the Rio Grande: analysis and policy implications. International Journal of Water Resources Development 27:291-314. doi: 10.1080/07900627.2011.571041

Finlayson B, Barnett J, Wei T, Webber M, Li M, Wang M, Chen J, Xu H, Chen Z (2013) The drivers of risk to water security in Shanghai. Reg Environ Change 13:329-340. doi: 10.1007/s10113-012-0334-1

Garnaut R (2011) Garnaut Climate Change Review - Update 2011, Update Paper Three: Global emissions trends. Australian National University, Canberra.

Garnaut R, Howes S, Jotzo F, Sheehan P (2008) Emissions in the Platinum Age: the implications of rapid development for climate-change mitigation, Oxford Review of Economic Policy 24:377-401. doi: 10.1093/oxrep/grn021

House-Peters L, Chang H (2011) Urban water demand modeling: review of concepts, methods and organizing principles. Water Resour Res 47:W05401. doi: 10.1029/2010WR009624

International Monetary Fund (2013) World economic outlook database October 2013. World economic and financial surveys. https://www.imf.org/external/pubs/ft/weo/2013/02/weodata/index.aspx (accessed 4 August 2016)

Parilla J, Trujillo JL, Berube A, Ran T (2015) Global metro monitor: an uncertain future 2014. The Brookings Institution. https://www.brookings.edu/wp-content/uploads/2015/01/bmpp_gmm_final.pdf (accessed 4 August 2016)

Jiang Y (2009) China's water scarcity. J Environ Manage 90:3185-3196. doi:10.1016/j.jenvman.2009.04.016

Li S and Liu Y (2011) Simulated scenarios for China's economic growth: 2011-2030. China Economist 3:56-69. (in Chinese)

Li M, Chen Z, Finlayson B, Wei T, Chen J, Wu X, Xu H, Webber M, Barnett J, Wang M (2014) Water diversion and sea-level rise: potential threats to freshwater supplies in the Changjiang River estuary. Estuar Coast Shelf Sci 165:52-60. doi: http://dx.doi.org/10.1016/j.ecss.2014.07.007

Liu SQ (2007) Urban water supply management in Shanghai. Water Science & Technology: Water Supply**.** 7:41-47. doi: 10.2166/ws.2007.039.

Lundqvist J, Tortajada C, Varis O, Biswas A (2005) Water management in megacities. Ambio 34:267-268. doi: http://dx.doi.org/10.1579/0044-7447-34.3.267

Mao Z, Shen H, Xu P (2000) The Pattern of saltwater intruding into the Changjiang Estuary and the utilization of freshwater resources. Acta Geogr Sin 55:243-250. (in Chinese)

McDonald R, Green P, Balk D, Fekete B, Revenga C, Todd M, Montgomery M (2011a) Urban growth, climate change, and freshwater availability. Proc Natl Acad Sci U S A 108:6312-6317. doi: 10.1073/pnas.1011615108

McDonald R, Douglas I, Revenga C, Hale R, Grimm N, Grönwall J, Fekete B (2011b) Global urban growth and the geography of water availability, quality, and delivery. Ambio 40:437–46. doi: http://dx.doi.org.ezp.lib.unimelb.edu.au/10.1007/s13280-011-0152-6

Milly P, Betancourt J, Falkenmark M, Hirsch R, Kundzewicz Z, Lettenmaier D, Stouffer R. (2008) Stationarity is dead: Whither water management? Science 319:546-547.

NBSC (National Bureau of Statistics of China) (2006) China Statistical Yearbook 2006. National Bureau of Statistics Press, Beijing. (in Chinese)

Oki T, Kanae S (2006) Global hydrological cycles and world water resource. Science 313:1068-1072.

OSLC (The office of Shanghai Local Chronicle) 2012. The chorography of Shanghai public utilities, 2010 ed. The office of Shanghai Local Chronicle, Shanghai, http://shtong.gov.cn. (in Chinese) (accessed 4 August 2016)

Ouda OKM (2014) Water demand versus supply in Saudi Arabia: current and future challenges. International Journal of Water Resources Development 30:335-344. doi: 10.1080/07900627.2013.837363

Padowski J, Gorelick S (2014) Global analysis of urban surface water supply vulnerability. Environ Res Lett 9:104004. doi: 10.1088/1748-9326/9/10/104004

Perkins D, Rawski T (2008) Forecasting China's economic growth to 2025. In: Brandt L, Rawski T (eds) China's great economic transformation. Cambridge University Press, Cambridge, pp 829-886

Qi C, Chang N (2011) System dynamics modeling for municipal water demand estimation in an urban region under uncertain economic impacts. J Environ Manage 92:1628-1641. doi: 0.1016/j.jenvman.2011.01.020

Seckler D, Molden U, Silva R, Barker R (1998) World water demand and supply, 1990 to 2025: Scenarios and issues. International Water Management Institute, Colombo, Sri Lanka

Shen H, Mao Z, Zhu J (2003) Saltwater intrusion in the Changjiang Estuary. China Ocean Press, Beijing

SMG (Shanghai Municipal Government) (2010) Answers to people's questions on Qingcaosha water source. http://www.shanghai.gov.cn (in Chinese) (accessed 4 August 2016)

SMG (Shanghai Municipal Government) (2011) The twelfth five-year plan for national economic and social development program of Shanghai. http://www.shanghai.gov.cn (in Chinese) (accessed 4 August 2016)

SMSB (Shanghai Municipal Statistics Bureau) 2014. The Shanghai Statistics Yearbook (Beijing: China Statistics Press). http://www.stats-sh.gov.cn/tjnj/nje14.htm?d1=2014tjnje/E0401.htm. (in Chinese) (accessed 4 August 2016)

Stevens B, Schieb P, Andrieu M, Bohlin E, Forge S, Blackman C, Morgan T, Stambrook D, Ashley R, Cashman A (2006) Infrastructure to 2030 – telecom, land transport, water and electricity. Organisation for Economic Co-operation and Development (OECD), Paris

Strzepek K, Boehlert B (2010) Competition for water for the food system. Phil Trans R Soc B 365:2927–2940. doi:10.1098/rstb.2010.0152

SWA (Shanghai Water Authority) (1998-2013) Shanghai water resource bulletin. Shanghai Water Authority. http://www.shanghaiwater.gov.cn (in Chinese) (accessed 4 August 2016)

SWA (Shanghai Water Authority) (2012) Report of the 12th five-year plan of renovation and construction of urban water supply facilities in Shanghai. http://www.wsa.gov.cn (in Chinese) (accessed 4 August 2016)

SWA (Shanghai Water Authority) (2013) The plan of raw water and treatment water supply of Shanghai. http://baike.baidu.com/view/3869265.htm (in Chinese) (accessed 4 August 2016)

Tortajada C (2006) Water management in Singapore, International Journal of Water Resources Development. 22:227-240. doi: 10.1080/07900620600691944

UNDESA (United Nations Department of Economic and Social Affairs) (2015) World population prospects: the 2015 revision, UNDESA. http://esa.un.org/unpd/wpp/Excel-Data/population.htm. (accessed 4 August 2016)

UNPD (United Nations Population Division) (2014) Population total and population in largest city. http://data.worldbank.org/indicator. (accessed 4 August 2016)

Varis O, Vakkilainen P (2001) China's 8 challenges to water resources management in the first quarter of the 21st Century. Geomorphology (Amst) 41:93-104. doi:10.1016/S0169-555X(01)00107-6

Vijayalaksmi DP, Babu KSJ (2015) Water supply system demand forecasting using adaptive neuro-fuzzy inference system. Aquatic Procedia 4:950-956. doi:10.1016/j.aqpro.2015.02.119

Vörösmarty C, Green P, Salisbury J, Lammers R (2000) Global water resources: vulnerability from climate change and population growth. Science 289:284-288.

Wei ZX, Zai GY, Yan XX (eds) (2010) Shanghai urban geology. Geology Press, Beijing.

Worthington A, Hoffman M (2008) An empirical survey of residential water demand modelling. J Econ Surv 22:842-871. doi: 10.1111/j.1467-6419.2008.00551.x

Xu Z, Takeuchi K, Ishidaira H, Zhang X (2002) Sustainability analysis for Yellow River water resources using the system dynamics approach. Water Resour Manag 16:239-261. doi: 10.1023/A:1020206826669

Zhang J, Gao S, Fen J, Yan L (2007) China's water resource management: strategic issues, governance, and government capabilities. The State Council Center for Development Research, Beijing

Zhang Z, Shao Y, Xu Z (2010) Prediction of urban water demand on the basis of Engel’s coefficient and Hoffmann index: case studies in Beijing and Jinan, China. Water Sci Technol 62:410-418. doi: 10.2166/wst.2010.290

Zhou S, McMahon T, Walton A, Lewis J (2000) Forecasting daily urban water demand: a case study of Melbourne. J Hydrol 236:153-164. doi:10.1016/S0022-1694(00)00287-0

Zhu Z, Ouyang T, Deng Q, Zhou H, Kuang Y (2004) Forecasting water demand and supply in South China. J Am Water Works Ass 96:159-172.

Figure Captions

Figure 1. A - Shanghai annual water consumption 1978 to 2013. B - Shanghai annual raw water supply 1978 to 2013.

Figure 2. A - Shanghai population 1978 to 2013 showing resident and migrant components. B - Shanghai GDP by sectors 1978 to 2013 in 2010 prices.

Figure 3. A - China total population projected to 2050. B - China urban population projected to 2050. (data from United Nations Population Division, http://esa.un.org/unpd/wup/CD-ROM/)

Figure 4. A - The relationship between a country's population and the population of its largest city. B - The relationship between a country's GDP and the GDP of its largest city.

Figure 5. Projections of annual water demand for Shanghai to 2050 based on three scenarios of population and GDP growth.

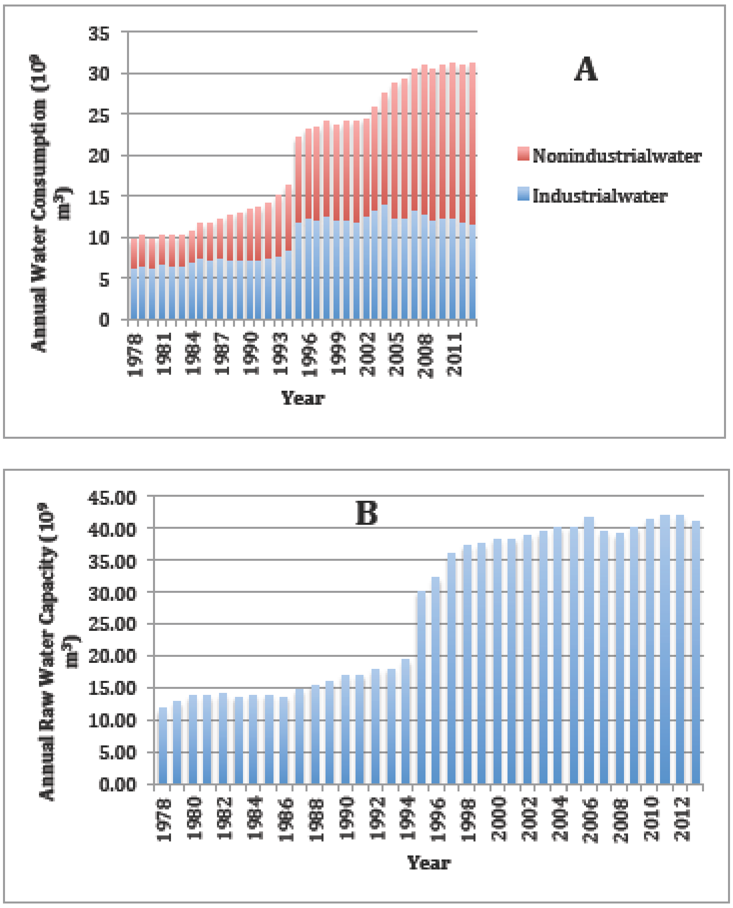
A
Annual Water Consumption (10^9 m³)
35
30
25
20
15
10
5
0
1978
1981
1984
1987
1990
1993
1996
1999
2002
2005
2008
2011
Year
Nonindustrialwater
Industrialwater
B
Annual Raw Water Capacity (10^9 m³)
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Year

Figure 1

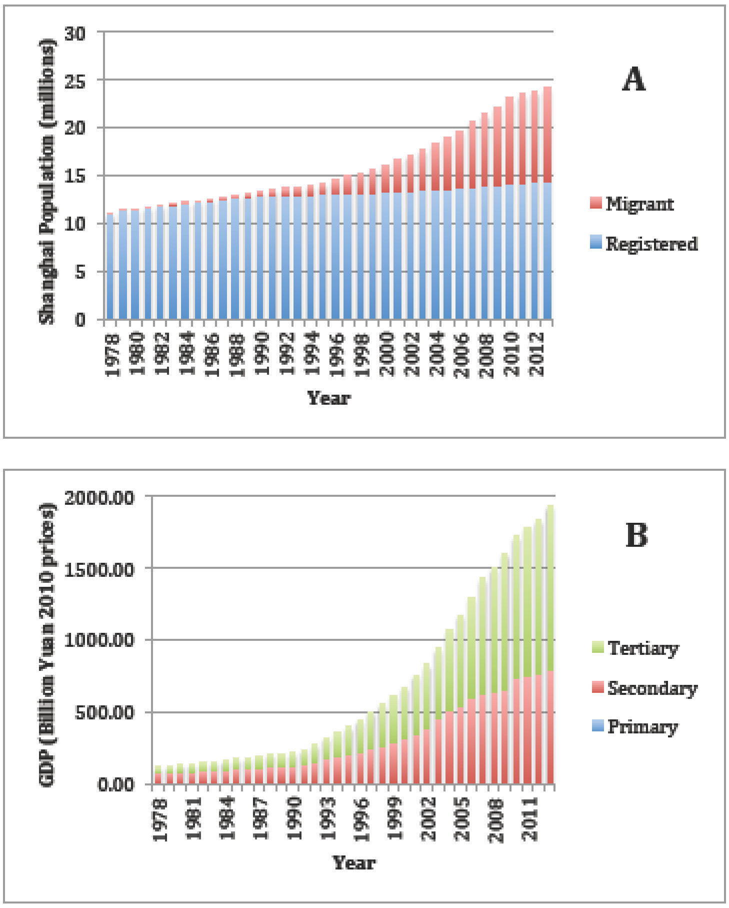
A
Shanghai Population (millions)
30
25
20
15
10
5
0
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Year
Migrant
Registered
B
GDP (Billion Yuan 2010 prices)
2000.00
1500.00
1000.00
500.00
0.00
1978
1981
1984
1987
1990
1993
1996
1999
2002
2005
2008
2011
Year
Tertiary
Secondary
Primary

Figure 2

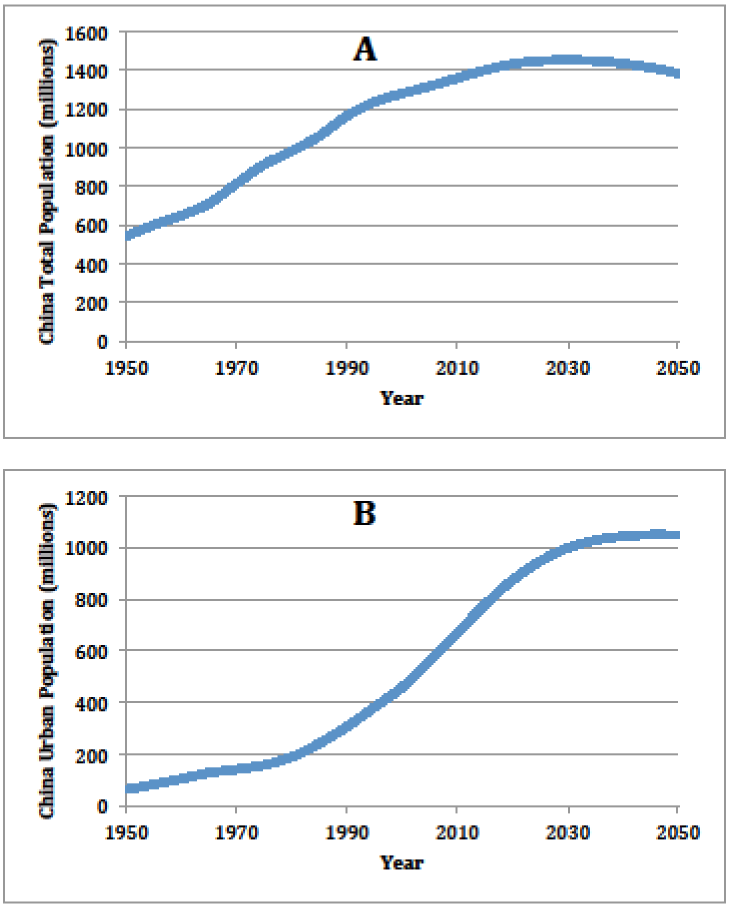
A
China Total Population (millions)
1600
1400
1200
1000
800
600
400
200
0
1950
1970
1990
2010
2030
2050
Year
B
China Urban Population (millions)
1200
1000
800
600
400
200
0
1950
1970
1990
2010
2030
2050
Year

Figure 3

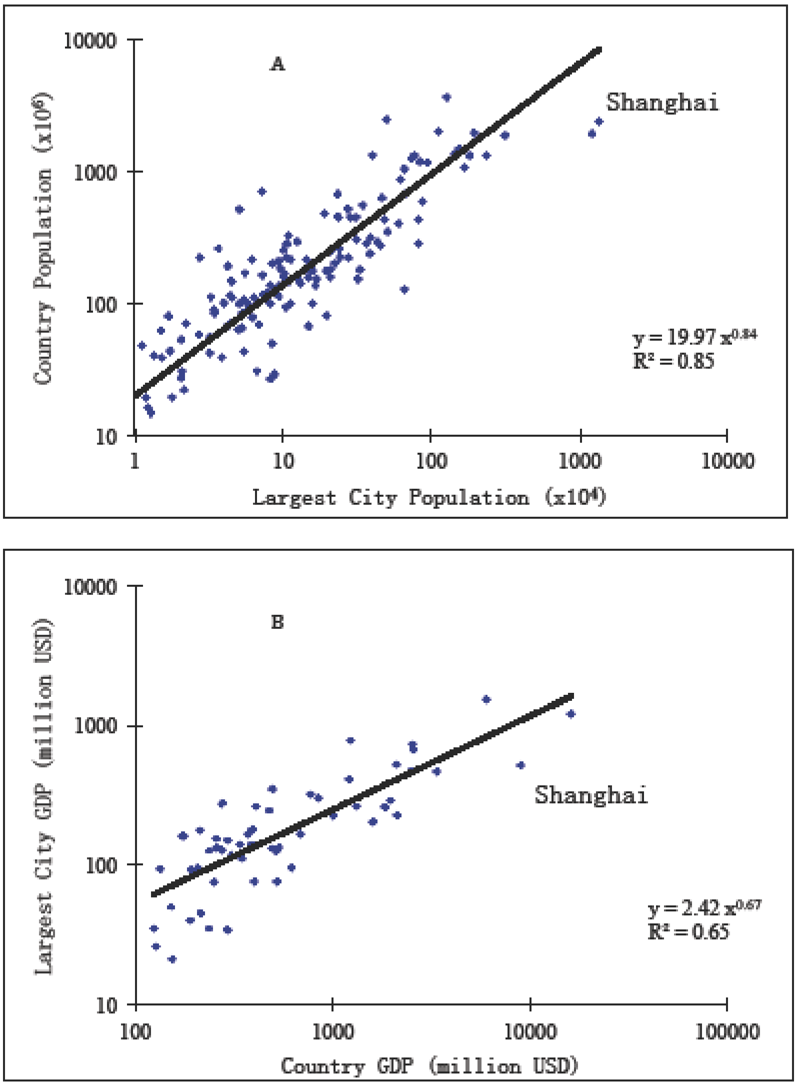
A
Country Population (x10⁶)
10000
1000
100
10
1
10
100
1000
10000
Largest City Population (x10⁴)
Shanghai
y = 19.97 x^0.84
R² = 0.85
B
Largest City GDP (million USD)
10000
1000
100
10
100
1000
10000
100000
Country GDP (million USD)
Shanghai
y = 2.42 x^0.67
R² = 0.65

Figure 4

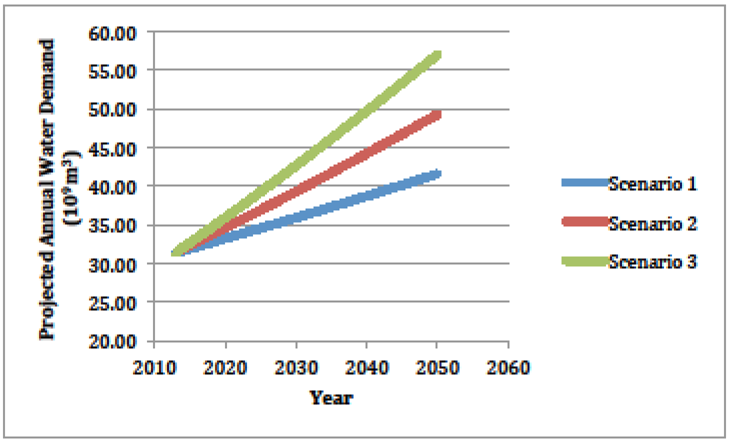
Projected Annual Water Demand ($10^9 m^3$)
60.00
55.00
50.00
45.00
40.00
35.00
30.00
25.00
20.00
2010
2020
2030
2040
2050
2060
Year
Scenario 1
Scenario 2
Scenario 3

Figure 5