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Urban Water Resource Utilization Efficiency in China

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Abstract: The efficient use of water resources directly affects environmental, social, and economic development; therefore, it has a significant impact on urban populations. A slacks-based measure for data envelopment analysis (SBM-DEA) has been widely used in energy efficiency and environmental efficiency analyses in recent years. Based on this model, data from 316 cities were examined and a category method was employed involving three different sorting techniques to empirically evaluate the efficiency of urban water resource utilization in China between 2000 and 2012. The overall efficiency (OE) of urban water resource utilization in China was initially low, but has improved over the past decade. The scale efficiency (SE) was higher than the pure technological efficiency (PTE); PTE is a major determining factor of OE, and has had an increasingly significant effect. The efficiency of water resource utilization varied according to the region, urban scale, and economic function. The OE score for the eastern China was higher than for the rest of the region, and the OE score for the western China was higher than for the central China. The OE score for urban water resource utilization has improved with urban expansion, except in the case of small cities. The SE showed an inverted 'U-shaped' trend with increasing urban expansion. The OE of urban water utilization in comprehensive functional cities was greater than in economic specialization cities, and was greater in heavy industry specialization cities than in other specialization cities. This study contributes to the field of urban water resource management by examining variations in efficiency with urban scale.

Keywords: urban water resource; utilization efficiency; urban scale; undesirable outputs; a slacks-based measure for data envelopment analysis (SBM-DEA); China

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1 Introduction

China's urban areas are poised for major economic development and are likely to accommodate the majority of the nation's residents in the near future. In 2012, the urbanization rate in China was 51.27%, with 6.9×10^8 persons residing in cities. Furthermore, 70.47% of fixed asset investments, 73.72% of economic gross, and 76.22% of consumption were concentrated in cities. Economic growth and the expansion of cities come with a high level of ecological and environmental risk; thus, many serious ecological and environmental problems in China are concentrated in cities. Water is a major factor for sustainable urban ecosystems. The proportion of urban fresh water consumption to total national fresh water resources has increased by 20 percent points over the last 50 years (Zhu *et al*., 2009). Furthermore, water pollution events occur frequently in China's cities (Yang *et al*., 2010). In 2012, 6.6×10^9 m^3 of sewage was discharged directly into the environment, accounting for 17.6% of the total volume of urban sewage, and causing serious ecological problems. With the growth of the urban population, researchers have focused on how to respond to the challenges of urban water utilization and the associated ecological and environment risks, and how to guarantee basic water resources for urban de-

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velopment and residential use. An objective assessment of urban water resource utilization efficiency is a premise for solving these problems (Zhang X *et al*., 2011). In this study, a data envelopment analysis (DEA) method was used to comprehensively estimate the input-output efficiency of urban water resource utilization in China.

The input-output efficiency for urban water resources has long been an important field in urban geographical science. Charnes *et al*. (1978) first proposed the DEA model to estimate the efficiency of different entities, namely, decision-making units (DMUs). The literature shows that DEA has recently been widely applied to evaluate the water utilization efficiency and environmental efficiency of DMUs. Cubbin and Tzanidakis (1998) used regression analysis and a DEA model to evaluate water resource production and comprehensive efficiency in Wales, the United Kingdom in 1998, and compared the relative merits of the two methods. Romano and Guerrini (2011) estimated the output-input ratio of a drinking water company in Italy, and discovered that the ownership structure, scale, and geographical location influenced the performance of the company. Sala-Garrido *et al*. (2012) used bootstrap technology to improve the DEA model, estimate the sewage disposal efficiency of a sewage disposal plant, and propose a method that improved the accuracy of the assessment of the cost-income of the sewage disposal plant. Alsharif *et al*. (2008) studied the spatial difference of water supply systemic ratios in Palestine and suggested that the systemic water supply efficiency of the Gaza region was less than that of the West Bank, attributing this difference primarily to the leakage rate of pipe nets. Worthington (2014) reviewed the literature concerning urban water system efficiency over the past 20 years, indicating that ownership and regulations were the main influencing factors. Meanwhile, models of resource optimization configuration gradually matured based on DEA models, and these studies concentrated on aspects of water resource configuration optimization (Li *et al*., 2013, Wu *et al*., 2013) and scientific resource management (Hu *et al*., 2006).

In China, Yang *et al*. (2009) discussed evaluation systems for water resource utilization efficiency, while Liu *et al*. (2007), Sun *et al*. (2010), Liao and Dong (2011), and Liu *et al*. (2013) assessed the water resource utilization efficiency of China at the province level with the DEA model. The results showed that water resource utilization efficiency in China was low, and that the combined structure of the input elements was not optimal. Water resource utilization efficiency in developed areas is higher than that in developing areas. The available water resources and economic structure were the key factors affecting water resource utilization efficiency (Qian and He, 2011). A common feature of these studies is that they model water consumption as an input, and economic value as output, without considering any undesirable outputs. This may not be reasonable in real production settings, because any water use will result in the emission of pollutants, e.g., COD. Additionally, a serious weakness of the research conducted in China is that it primarily focuses on provincial regions, and uses too few samples to allow analysis of spatial trends in water utilization efficiency within a province. The diversity of urban water utilization efficiency at different population scales and for different functions was not addressed in any of these studies. Some recent studies of environmental efficiency (Bian and Yang, 2010) and industry (Zhang C *et al*., 2011; He *et al*., 2013) have contributed to water resource utilization efficiency and evaluation problems by considering all of the factors involved in production activities. For example, Wang and Qu (2011) studied China′s industrial productivity using undesirable outputs in DEA models. Liu and Zhang (2012) evaluated the regional environmental efficiency in China using slacks-based DEA models, and also considered undesirable environmental outputs in their study.

Based on the above discussion, this study focuses on evaluation systems of urban water resource utilization efficiency, taking into account the positive economic and negative environmental outputs, using a DEA model to measure the water resource utilization efficiency ratio of prefecture-level cities in China. The aims of the study are to improve understanding of the relationship of water resource utilization efficiency with urban scale and function, and to investigate the spatial distribution of urban water resource utilization efficiency, particularly whether there is a scale threshold for maximum urban water resource utilization efficiency.

2 Materials and Methods

2.1 Study area

The attempt of this study is made to calculate the urban water resource utilization efficiency for a sample of 316 central cities of prefecture-level regions of China, from the years 2000 to 2012. Sun *et al*. (2011) have proved that the diverse GDP structure gives rise to discrepancies in regional water resource utilization efficiency in China. Urban areas are spaces dominated by non-agricultural industry, so the study eliminated agricultural water inputs and outputs and focused on industrial and residential water utilization in urban built-up areas. The centers of the urban built-up areas of each prefecture-level city or region were chosen for this study based on China′s regional administrative divisions at the end of 2012. The study area did not include the Hong Kong, Macao, and Taiwan regions due to data unavailable. Each municipality, such as Beijing, Tianjin, Shanghai, and Chongqing, was taken as one sample in this study. The cities of Lhasa and Sansha were not included because there were no complete statistical datasets for the study period. Some prefecture-level administrative offices, autonomous prefectures, and leagues were also excluded because their administrative centers were not city. Details of the sample cities are shown in Table 1. The quantity of sample cities remained the same throughout the study period. The urban centers′ statistical units for each city, based on administrative divisions at the end of 2012, remained stable even if the administrative division changed during the study period. For example, the statistical unit of Lijiang City was in the Gucheng District at the end of 2012, but fell within Lijiang County before the city′s establishment in 2004.

2.2 SBM-DEA model

DEA is an effective tool for efficient resource allocation of multi-input and multi-output decision-making units in the field of management science, systems engineering, and decision analysis (Sueyoshi and Goto, 2011). The principle of a DEA model is often that less input and more output lead to higher efficiency. However, in some fields, such as environmental research, smaller outputs (e.g., pollution) are desirable. These are called undesirable outputs. It leads to a measurement error that including these indexes directly into the DEA model, so these outputs must be transformed.

There are a series of methods for disposing of undesirable outputs, such as the converting to input method (Hailu and Veeman, 2001), the reciprocal transformation method (Seiford and Zhu, 2002), the hyperbolic method (Johnson and McGinnis, 2009), the shadow pricing method (Leleu, 2013), and the slacks-based measure (SBM) method (Tone, 2001; Du *et al*., 2010). Different ′undesirable output′ models measure the efficiencies of DMUs from different perspectives, and the efficiency values and rankings of DMUs are not identical because of measurement errors (He *et al*., 2013). This makes it difficult to choose a specific DEA model to use in practice on undesirable outputs. The SBM method is the only method that does not involve radial measurements. Radial measurement means that the indexes transform along the radial direction, and includes the assumption that inputs and outputs increase efficiency in equal proportions. The SBM model uses slack variables as weighting variables for the transformation of undesirable outputs that reflect the environmental efficiency evaluation, and guarantee the data structure unchanged. This model is characterized by non-radial measurements, and therefore avoids radial measurement errors and performs better than other models at solving efficiency problems that involve undesirable outputs (Liu *et al*., 2010). Therefore, the SBM model was used to deal with the undesirable outputs in this study.

Table 1 Summary of sample cities′ sources

Regions	Numbers of prefecture level regions	Numbers of selected city	Unselected regions	Illustrating for unselected region
Municipality	4	4		
Prefecture level city	285	283	Lhasa and Sansha	Lack of data
Autonomous prefectures and leagues	33	22	Aba, Ganzi in Sichuan Province; Wenshan, Nujiang and Diqing in Yunnan Province; Alxa League in Inner Mongolia; Five autonomous prefectures in Qinghai Province	Administrative centers were not city
Prefecture administrative office	15	7	Da Hinggan Ling Prefecture in Heilongjiang Province; Haidong in Qinghai Province; Six prefecture regions in Tibet	Administrative centers were not city
Sum	337	316		

Note: This table does not contain Hong Kong, Macao, and Taiwan regions of China

According to Tone (2001; 2003) and Sun *et al.* (2014), the SBM-DEA model can be written as follows:

$$\rho = \min\left(\frac{1-\frac{1}{N}\sum_{n=1}^{N} s_n^x / x_{k'n}^{t'}}{1+\frac{1}{M+I}\left(\sum_{m=1}^{M} s_m^y / y_{k'm}^{t'} + \sum_{i=1}^{I} s_i^b / b_{k'i}^{t'} \right)} \right)$$

$$\begin{aligned} s.t. \quad & \sum_{t=1}^{T}\sum_{k=1}^{K} z_k^t x_{kn}^t + s_n^x = x_{k'n'}^{t'} \quad n=1,\ldots,N \\ & \sum_{t=1}^{T}\sum_{k=1}^{K} z_k^t y_{km}^t - s_m^y = y_{k'm'}^{t'} \quad m=1,\ldots,M \\ & \sum_{t=1}^{T}\sum_{k=1}^{K} z_k^t b_{ki}^t + s_i^b = b_{k'i}^{t'} \quad i=1,\ldots,I \\ & z_k^t \geq 0,\ s_n^x \geq 0,\ s_m^y \geq 0,\ s_i^b \geq 0,\ k=1,\ldots,K \end{aligned} \tag{1}$$

where the objective function ρ is the OE of urban water resources utilization. There are $K \times T$ DMUs and three factors associated with each DMU: inputs, good outputs, and undesirable outputs, as represented by three vectors $x = (x_1,\ldots, x_n) \in R^{+N}$, $y = (y_1,\ldots, y_m) \in R^{+M}$ and $b = (b_1,\ldots, b_i) \in R^{+I}$ respectively. The input and output value of the first k' DMU at t period is represented by vector ($x_{k'n}^t$, $y_{k'm}^t$, $b_{k'i}^t$). The vectors (s_n^x, s_m^y, s_i^b) and ($z_1^1,\ldots, z_k^t$) denote input and output slack and the weight of $K \times T$ DMUs respectively. The objective function ρ strictly decreases with respect to (s_n^x, s_m^y, s_i^b) and the objective value satisfies $0 < \rho \leq 1$. The first k' DMU is efficient in the presence of undesirable outputs, if and only if $\rho = 1$. While it is inefficient, i.e., $\rho < 1$, it can be improved and made efficient by deleting the excesses in inputs and undesirable outputs and augmenting the shortfalls in desirable outputs.

$$\sum_{t=1}^{T}\sum_{k=1}^{K} z_k^t = 1 \tag{2}$$

Also, adding the constraint Equation (2) to Equation array (1) transforms the model from ′constant returns to scale (CRS)′ into ′variable returns to scale (VRS)′ form. With the VRS model, OE is separated into pure technological efficiency (PTE) and scale efficiency (SE), namely $\rho_{OE} = \rho_{PTE} \times \rho_{SE}$. However, Equation array (2) is not linear; using the transformation by Charnes and Cooper (1962), an equivalent linear problem is produced to calculate the results.

2.3 Measurement system for urban water resource utilization efficiency

The urban water system was considered as an independent evaluation system containing inputs and outputs. Each city was taken as a DMU with quantitative indicators. Some researchers argue that the selection of input and output indices should not be decided by data availability alone, but also by the number of DMUs (Dyson *et al.*, 2001). Two widely used rules of thumb are suggested for empirical application: the number of DMUs should be larger than the product, and should be at least two times larger than the sum of the number of inputs and outputs (Fang and Guan, 2011). Therefore, for the urban water resource analysis, reference other scholar′s researches (Sun and Liu, 2009; Fang and Guan, 2011; Liao and Dong, 2011), three inputs and two outputs were selected: capital investment, labor force, and water input were taken as inputs, and economic output and environmental waste were taken as outputs. For this study, the annual average capital stock (X_1), the number of employees (X_2), and the total quantity of urban water supply (X_3) were chosen to quantify these inputs. Because of the lack of statistical information, the ′population with access to water supply′ index was used for X_2. Values for X_3 were obtained directly from the statistics yearbook. The GDP index (Y_g) and the sewage discharge pollution quantity index (SDPQI) (Y_b) were chosen for economic output and environmental waste, respectively. The GDP index calculated at comparable price. The calculating formula of SDPQI is as follows:

$$E_{it} = A_{it} \times (P_{it} - W_{it}), \tag{3}$$

where E_{it} is the ith city SDPQI for year t; P_{it} is the t year quantity of discharged wastewater in ith city; W_{it} is the t year capacity of the wastewater treatment plant in city i; and A_{it} is the ith city pollution intensity of untreated sewage for year t. Usually, the sewage pollution intensity for each city is confirmed by the concentration of pollutants in wastewater, but these data were unavailable. Therefore, the level of sewage treatment was used as an indicator of urban sewage pollution intensity. If a city had a wastewater treatment plant that uses deep treatment technology, it was assumed that the pollution intensity of the city was low; otherwise, the pollution intensity was assumed to be high. In this study, the intensity index values are defined as 3 (no secondary and tertiary level deep sewage treatment plants) and 1 (available secondary and tertiary deep sewage treatment plants). The details of the secondary and tertiary deep sewage treatment plants in each city are shown in Fig. 1.

All data in this study were sourced from public statistical yearbooks in China. The indexes of water supply, sewage discharge, and urban population came from the *China Urban Construction Statistics Yearbook* (MHURD, P. R. C., 2001–2013). The indexes of GDP and average capital stock came from the *China City Statistical Yearbook* (DUS, NBSC, 2001–2013), and were calculated through the perpetual inventory method after 2004. Statistical yearbooks for some provinces from 2001 and 2013 were also the source of some indexes, including the *Guizhou* (GPBS and NBSSOG, 2001–2013), *Inner Mongolia* (IMARBS, 2001–2013), *Jilin* (BSJP, 2001–2013), *Qinhai* (QPBS and NBSSOQ, 2001–2013), *Yunnan* (SBYP, 2001–2013), and *Xinjiang Statistical Yearbooks* (SBXUAR, 2001–2013). Each index was normalized to lie between 0 and 1. The details of the index datasets are shown in Table 2.

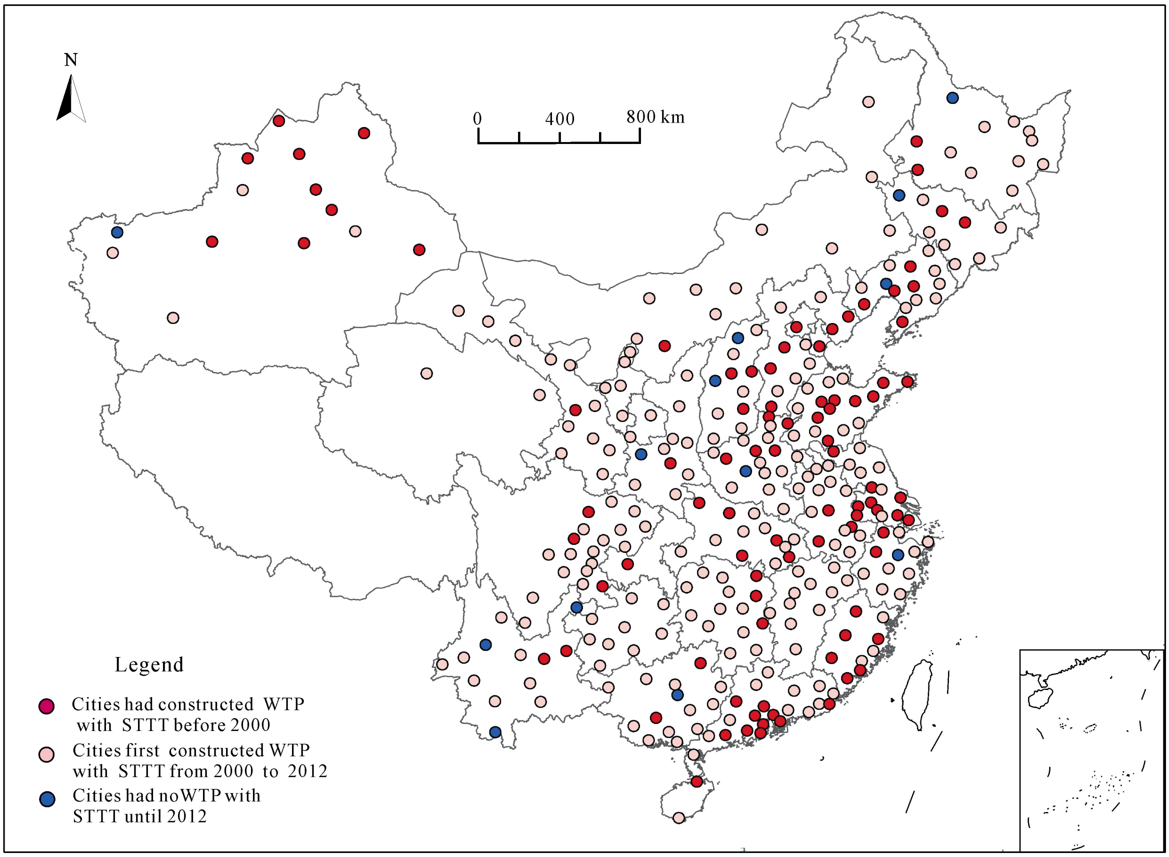

Fig. 1 Spatial distribution of cities having Wastewater Treatment Plant (WTP) with Secondary and Tertiary Treatment Technology (STTT) in China from 2000 to 2012

Table 2 Summary of input and output indices for 316 cities in China

Year	Category	Index	Unit	Mean	SD	Middle	Min.	Max.
2000	Input	Annual average capital stock (X_1)	10^4 yuan (RMB)	467131.7	1206988.9	189121.5	12965.0	16977088.0
		Number of employees (X_2)	10^4 persons	64.21	107.40	33.23	4.40	1136.82
		Total quantity of urban water supply (X_3)	10^4 m^3	12628.3	24361.4	5626.5	219.0	291109.0
	Output	GDP Y_g (desirable)	10^4 yuan	1536373.1	3446506.2	608682.0	26149.0	40986400.0
		SDPQI Y_b (undesirable)	–	10965.8	13284.3	6915.0	200.0	96858 .0
2012	Input	Annual average capital stock (X_1)	10^4 yuan	5937852.7	9772156.5	2609787.0	137421.0	72807192.0
		Number of employees (X_2)	10^4 persons	108.63	211.71	52.30	4.00	2380.00
		Total quantity of urban water supply (X_3)	10^4 m^3	14284.5	29153.7	5550.0	359.0	309704.0
	Output	GDP Y_g (desirable)	10^4 yuan	10505062.3	22030000.0	3789312.0	241692.0	199453700.0
		SDPQI Y_b (undesirable)	–	1369.7	2806.0	578.5	200.0	26351.0

3 Analysis of input-output efficiency for urban water resources

3.1 General characteristics

3.1.1 OE, PTE and SE score

The average OE for urban water resources was low, but has gradually improved over the last 12 years. As shown in Fig. 2, the average OE scores for urban water resource utilization in China improved from 0.167 in 2000 to 0.396 in 2012; thus, the efficiency increased by 0.229. Specifically, two cities achieved optimal efficiency, accounting for 0.6% of the total number of cities in 2012. Also nine cities reached 80% to 99.9% of optimal efficiency; accounting for 2.8% of the total, and 19 cities achieved 60%–80% of optimal efficiency, accounting for 6.1% of the total. Moreover, 96 cities reached 40%–60% of optimal efficiency, accounting for 29.7% of the total. The number of cities with OE values below 40% of optimal efficiency was 192, accounting for 60.8% of the total. It is clear that the OE for China′s urban water resources has not achieved optimal status and needs to be improved. The spatial distribution of urban water resource utilization efficiency is shown in Fig. 3.

The average SE for urban water resources was superior to PTE, although both exhibited upward trends. From 2000 to 2012, the average PTE scores for urban water resource utilization in China improved from 0.294 to 0.435, and the average SE scores improved from 0.591 to 0.923. Thus, PTE increased by 0.141, while SE

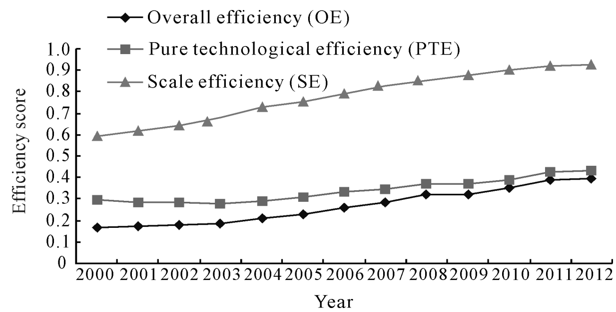

Fig. 2 Efficiency results for urban water resource in China from 2000 to 2012

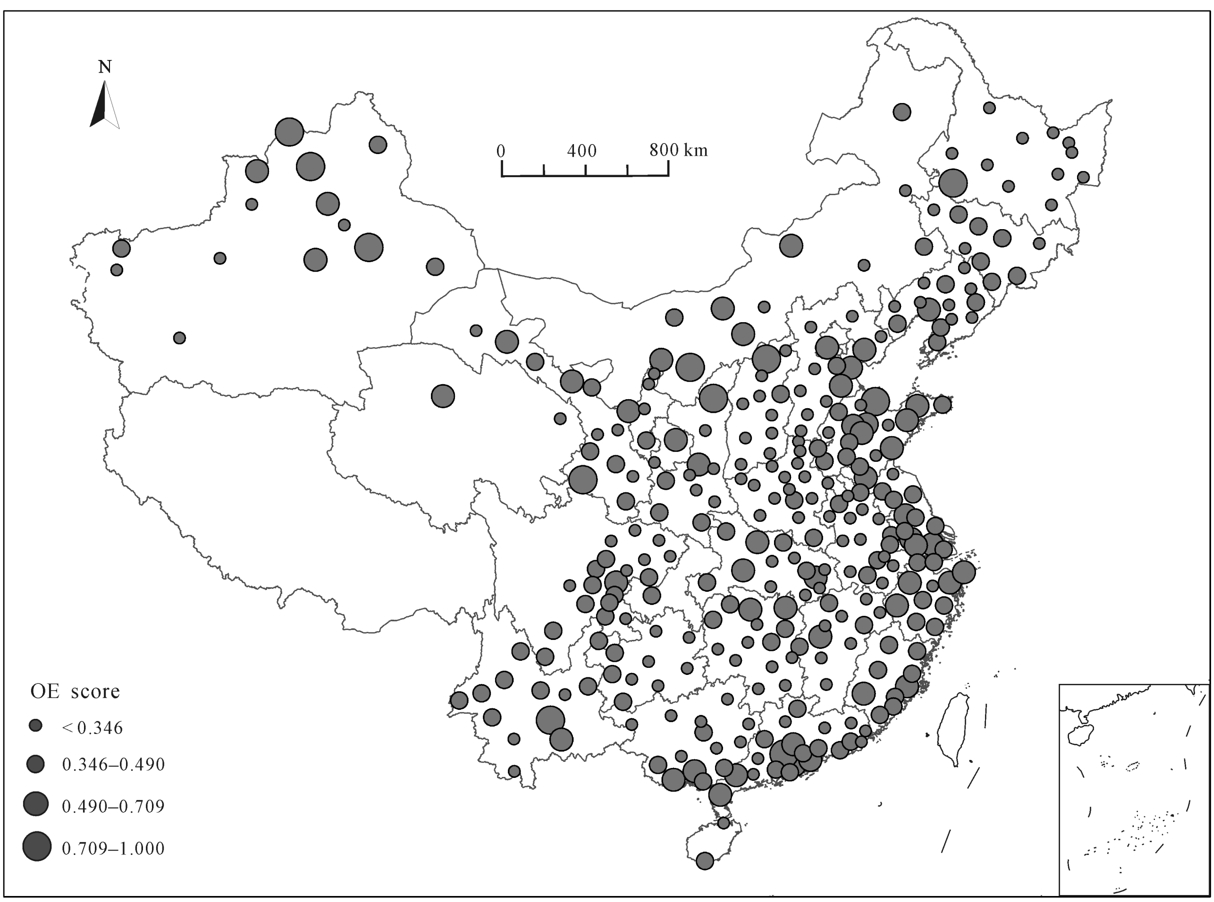

Fig. 3 Spatial distribution of China′s urban water resources overall efficiency (OE) in 2012

increased by 0.432. There were 301 cities for which the SE score was higher than the PTE score, accounting for more than 95% of cities. Meanwhile, the number of cities (236 samples) with SE scores reaching more than 90% of the optimal SE was higher than the number of cities (15 samples) with PTE scores reaching 90% of optimal values. This clearly indicates that the SE was superior to the PTE for urban water resources in China.

PTE was the determining factor for OE, and its defining role increased over the study period. The relationships between OE, PTE, and SE are shown in Fig. 4. In 2000 and 2012, the SE was distributed above the 45° diagonal, near the optimal level of effectiveness, and was not strongly correlated with OE. This indicates that the SE for urban water resources did not determine the OE score. The relationship between PTE and OE shows that most samples fall on the periphery of the 45° line, suggesting that these two variables have a higher correlation than seen between SE and PTE. The correlation coefficient of PTE and OE was 0.763 in 2000, but 0.922 in 2012, showing that PTE has become an increasingly significant factor over the last 12 years. These results are consistent with the findings of Li *et al*. (2005) and Guo *et al*. (2009).

3.1.2 Impact factors of water resource utilization efficiency

The level of economic growth is a major factor in water resource utilization efficiency. Economic growth is often accompanied by increased urbanization population, a larger proportion of non-agricultural industry, and upgrading of industrial infrastructure, which in turn improves water utilization efficiency. Economic growth also has an industrial agglomeration effect, thus improving the per-unit water utilization efficiency. The GDP output per m^3 of urban water for all prefecture-level cities increased from 115.9 yuan/m^3 to

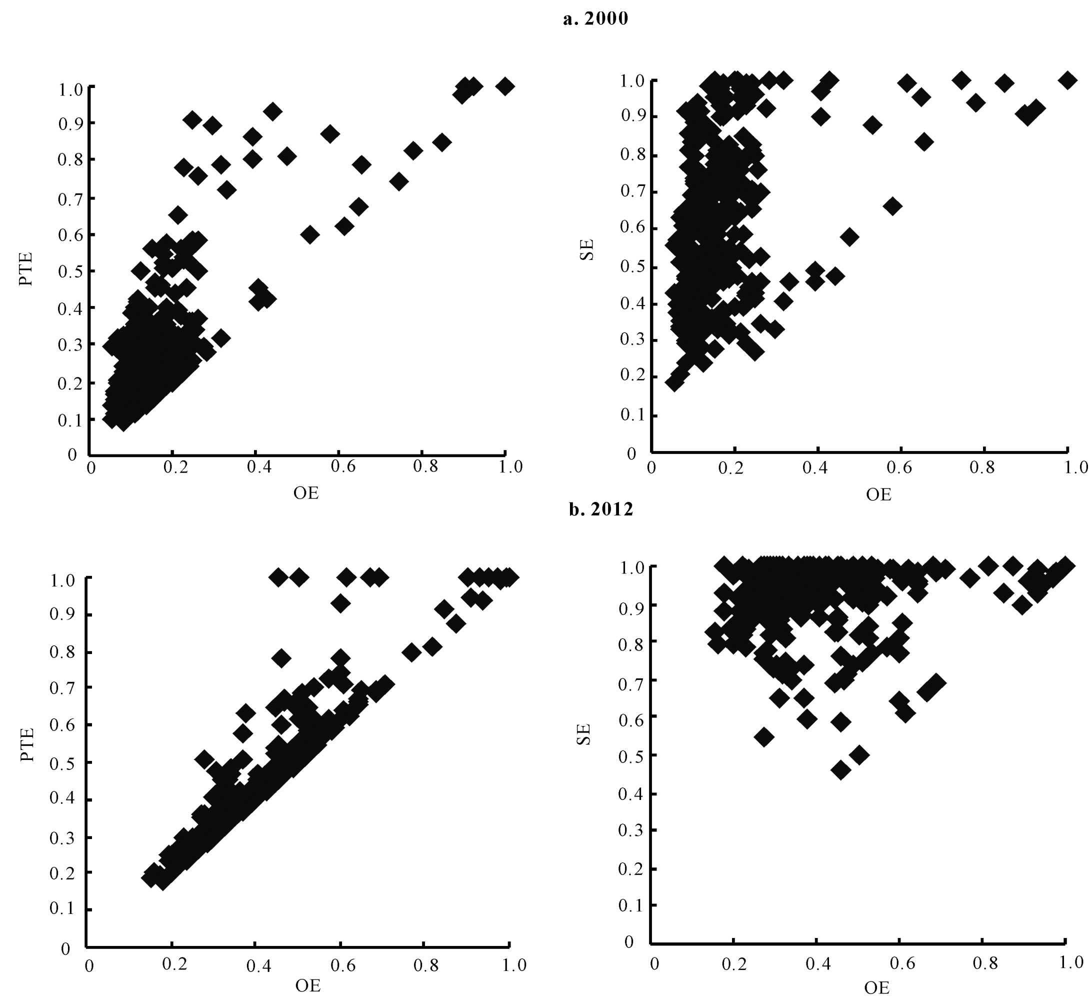

Fig. 4 Relationship among overall efficiency (OE), pure technological efficiency (PTE), and scale efficiency (SE)

625.9 yuan/m^3 from 2000 to 2012. Economically advanced cities also have the finances to increase water supply capacity and improve drainage facility services.

According to the environmental theory of the Kuznets curve, the pollution of an urban environment varies as an inverted 'U-shaped' trend with urban scale expansion. In 2000, all cities in China were in a period of rapid economic expansion. As the predominant urban manager, the government tended to encourage high-value industries, while frequently neglecting these industries' effects on the environment. Manufacturing, in particular, became a major industry in China. Various cities faced different water pollution issues; water resources had a high negative output, which influenced their overall efficiency. By 2012, the exacerbated problem of urban water pollution began to restrict urban economic development and affect residents' daily lives. The government therefore increased investment in environmental protection, improved the water supply, constructed dewatering and treatment facilities to improve the efficiency of concentrated urban sewage disposal, reduced the negative environmental output, and thereby improved total technological water resource utilization efficiency.

The government's environment regulation also improved the water efficiency in China. From 2000 to 2012, 211 prefecture-level cities constructed new secondary-level wastewater treatment plants, and direct sewage discharge was reduced from 1.92×10^6 m^3 to 6.60×10^5 m^3 in all prefecture-level cities in China. As a result, the negative output of the urban environment has greatly decreased, and overall water utilization efficiency has improved. Clearly, the economic growth, the government's environmental regulations, and awareness of environmental protection issues are the main influences on urban water utilization efficiency improvement.

3.2 Classification comparison

From the perspective of China's economic development, the mainland of China is usually divided into three regions, as shown in Table 3. Cities are usually divided into five groups according to the population size, as shown in Table 4, and into two categories and eight sub-categories according to economic function (Zhou and Sun, 1997), as shown in Table 5.

3.2.1 Regional comparison

From the regional perspective, the water resource utilization efficiency varied by region: the OE score for the eastern China was higher than that for other regions, and the OE score was higher for the western China than for the central China. The mean values of OE for urban water resources in 2000 for the eastern China, the central China, and the western China were 0.182, 0.139, and 0.182, respectively (Table 6), whereas in 2012, these scores were 0.432, 0.358, and 0.403, respectively. The number of cities with OE values between 0.500 and 1.000 were 28, 13, and 18, respectively, and these accounted for 27.7%, 11.4%, and 17.8%, respectively, of the total city number in each of the three regions.

Factors influencing the OE were not identical for the three regions. In 2012, the mean score of PTE on the urban water resources for the eastern China was greater than that for the other two regions; similarly, the score for the western China was greater than for the central China. The mean SE was higher in the western China than in the other two regions. It follows that the main

Table 3 Regional delimitation

Region	Province, autonomous region, and municipality	City quantity
Eastern China	Liaoning, Beijing, Tianjin, Hebei, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, Hainan	101
Central China	Jilin, Heilongjiang, Inner Mongolia, Shanxi, Henan, Hubei, Hunan, Jiangxi, Anhui	114
Western China	Shaanxi, Gansu, Qinghai, Ningxia, Tibet, Xinjiang, Yunnan, Guizhou, Sichuan, Chongqing, Guangxi	101

Table 4 Urban population scale delimitation

Urban rank	Population scale (10^4 persons)
Super city	>300
Mega city	100–300
Large city	50–100
Mid-sized city	20–50
Small city	<20

Table 5 Economic function classification of cities

Category	City function	City quantity
Comprehensive function city	Country's most important large-scale integrated city	10
	Important comprehensive city	23
	Comprehensive manufacturing city	30
Economical specialization city	Specialization of mining city	40
	Specialization of heavy industry city	50
	Specialization of light industry city	44
	Traffic city	29
	Commercial city	52
	Tourist city	17
Others	Cities in border areas	8
	No prominent function city	13

Table 6 Variations of urban water resource efficiency in three regions

Region	2000	2004	2008	2012
Eastern China	0.182/0.268/0.683	0.279/0.279/0.816	0.351/0.389/0.883	0.432/0.484/0.916
Central China	0.139/0.255/0.575	0.173/0.247/0.705	0.269/0.317/0.843	0.358/0.393/0.920
Western China	0.182/0.363/0.516	0.229/0.348/0.659	0.340/0.414/0.820	0.403/0.433/0.935
Total	0.167/0.294/0.591	0.209/0.289/0.725	0.318/0.371/0.854	0.396/0.435/0.923

Note: Three numbers in each column are OE/PTE/SE, respectively

reason for the lower OE in the western China was the lower PTE score. The OE in the central China was lower than in other regions because of both the lower PTE and the lower SE. From the perspective of temporal evolution, the spatial distribution of urban water resource OE in China did not change, but retained 'eastern China > western China > central China' characteristic.

These results are not entirely consistent with the findings of Sun *et al*. (2014) and Fang and Guan (2011). This is probably because of the difference in research objectives. The basic samples in Sun *et al*. (2014) and Fang and Guan (2011) consisted of provinces, whereas the samples in this study were cities with varied industrial structures, which probably caused the difference in water resource utilization efficiencies. Most water resource studies indicate that water utilization efficiency in the central China is higher than in the western China, but the findings of this paper suggest the opposite. These studies have indicated that the scale and efficiency of water utilization in agriculture is the main factor for the difference between the central and the western China (Sun *et al*., 2011). However, urban areas follow a different trend. Urban water utilization efficiency in the western China is higher than that in the central China. The GDP output per ton of urban water in the western China is 736.4 yuan/m^3, higher than 633.2 yuan/m^3 in the central China. Meanwhile, non-agricultural industries water efficiency in the western China (237.4 yuan/m^3 in 2013) is higher than that in the central China (195.8 yuan/m^3 in 2013) (NBSC, 2014). So, the higher economic outputs lead to higher urban water resources utilization efficiency in the western China.

3.2.2 Scale comparison

The OE of urban water resource utilization gradually improved with the increase of the urban population in China, except in the small cities group, from 2000 to 2012 (Fig. 5). In 2012, the mean values of urban water utilization efficiency for medium, large, mega, and super cities in China were 0.366, 0.373, 0.423, and 0.442, respectively. The OE for super cities, which had the highest score among these four groups, was larger than for the medium cities by 0.076. The small cities had the highest OE score among the five city scales. These patterns were also seen in 2000, 2004, and 2008.

The mean value of water resource SE follows a characteristic inverted 'U-shaped' trend with increasing urban population scale (Fig. 6). From 2000 to 2008, the value of SE for mega cities was the highest, while the lowest value was found for small cities and super cities.

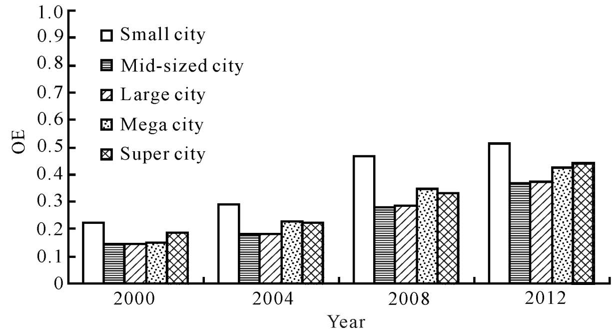

Fig. 5 Diversity of overall efficiency (OE) of urban water resource among different urban population scales

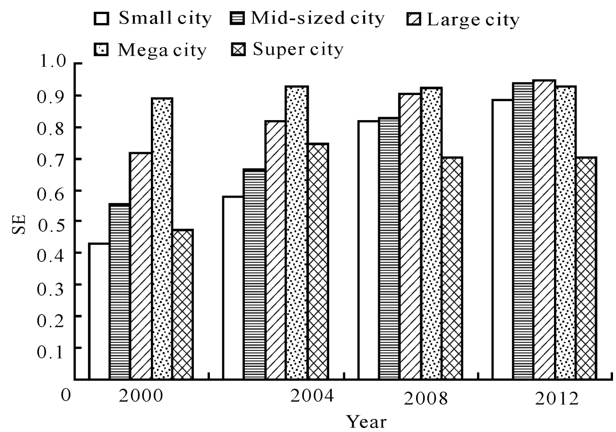

Fig. 6 Diversity of scale efficiency (SE) of urban water resource among different urban population scales

The trend in urban water resource SE scores is as follows: small cities < mid-sized cities < large cities < mega cities > super cities. In 2012, the SE values of all city types were over 0.900 except for the small and super cities. Water supply has scale merit, but the expansion of a city has negative effects that offset this improved merit. Therefore, there is an optimum size at which the water resource utilization efficiency can be maximized. The optimum scale of Chinese cities is maga city from 2000 to 2008, but change to large city in 2012.

3.2.3 Urban function comparison

The OE for the utilization of urban water resources also varied according to the comprehensive function and industry specialization of the sample cities. As shown in Table 7, the efficiency scores for cities in a comprehensive function category (0.436) were higher than the scores for cities in an industry specialization category (0.381). From the sub-function perspective, the manufacturing cities had better efficiency scores than other comprehensive function cities. It was also found that mining specialization cities had better efficiency scores than other cities, and also had the highest sub-group score compared to other economic specialization cities, while tourist cities and commercial cities had the lowest efficiency scores.

The difference in OE scores between comprehensive function cities and industry specialization cities has expanded over the last 12 years. The OE score gap increased from 0.017 in 2000 to 0.055 in 2012. The manufacturing cities consistently had the highest OE scores during the study period. In economic specialization cities, the mining and heavy industry specialization cities became the most efficient over the study period. Full details of how the urban water resource utilization efficiency varies with urban function can be seen in Table 7. Differences in the water resource utilization efficiency due to urban function reflect the differing abilities of the various industries to efficiently manage water resources, and these variations also affect the spatial distribution of water resource utilization efficiency across China.

4 Discussion

In this paper, the temporal and spatial variations of urban water utilization efficiency in China are presented. The results show that urban water resource utilization efficiency has increased over the last 12 years, but can still be low. The study proves the existence of clear differences in efficiency between different regions, urban scales, and urban functions. In addition, a core finding of this study is the discovery of an optimum population size for maximum efficiency. If the urban population size exceeded this optimal scale, the SE for urban water resources decreased, and water utilization efficiency could not be improved further. This result is consistent with the researches for urban environment efficiency (Xu, 2009) and land use efficiency (Wu *et al*., 2011). So far, this conclusion can was only proved to exist in China. In other countries, the efficiency research objects always water plants (Alsharif *et al*., 2008; Romano and Guerrini, 2011; Worthington and Helen, 2014), and no direct evidence to determine exists for optimal scale of urban water efficiency.

The SBM-DEA model proposed in this paper fits the purpose of this study, and if appropriate evaluation indexes are found, this model could be extended to study

Table 7 Efficiency of urban water resource clustered by economic function

Urban economic function	2000	2004	2008	2012
Comprehensive function city	**0.171**	**0.234**	**0.332**	**0.436**
Country′s most important large-scale integrated city	0.177	0.227	0.335	0.454
Big important comprehensive urban district	0.161	0.217	0.304	0.389
Comprehensive manufacturing city	0.177	0.250	0.353	0.466
Economical Specialization city	**0.154**	**0.194**	**0.301**	**0.381**
Specialization of mining city	0.170	0.216	0.320	0.432
Specialization of heavy industry city	0.145	0.203	0.337	0.410
Specialization of light industry city	0.166	0.203	0.290	0.359
Traffic city	0.144	0.170	0.302	0.383
Commercial city	0.150	0.172	0.265	0.330
Tourist city	0.135	0.205	0.287	0.389
Others	**0.295**	**0.299**	**0.467**	**0.445**
Cities in border areas	0.426	0.460	0.591	0.474
No prominent function city	0.214	0.200	0.391	0.427

the efficiency of urban water plants, sewage treatment plants, and water system pipe networks. The basic spatial sample, from province deep into prefecture-level cities, used in this research provided a more detailed picture of urban water management than that in previous studies. More than 300 county-level cities that had limited statistical data were excluded from this study, because statistical data on the economy, population, and water resource utilization of cities in China are inconsistent between prefecture-level cities and county-level cities. The next step, therefore, should be to use an appropriate assessment index system to evaluate the urban water utilization efficiency for all cities in China, including both prefecture-level and county-level cities. More detailed data should be made publicly available, including the operating costs of plants, leakage rates for water supplies and drainage pipe networks, and the concentration of pollutants in the input and output water in sewage treatment plants. This research provides a preliminary understanding of the differences in the efficiency of China′s urban water resource utilization among different areas and cities. For each city, only the overall efficiency of the water resource utilization is provided, rather than an in-depth study on the small-scale mechanisms that influence urban water resource utilization efficiency. Environmental regulations also have a significant effect on urban water resource utilization efficiency in China, but this effect was not analyzed deeply in this study owing to limited data.

5 Advice for Urban Planners

The scarcity of available per capita water resources in China indicates that it is important to improve comprehensive urban water resource utilization efficiency. For policy makers and planners, the key to improving both PTE and SE lies in the consideration of two aspects, as set out below.

5.1 Methods for improving PTE

There are several important ways of improving the PTE for urban water resources. An important aspect of improving the urban water supply and demand system efficiency is determining the appropriate level of investment in water conservation and water pollution control to achieve efficiency in both areas while satisfying the development needs of the city. The model presented in this paper can provide redundancy or inadequacy values (variables s^- and s^+) for all the DMUs′ inputs and outputs. Planners can adjust the input-output proportion between these factors by varying s^- and s^+. Urban system design is also important, and should include consideration of how to build better and more efficient water system networks, how best to locate water sources and water treatment plants, and how to evaluate the economic rationality of the water supply network. Reducing waste in water utilization should also be considered in urban design. Water resource management key factors should be optimized, such as the number of employees, and levels of investment and total water supply.

Urban water demand is comprised of countless small-scale enterprises involving cities and their residents. In terms of urban management, economic tools can also be used to improve the efficiency of the users' water utilization and increase the PTE. Regulation of water price provides an effective economic tool for water resource supply and demand adjustment, with the function of regulating and improving water utilization. The current price of water in China is generally low, and it is easy for water to be wasted, resulting in low efficiency in the use of water resources. Increasing the price of water and imposing a pollution charge as standard is an important way to improve the efficiency of utilizing water resources. China's urban policy makers often use management methods such as water use quotas, but it requires further study that whether those methods providing an acceptable balance between resident's needs and improving the water resource utilization efficiency.

5.2 Methods for improving SE

In order to improve the SE for the major cities in China, the urban population scale should be guided by the optimum scale range for maximum urban water resource utilization efficiency. Returns to scale differed among the various urban scales (Fig. 7). In 2012, large cities (0.5×10^6–1.0×10^6 persons) had the largest portion of increasing returns to scale, about 67.9% of the total quantity. The efficiencies of super cities all had decreasing returns to scale. As shown in Fig. 5 and Fig. 6, the SE and returns to scale were favorable only if the population scale remained at 0.5×10^6–1.0×10^6 in 2012. According to this conclusion, policies should encourage new urban populations to concentrate in small and mid-sized cities. These cities will eventually expand to form large cities. If the population scale is larger than the optimal scale range, there is no need to encourage migration, as appropriate control policies for the total population scale can be applied. Super cities should strictly control the urban population scale, but moderate controls should be sufficient for mega cities (which have decreasing returns to scale). Financial support should therefore prioritize water system renewal in large and mid-sized cities, in order to optimize the factors combination of water resources and improve the PTE. Small cities have high environmental benefits and low economic outputs, for which expanding economic benefits

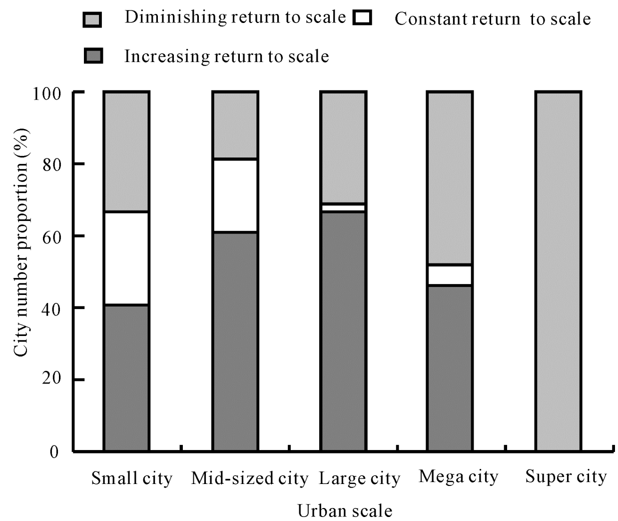

Fig. 7 Urban water scale efficiency (SE) discrepancies inside tier cities of China with same size in 2012

are the main goal. Thus, different efficiency strategies for water resources are appropriate for different types of cities.

In conclusion, the major practical insight from this study is that the PTE and SE of water resources should be improved by management of urban water supply and demand. Relevant adjustments of water resource factors, such as the use of water pricing controls, can improve efficient management of water resources and have a positive influence on residents and businesses, and should be the focus of policy makers and of further research.

6 Conclusions

In this study, the DEA model was used to analyze the urban water resource utilization efficiency across China. The effects of various phenomena on urban water utilization were investigated and explained, and methods for improving urban water resource management were discussed. The results show that the OE of urban water resource utilization had low scores in China, but have improved over the past 12 years. The SE was higher than the PTE. The PTE was a major determinant of the OE, and its influence has increased over the study period. Economic development, government environmental regulations, and awareness of environmental protection issues are the main factors influencing overall urban water utilization efficiency. Water resource utilization efficiency varied by region: the OE score for the eastern China was higher than for other regions, and the OE score for the western China was higher than for the central China. The urban OE has improved with increasing population sizes. The SE followed an inverted 'U-shaped trend' with increasing urban scale. The urban water utilization efficiency in comprehensive functional cities was greater than that in economic specialization cities, and was greater in mining and heavy industry specialization cities than that in other specialization cities. A core finding of this study is the discovery of an optimum population size for maximum efficiency. These results can help policy makers and urban planners to improve the efficiency of urban water resource management in China. The PTE and SE values for urban water resources can indicate where changes need to be made, either in expanding urban scales or through optimizing resource allocation. This study also provides a reference for other countries for the study and management of water resources.

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