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Do water-saving policies improve water-use technical efficiency? Evidence from the water-receiving cities of China's South-North Water Transfer Project

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Abstract

China has implemented a series of water-saving policies in response to the growing threat of water shortages. However, it remains unclear whether these water-saving policies, which aim to reduce water-use intensity, will actually improve water-use technical efficiency. This study scrutinizes water-use technical efficiency within an extended human-environment framework by using the case of China's South-North Water Transfer Project (SNWTP). An improved estimation method for water-use technical efficiency based on stochastic frontier analysis is adopted to empirically investigate the variations in water-use intensity and technical efficiency in the

SNWTP's water-receiving cities. This study argues that there is no definitive link between improvements in water-use technical efficiency and decreases in water-use intensity, and thus water-saving policies oriented toward reducing water-use intensity do not necessarily increase water-use technical efficiency. In addition, achieving the goals of water-saving policies by reducing water use intensity alone remains challenging and requires improving the water-use technical efficiency caused by endogenous technological progress. Finally, setting a unified target to reduce water-use intensity leads to inequitable sharing of water-saving tasks between regions, resulting in conflicts of interest among government bureaucracies.

Keywords: *Water-saving policy; South-North Water Transfer Project; STIRPAT; Water-receiving city; Water-use technical efficiency; Water-use intensity*

1 Introduction

China's rapid growth has caused increasingly severe water scarcity in the past forty years (Jiang, 2015). In the most water-deficient North China region, annual water availability per capita is only half of the international water scarcity threshold (Barnett et al., 2015). In order to save water, the government first proposed to construct a water-saving society in the *Water Law* (National People's Congress, 2002), and has since formulated a national water-saving action plan (National Development and Reform Commission & Ministry of Water Resources, 2019). The effectiveness of all water-saving policies in China is measured by using the water-use intensity (WUI), defined as the amount of water used per unit of GDP.

The concept of water-use intensity in China is close to water-use efficiency (WUE), which is the value added per unit of water withdrawn and is made up of the combined WUE of the agricultural, industrial, and service sectors (Giupponi et al., 2018), as defined by UN-Water (2017). Technical efficiency, as defined by Farrell (1957), is an economic measure of management capability. In contrast, this idea of WUE is a physical measure of a specific technology under the assumed management level. However, due to poor management, water-use technologies with high WUE are likely to have low water-use technical efficiency (WUTE). WUTE is the proportion of the lowest practicable water use to the observed water usage at a specific input level (Karagiannis et al., 2003). Since WUTE gives information on how much water may be reduced without changing inputs, it has more of an economic than a physical connotation.

This study examines whether China's water-saving policies can improve water management, thereby enhancing WUTE. However, can a reduction in WUI really reflect improvements in WUTE? Do water-saving policies oriented to reducing WUI improve WUTE? These issues concerning the relations between WUI and WUTE have gotten scant consideration in previous studies. To date, many studies examined the contribution of agricultural water−use technology to water-saving from the perspective of WUI. Most of these studies focus on improving agricultural irrigation technology on WUI (Fishman et al., 2015; Nazari et al., 2018) and improving the WUI of crops themselves (Farooq et al., 2019). Existing studies mostly examined WUI changes based on sites and crops on a local scale (Cao et al., 2018; Grassini et al., 2015). These studies provided important information about the influence of specific water-saving measures on WUI. However, these water-saving measures do not always bring real water savings. Some water-saving measures may trigger a rebound effect and expand the total area irrigated, increasing water consumption rather than decreasing it (Berbel et al., 2015). Therefore, understanding local WUI may not help regional or national water-saving policy design.

Furthermore, existing studies tended to use WUI as a univariate measurement of productivity, without considering other factors that may explain productivity variations. Most of these studies attributed all output variations to water input (Nazari et al., 2018). However, some economic and social factors also affect productivity variations (Geng et al., 2019). The change of natural resource management to stimulate technology absorption can be facilitated by population and economic expansion (Kurtz & Brooks, 2011), which will enhance WUTE. Environmental rules for water management can also encourage changes in the industrial structure and spur the development of water-use technology, resulting in enhanced WUTE (Zhou & Tol, 2005). Therefore, using univariate measurements of WUI might not fully understand the source of productivity variations. If these measurements constitute the basis for formulating national or regional water-saving policies, a series of problems may arise (Scheierling et al., 2014).

To our knowledge, the current studies focused more on estimating WUTE, instead of considering the influence of various human activities on the frontiers of resource consumption within the human-environment framework. These studies often used traditional data envelopment analysis (DEA) to estimate WUTE (Lee et al., 2011; Long & Pijanowski, 2017); or used a DEA-based approach that decomposes productivity change to measure the sources of water-productivity change (Deng et al., 2016; Miao et al., 2018; Speelman et al., 2008; Wang et al., 2015). However, a limitation of DEA approaches is that they assume that all variables can be precisely observed and measured without errors. Such strong assumption rarely implies the possibility of inconsistent DEA estimators (Njuki & Bravo-Ureta, 2018). Other studies used SFA to examine WUTE (Dhehibi et al., 2007; Karagiannis et al., 2003; Njuki & Bravo-Ureta, 2018). SFA's statistical noise assumption, which takes data mistakes and missing variables into account, is its key advantage compared to DEA. (Filippini & Zhang, 2016). However, the effects of unobserved heterogeneity, unrelated to inefficiency, are not considered in existing SFA studies (Farsi et al., 2005).

This study aims to correlate existing studies on water-saving policies (Giannoccaro et al., 2022; Liu et al., 2022) with the literature on water use technical efficiency (Sheng & Qiu, 2022) to develop an extended human-environment framework that takes into account the drivers of water consumption. This study then uses this framework to examine the case of China's South-North Water Transfer Project (SNWTP) to understand changes in WUTE in its receiving cities. Since the SNWTP's water-receiving cities are the regions most significantly affected by water-saving policies, the SNWTP offers a perfect case study to evaluate variations in WUTE and WUI in these cities. By combining the analysis of Chinese water-saving policy documents, this study argues that there is no definitive link between improvements in WUTE and decreases in WUI, and thus water-saving policies oriented toward reducing WUI do not necessarily increase WUTE. In addition, achieving the goals of water-saving policies by reducing WUI alone remains challenging and requires improving the WUTE caused by endogenous technological progress.

Finally, setting a unified target to reduce WUI leads to inequitable sharing of water-saving tasks between regions, resulting in conflicts of interest among government bureaucracies.

Empirically, in the limited literature on the complex association between water-saving policies and WUTE in the Chinese socioeconomic context (Du et al., 2021; Su et al., 2021), this study adds additional empirical analysis and evidence by focusing on SNWTP-induced changes in WUTE in China. Theoretically, by exploring the complex linkages between water-saving policies and WUTE, this study adds to the existing literature investigating WUTE from a human-environmental framework (Sheng & Qiu, 2023). Studies on water-saving policies have not followed suit in this regard: although the impact of water-saving policies on WUI has received widespread attention (Zhang et al., 2020; Zhang et al., 2021), no studies have yet problematized the differences between WUI and WUTE. In addition, this study's improved WUTE estimation method considers individual time-varying and time-invariant inefficiencies and provides a feasible methodology for examining WUTE.

2 Methods and materials

2.1 Extended STIRPAT model

The IPAT model stipulates that environmental impact (*I*) is the product of three anthropogenic drivers: population (*P*), affluence (*A*), and technology (*T*); hence $I = PAT$. Thereafter, Dietz and Rosa (1994) refined the IPAT model, recognizing stochastic impacts by regression on population, affluence, and technology (STIRPAT). In order to investigate the impact of population and affluence on water consumption, population size (*pop*) and per capita

GDP (*pgdp*) are utilized in the extended STIRPAT model as the independent variables, while water consumption (*cons*) serves as the dependent variable. This dependent variable reflects variations in water consumption brought on by various human activities.

Many demographic factors, such as population size, urbanization, population structure, and family size, may affect water consumption (Harlan et al., 2009; March et al., 2012; Srinivasan et al., 2013). However, population size significantly impacts resource utilization more than urbanization and other demographic characteristics (Liddle, 2014). Therefore, population size is selected to reflect the impact of the population driver on water consumption.

In current STIRPAT studies, per capita GDP is commonly used as a proxy for affluence (such as Liddle, 2013; Wei, 2011). Empirical studies indicate that the demand for water by residential, manufacturing, and service consumers is relatively inelastic, though not perfectly so (such as Dharmaratna & Harris, 2012; Price et al., 2014). In addition, the effect of water prices is not considered in this study since water consumption tends to be price-inelastic (Olmstead & Stavins, 2009). The primary reasons for the price inelasticity are the lack of similar substitutes for different water uses and the fact that water costs often represent a small share of the domestic budget (Asprilla Echeverría, 2020). Moreover, significant increases in water prices are required to achieve water savings, which are often politically unacceptable (Rodriguez-Sanchez et al., 2018).

Following York et al. (2003), the proportions of manufacturing and service industry output (*manu* and *serv*) are used as independent variables to reflect the impacts of technical progress triggered by changes in the industrial structure on water consumption. WUTE is enhanced and water consumption is decreased as the industrial structure transforms from heavy industry to high-tech and knowledge-based sectors (Zhou & Tol, 2005).

In addition, exogenous technical progress drives technological innovations that lower water consumption through water saving, water recycling, and expanded WUE services (Cheng et al., 2009). Therefore, the underlying water demand trend (*UWDT*) as a function of time (*t*) is adopted to capture exogenous technical progress (Hunt et al., 2003). Moreover, *WUTE* is used as another indicator to capture technical progress. Finally, the water consumption function is set as follows:

$$cons_{it} = f(pop_{it}; pgdp_{it}; manu_{it}; serv_{it}; uwdt_{it}; wue_{it}) \tag{1}$$

where $cons_{it}$ is the total water consumption of the *i*-th individual in *t*-th year, pop_{it} represents population size, $pgdp_{it}$ represents per capita GDP, $manu_{it}$ and $serv_{it}$ represent the proportions of manufacturing and service industry output, respectively; $UWDT_{it}$ represents the underlying water demand trend, and $WUTE_{it}$ represents water-use efficiency.

According to Zhang (2017), the logarithmic form of the extended STIRPAT model is as follows:

$$\ln cons_{it} = \beta_0 + \beta_1 \ln pop_{it} + \beta_2 \ln pgdp_{it} + \beta_3 \ln manu_{it} + \beta_4 \ln serv_{it} + \beta_5 \ln t + \beta_6 (\ln t)^2 + \nu_{it} + \tau_{it} + \eta_i \tag{2}$$

where ln *t* and (ln *t*)^2 are used to represent the non-linear path of *UWDT* to model the effect of exogenous technical progress, β_0 is the intercept term, and β_j (j=1, 2,…, 6) is the coefficient of the *j*-th independent variable. The error term in Eq. (2) consists of three parts: $\tau_{it} > 0$ and $\eta_i > 0$ are the transient and persistent water-use inefficiencies, and ν_{it} is white noise.

2.2 Estimation of WUTE

2.2.1 Basic model for estimating WUTE based on STIRPAT

Kumbhakar and Heshmati (1995) proposed a three-step approach to estimate both persistent and time-varying inefficiencies. Using this approach, a basic model for estimating WUTE based on STIRPAT is:

$$\ln cons_{it} = \beta_0^* + \beta_1^* \ln pop_{it} + \beta_2^* \ln pgdp_{it} + \beta_3^* \ln manu_{it} + \beta_4^* \ln serv_{it} + \beta_5^* \ln t + \beta_6^* (\ln t)^2 + \nu_{it} + \tau_{it}^* + \eta_i^* \qquad (3)$$

where $\beta_0^* = \beta_0 + E(u_{it}) + E(\eta_i)$; $\tau_{it}^* = \tau_{it} - E(\tau_{it})$; and $\eta_i^* = \eta_i - E(\eta_i)$. Following Kumbhakar and Heshmati (1995), the following persistent water-use technical efficiency (PWE) can be obtained:

$$\widehat{\eta_i} = \widehat{\eta_i^*} - min\left(\widehat{\eta_i^*}\right) \qquad (4)$$

Thus, persistent water-use technical efficiency is $PWE_i = e^{-\widehat{\eta_i^*}}$. PWE indicates that the *i*-th individual achieves optimal efficiency, while the inefficiency levels of other individuals are relatively the best.

After that, the time-varying transient water-use technical efficiency (TWE) can be further estimated. According to Jondrow et al. (1982), the estimate of TWE ($\widehat{\tau_{it}}$) is the conditional mean of the inefficiency term ($E[\tau_{it} \mid \tau_{it} + \nu_{it}]$). Thus, $TWE_{it} = e^{-\widehat{\tau_{it}}}$. Finally, WUTE is the product of PWE and TWE, that is:

$$WUTE_{it} = e^{-(\widehat{\eta_i} + \widehat{\tau_{it}})} = PWE_i \cdot TWE_{it} \qquad (5)$$

2.2.2 Improved model for estimating WUTE based on STIRPAT

The effects of unobserved heterogeneity, unrelated to inefficiency, are not considered in estimating WUTE in the above basic model. However, there may be unobserved bias when applying random-effects models (Farsi et al., 2005). In order to address these unobserved time-invariant effects, a term μ_i is necessary to capture the individual time-invariant effects.

Meanwhile, in order to consider individual time-invariant effects without presupposing the distribution of μ_i, Zhang (2017) proposed to make Mundlak adjustments to the stochastic frontier model (Mundlak, 1978). This means that an auxiliary equation needs to be supplemented to the principal stochastic frontier model to extract the unobserved features from the water-use inefficiency term.

$$\eta_i = \mu_i + \varphi_i$$

$$\mu_i = \gamma \cdot \overline{X_i} = \gamma \cdot \frac{\sum_{t=1}^{T} X_{it}}{T} \tag{6}$$

$$\varphi_i \backsim iid\ \mathrm{N}\left(0, \sigma_\delta^2\right)$$

where X_{it} indicates the vector of all independent variables, $\overline{X}_i$ indicates the mean vector of the respective independent variables, and γ indicates the corresponding coefficients of the independent variables.

According to Eq. (6), the persistent water-use inefficiency term is only $\gamma_i > 0$ after extracting some time-invariant individual features that do not affect inefficiency. The transient inefficiency of an individual over time can also be captured by $\tau_{it} > 0$. According to Zhang (2017), an improved model for estimating WUTE based on STIRPAT can be obtained by adding an auxiliary equation to Eq. (2).

$$\ln cons_{it} = \beta_0 + \beta_1 \ln pop_{it} + \beta_2 \ln pgdp_{it} + \beta_3 \ln manu_{it} + \beta_4 \ln serv_{it} + \beta_5 \ln t + \beta_6 (\ln t)^2 + \gamma_1 \overline{\ln pop_{it}} + \gamma_2 \overline{\ln pgdp_{it}} + \gamma_3 \overline{\ln manu_{it}} + \gamma_4 \overline{\ln serv_{it}} + \nu_{it} + \tau_{it} + \varphi_i \tag{7}$$

Similarly, the three-step approach can also be applied to estimate PWE, TWE, and WUTE. Due to the possible endogeneity between water consumption and per capita GDP, the estimation results may be biased. However, the bias caused by the endogeneity between water consumption and GDP per capita is negligible compared to the unobserved heterogeneity (Filippini & Zhang, 2016). Therefore, estimates of WUTE are primarily concerned with unobserved heterogeneity rather than endogeneity.

2.3 Study area

China's SNWTP attempts to alter the uneven geographical distribution of water by building three water transfer routes (East, Middle, and West) from the Yangtze River basin to northern and northwestern China. As a result, the SNWTP has grown to be one of the biggest and most complex inter-basin water transfer projects in the entire world (Pohlner, 2016). The eastern route is mainly based on the Jiangbei Water Transfer Project in Jiangsu Province, which was expanded and extended northward, making full use of the existing rivers in the Beijing-Hangzhou Canal and the Huai and Hai River basins for water delivery (Sheng & Webber, 2017). The middle route uses a new trunk canal to transport water to Beijing by diverting water from the Danjiangkou Reservoir in the middle and upper portions of the Han River, the major tributary of the Yangtze River. Due to topographic complexity and ecological concerns, the western route, which intends to bring water from the upper Yangtze River tributaries, is still in the design stages (Ma et al., 2016). The Yangtze, Huai, Yellow, and Hai rivers are all connected by the SNWTP, attempting to create a "four-horizontal and three-long" water network in China. Ultimately, the SNWTP has invested more than 240 billion CNY (Zhao, 2014) and relocated more than 300,000 people (Rogers et al., 2016).

The rapid economic growth and urbanization of cities along the SNWTP have significantly increased water consumption. In order to slow down the overconsumption of water transferred from the SNWTP, China has made "water saving before water transfer" one of the three objectives of SNWTP's water management (State Council, 2014). China initially recommended the creation of a water-saving society in the water law at the start of the project (People's Republic of China, 2002), and accordingly formulated three five-year plans for creating a water-saving society (Ministry of Water Resources, 2012; National Development and Reform Commission et al., 2007; National Development and Reform Commission et al., 2017). China also suggested implementing the most stringent water management system in an effort to institutionally support the adaptation of economic and social growth to the carrying capacity of water resources in order to improve WUI (State Council, 2012a).

Construction of the Eastern and Central Routes Phase I projects started in December 2002 and December 2003, and were finished and began to transfer water in December 2013 and December 2014. With a combined line length of approximately 2,900 kilometers, the two routes currently in use can supply 27.8 billion cubic meters of fresh water per year from the Yangtze River basin to the drought-stricken North China Plain (Ministry of Water Resources, 2002). The SNWTP involves 40 water-receiving cities in six provinces or municipalities, including Beijing, Tianjin, Hebei, Henan, Shandong, and Jiangsu (see Figure 1).

Fig. 1 The water-receiving cities of China's SNWTP

2.4 Data source

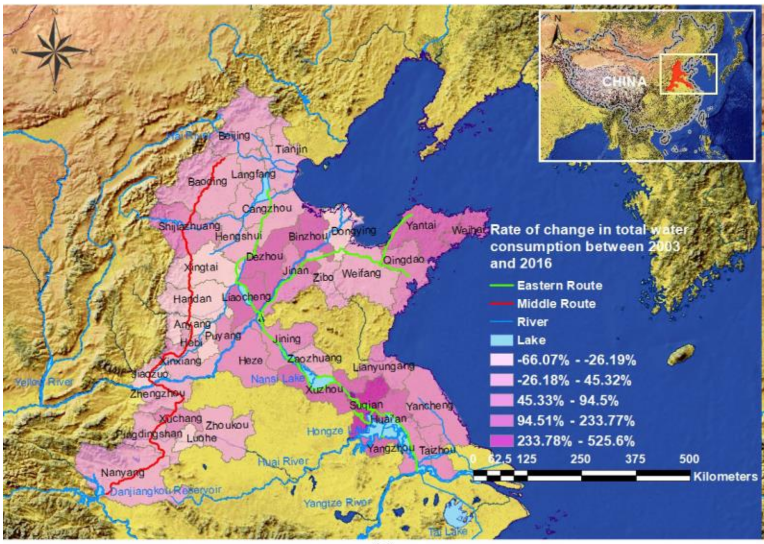
This study takes 2003, the SNWTP's official beginning, as the starting year; 2016 is the last year for which data is available. Population size, per capita GDP, the proportions of manufacturing and service industry output, and total water consumption from 2003 to 2016 are derived from the *China Urban Statistical Yearbook*. Table 1 summarises the variables; the trends of the variables in these 40 cities between 2003 and 2016 are shown in Figure 2.

Table 1

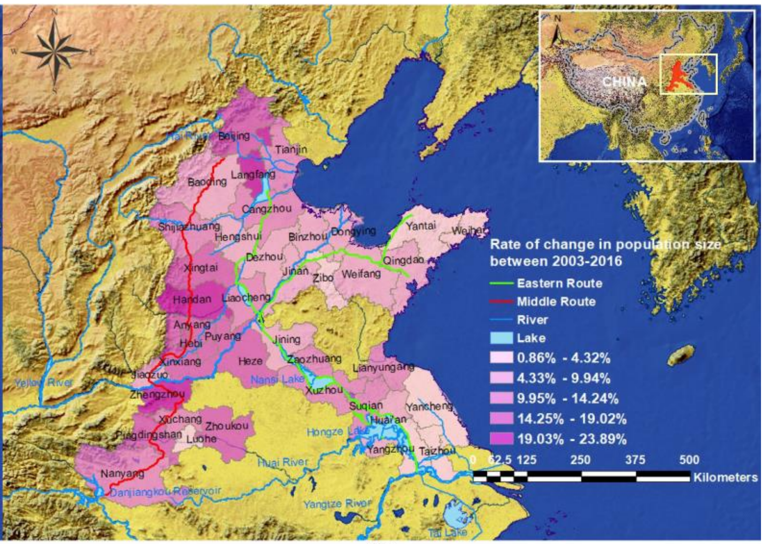
The list of variables

Variables	Descriptions	Units	Obs.	Mean	Std. Dev.	Min	Max
Dependent variables							
cons	Total water consumption	million m^3	560	165.85	11.06	12.89	1893.86
Independent variables							
pop	Total population	100,000 people	560	64.37	1.18	14.63	135.40
pgdp	Per capita GDP	CNY	560	3,8192.32	1,394.16	3,317.44	189,579.99
manu	The proportion of manufacturing industry output	%	560	53.28	0.37	19.26	82.28
serv	The proportion of service industry output	%	560	34.84	0.42	13.59	80.23

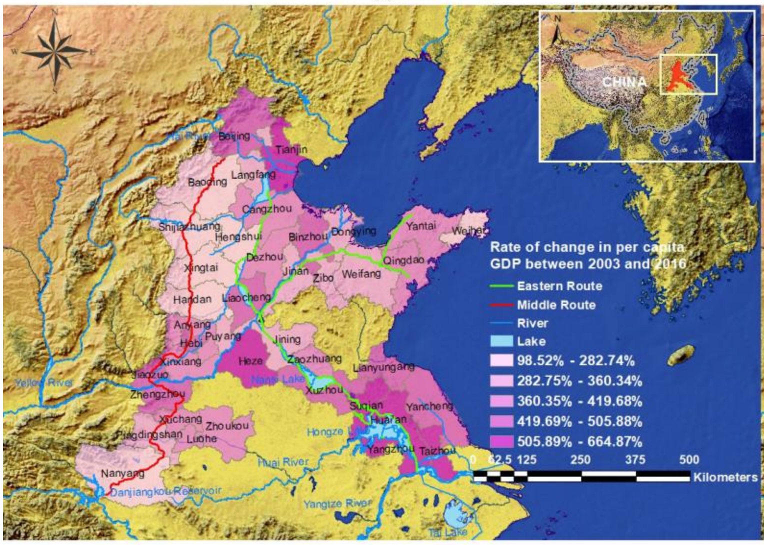
According to Figure 2(a), the water-receiving cities in which water consumption increased by more than 100% between 2003 and 2016 are concentrated in Jiangsu and Shandong in the eastern route area. These areas contain rapidly developing industries that have triggered rapid growth in water consumption. On the contrary, the water consumption of some cities in Hebei and Henan in the middle route area has declined. Figure 2(b) shows that the five cities with the largest population growth (Zhengzhou, Handan, Langfang, Fuyang, and Beijing) are all situated in the middle route area. According to Figure 2(c), the growth of per capita GDP is in stark contrast to the trend of population growth: the five cities with the largest increase in per capita GDP (Heze, Suqian, Taizhou, Yangzhou, and Huai'an) are all located in the eastern area. Figure 2(d) demonstrates that the proportions of manufacturing industry output in 72.5% of the 40 water-receiving cities have declined, especially in Beijing, Weihai, Dongying, Qingdao, and Langfang in the Bohai Rim region (where the proportion has fallen by more than 20%). On the contrary, the proportion of the service industry output in water-receiving cities has increased significantly except in Hebi (see Figure 2(e)). The proportion of service industry output in six cities (Dongying, Nanyang, Langfang, Huai'an, Weihai, and Heze) has increased by more than 50%.


Rate of change in total water consumption between 2003 and 2016
Eastern Route
Middle Route
River
Lake
-66.07% - -26.19%
-26.18% - 45.32%
45.33% - 94.5%
94.51% - 233.77%
233.78% - 525.6%
0 62.5 125 250 375 500 Kilometers
CHINA
Beijing
Tianjin
Langfang
Baoding
Cangzhou
Shijiazhuang
Hengshui
Binzhou
Dongying
Yantai
Weihai
Dezhou
Jinan
Zibo
Weifang
Qingdao
Xingtai
Handan
Liaocheng
Anyang
Hebi
Puyang
Jining
Xinxiang
Jiaozuo
Heze
Zaozhuang
Lianyungang
Yellow River
Zhengzhou
Nansi Lake
Xuzhou
Suqian
Huai'an
Yancheng
Xuchang
Zhoukou
Pingdingshan
Luohe
Hongze Lake
Yangzhou
Taizhou
Nanyang
Huai River
Danjiangkou Reservoir
Yangtze River
Tai Lake

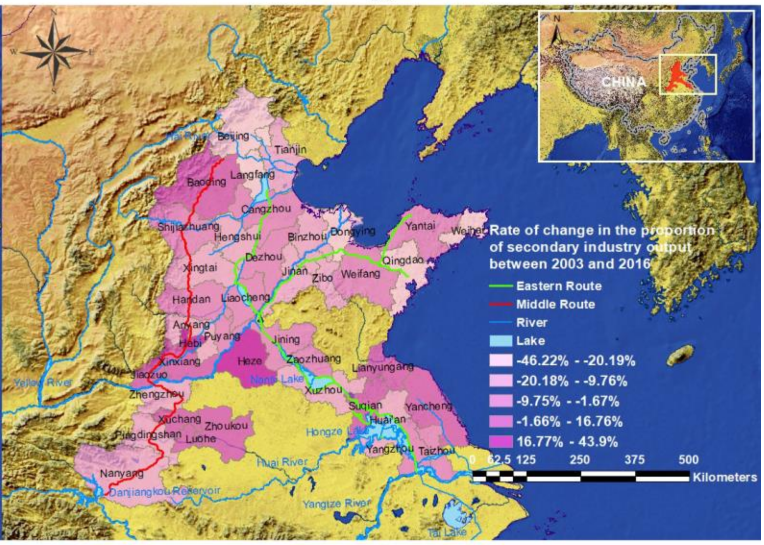
(a)


Rate of change in population size between 2003-2016
Eastern Route
Middle Route
River
Lake
0.86% - 4.32%
4.33% - 9.94%
9.95% - 14.24%
14.25% - 19.02%
19.03% - 23.89%
0 62.5 125 250 375 500 Kilometers
CHINA
Beijing
Tianjin
Langfang
Baoding
Cangzhou
Shijiazhuang
Hengshui
Binzhou
Dongying
Yantai
Weihai
Dezhou
Jinan
Zibo
Weifang
Qingdao
Xingtai
Handan
Liaocheng
Anyang
Hebi
Puyang
Jining
Xinxiang
Jiaozuo
Heze
Zaozhuang
Lianyungang
Yellow River
Zhengzhou
Nansi Lake
Xuzhou
Suqian
Huai'an
Yancheng
Xuchang
Zhoukou
Pingdingshan
Luohe
Hongze Lake
Yangzhou
Taizhou
Nanyang
Huai River
Danjiangkou Reservoir
Yangtze River
Tai Lake

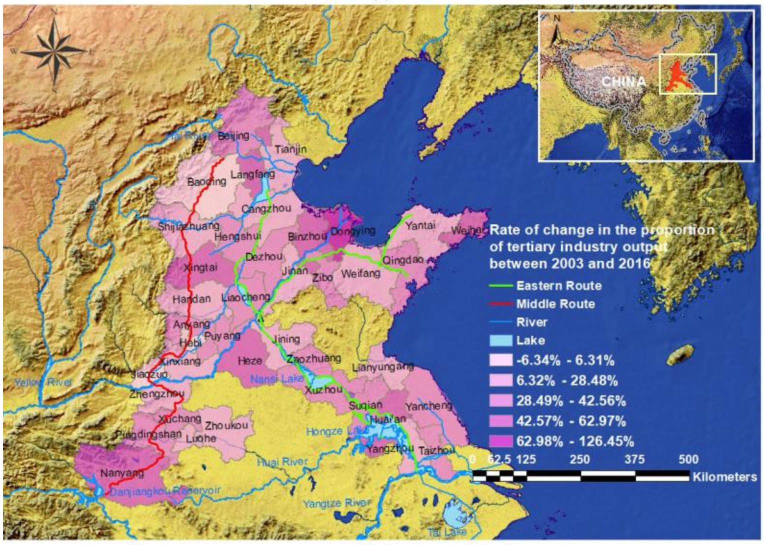
(b)


Rate of change in per capita GDP between 2003 and 2016
Eastern Route
Middle Route
River
Lake
98.52% - 282.74%
282.75% - 360.34%
360.35% - 419.68%
419.69% - 505.88%
505.89% - 664.87%
0 62.5 125 250 375 500 Kilometers
CHINA
Beijing
Tianjin
Langfang
Baoding
Cangzhou
Shijiazhuang
Hengshui
Binzhou
Dongying
Yantai
Weihai
Dezhou
Jinan
Zibo
Weifang
Qingdao
Xingtai
Handan
Liaocheng
Anyang
Hebi
Puyang
Jining
Xinxiang
Jiaozuo
Heze
Zaozhuang
Lianyungang
Yellow River
Zhengzhou
Nansi Lake
Xuzhou
Suqian
Huai'an
Yancheng
Xuchang
Zhoukou
Pingdingshan
Luohe
Hongze Lake
Yangzhou
Taizhou
Nanyang
Huai River
Danjiangkou Reservoir
Yangtze River
Tai Lake

(c)


Rate of change in the proportion of secondary industry output between 2003 and 2016
Eastern Route
Middle Route
River
Lake
-46.22% - -20.19%
-20.18% - -9.76%
-9.75% - -1.67%
-1.66% - 16.76%
16.77% - 43.9%
0 62.5 125 250 375 500 Kilometers
CHINA
Beijing
Tianjin
Langfang
Baoding
Cangzhou
Shijiazhuang
Hengshui
Binzhou
Dongying
Yantai
Weihai
Dezhou
Jinan
Zibo
Weifang
Qingdao
Xingtai
Handan
Liaocheng
Anyang
Hebi
Puyang
Jining
Xinxiang
Jiaozuo
Heze
Zaozhuang
Lianyungang
Yellow River
Zhengzhou
Nansi Lake
Xuzhou
Suqian
Huai'an
Yancheng
Xuchang
Zhoukou
Pingdingshan
Luohe
Hongze Lake
Yangzhou
Taizhou
Nanyang
Huai River
Danjiangkou Reservoir
Yangtze River
Tai Lake

(d)


Rate of change in the proportion of tertiary industry output between 2003 and 2016
Eastern Route
Middle Route
River
Lake
-6.34% - 6.31%
6.32% - 28.48%
28.49% - 42.56%
42.57% - 62.97%
62.98% - 126.45%
0 62.5 125 250 375 500 Kilometers
CHINA
Beijing
Tianjin
Langfang
Baoding
Cangzhou
Shijiazhuang
Hengshui
Binzhou
Dongying
Yantai
Weihai
Dezhou
Jinan
Zibo
Weifang
Qingdao
Xingtai
Handan
Liaocheng
Anyang
Hebi
Puyang
Jining
Xinxiang
Jiaozuo
Heze
Zaozhuang
Lianyungang
Yellow River
Zhengzhou
Nansi Lake
Xuzhou
Suqian
Huai'an
Yancheng
Xuchang
Zhoukou
Pingdingshan
Luohe
Hongze Lake
Yangzhou
Taizhou
Nanyang
Huai River
Danjiangkou Reservoir
Yangtze River
Tai Lake

(e)

Fig. 2 Rate of change in (a) total water consumption, (b) total population, (c) per capita GDP, (d) the proportion of manufacturing industry output, and (e) the proportion of service industry output between 2003 and 2016

3 Results

3.1 Empirical findings

Table 2 displays the outcomes. The positive population elasticity suggests that continued population growth triggers a significant increase in water use (Zhao et al., 2014). The income elasticity is relatively large, suggesting that the water-receiving cities are undergoing a water-intensive development phase. The elasticity of *manu* is significantly negative, while that of *serv* is not significant. This suggests that the growth of the manufacturing sector, as opposed to the service sector, lowers the demand for agricultural water and decreases water use. The coefficients of t and t^2 are both significant, demonstrating that the impact of *UWDT* is relatively strong. It means that the common underlying trend in water consumption has decreased as a result of continuous exogenous technical progress.

Table 2

The estimation results

Models	**Basic Model**	**Improved Model**
ln *pop*	0.4894*** (0.1565)	1.7395*** (0.5311)

ln *pgdp*	0.8743***	0.7119***
	(0.0885)	(0.1117)
ln *manu*	−0.4960**	−0.4408**
	(0.2097)	(0.2140)
ln *serv*	0.2428	0.0881
	(0.1503)	(0.1538)
ln *t*	−0.1014*	−0.1368**
	(0.0621)	(0.0622)
$(\ln t)^2$	−0.1471***	−0.0588*
	(0.0278)	(0.0351)
Mundlak adjustment	No	Yes
Constant	3.6855	4.2200
	(2.8799)	(6.3260)
Log-likelihood	17.43	17.43
Observations	560	560

Note: *, **, and *** represent significance at 10%, 5%, and 1% levels, respectively.

3.2 WUTE estimates

Figure 3 shows WUTE in the water-receiving cities as estimated by the two models. Since unobserved individual time-invariant effects are interpreted as inefficiency in the basic model, the WUTE in some water-receiving cities estimated by the basic model is less than that estimated by the improved model. The WUTE in the improved model is higher after separating these effects from the inefficiency term. However, the Pearson correlation coefficient between the water-use efficiencies estimated by the two models is 0.974, which indicates that the estimated water-use efficiencies from the two models are highly correlated. Thus, the estimated WUTE levels are robust. The estimated results of the improved model are used in the subsequent analysis to avoid loss of the general characteristics of individual WUTE levels.

According to Figure 3, urban WUTE in water-receiving cities is not completely related to the level of economic development. Not all economically developed cities have shown high levels of WUTE. For example, Beijing and Tianjin have the highest per capita GDP (the per capita GDP of the two cities in 2106 was 189,579.99 CNY/person and 172,638.90 CNY/person, respectively). However, the improved model indicates that the WUTE of the two cities in 2016 is 0.1747 (ranked 36th) and 0.1950 (ranked 34th), respectively. On the contrary, some cities with low economic development have high WUTE (such as Cangzhou, Langfang, Xuchang, and Hengshui). Figure 3 also demonstrates that the WUTE in water-receiving cities has not changed significantly over time. Only a small number of water-receiving cities have continued to improve WUTE, such as Suqian. However, WUTE in most water-receiving cities only fluctuates with time; some water-receiving cities have even experienced a continuous decline in water-use efficiencies, such as Beijing and Tianjin.

There may be variations in the WUTE due to the economic and racial disparities between the water-receiving cities in the eastern and middle routes. Thus, this study analyzed the differences in WUTE between the two types of cities using a one-way ANOVA. The outcomes are displayed in Table 3.

Table 3

ANOVA results

Models	**Basic Model**	**Improved Model**
F-statistic	0.7614	0.0560
p-value	0.3884	0.8142

Table 3 shows no significant difference in the WUTE estimated by the two models for the water-receiving cities in the eastern and middle routes.

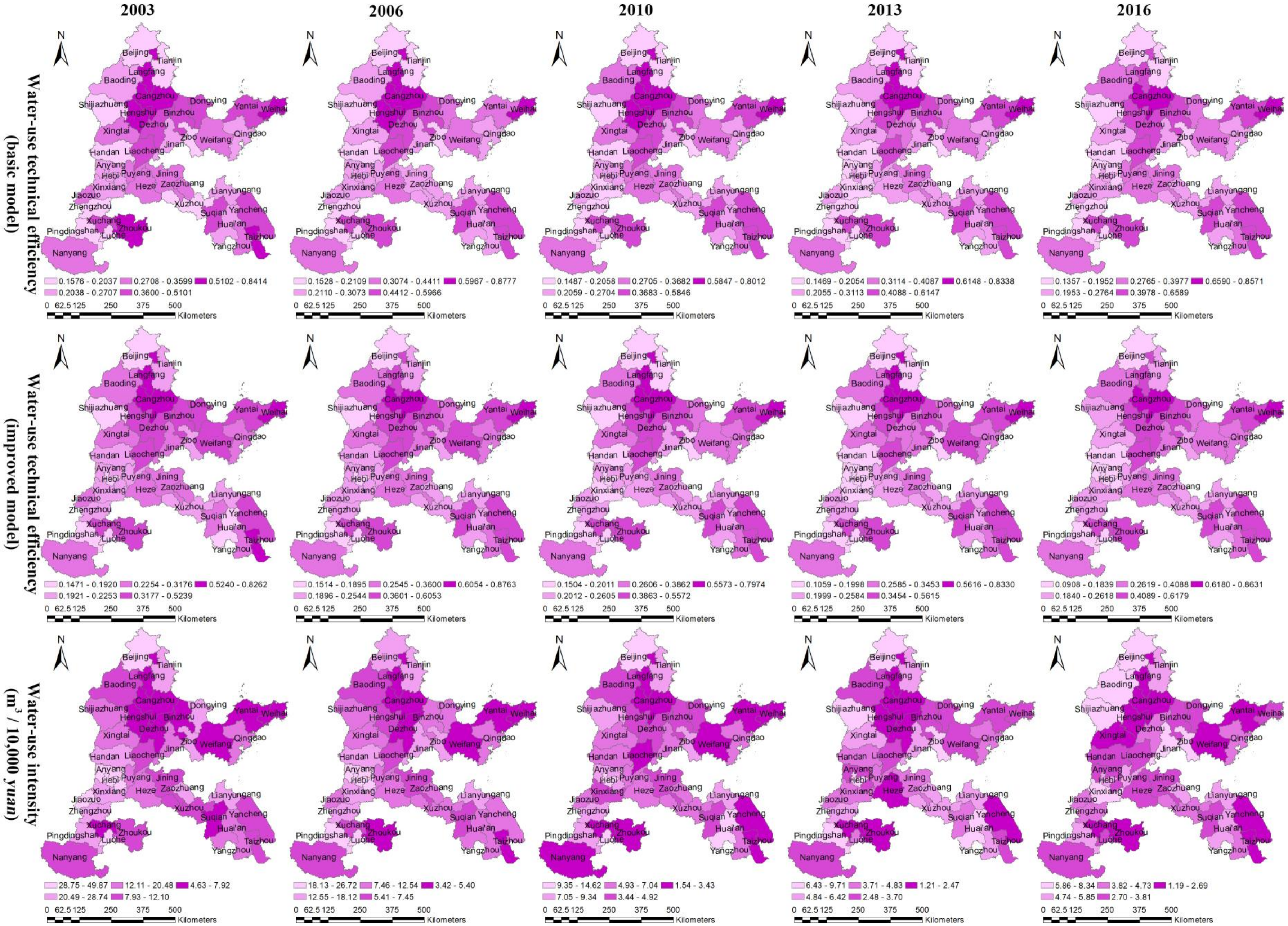


Fig. 3 WUTE and WUI in the SNWTP's water-receiving cities

3.3 Comparison of WUI and WUTE

WUI is also shown in Figure 3. The Pearson and Spearman correlation coefficients between WUTE and WUI are −0.443 and −0596: the two are negatively correlated. However, the absolute values of the two correlation coefficients are not large. According to Figure 3, some cities with low WUTE have low WUI, such as Handan in 2010, 2013, and 2016. On the contrary, some cities with high WUTE have high WUI, such as Baoding in 2016. These results all demonstrate that there is a difference between WUTE and WUI, and that the latter is not a good proxy for the former.

Moreover, the average WUI and WUTE of the 40 water-receiving cities are plotted in Figure 4 to compare the differences in WUTE and WUI. Fig. 4 shows that between 2003 and 2016, the average WUI of the 40 water-receiving cities decreased steadily. However, the WUTE of these water-receiving cities is characterized by a sustained fluctuation rather than a significantly rising trend.

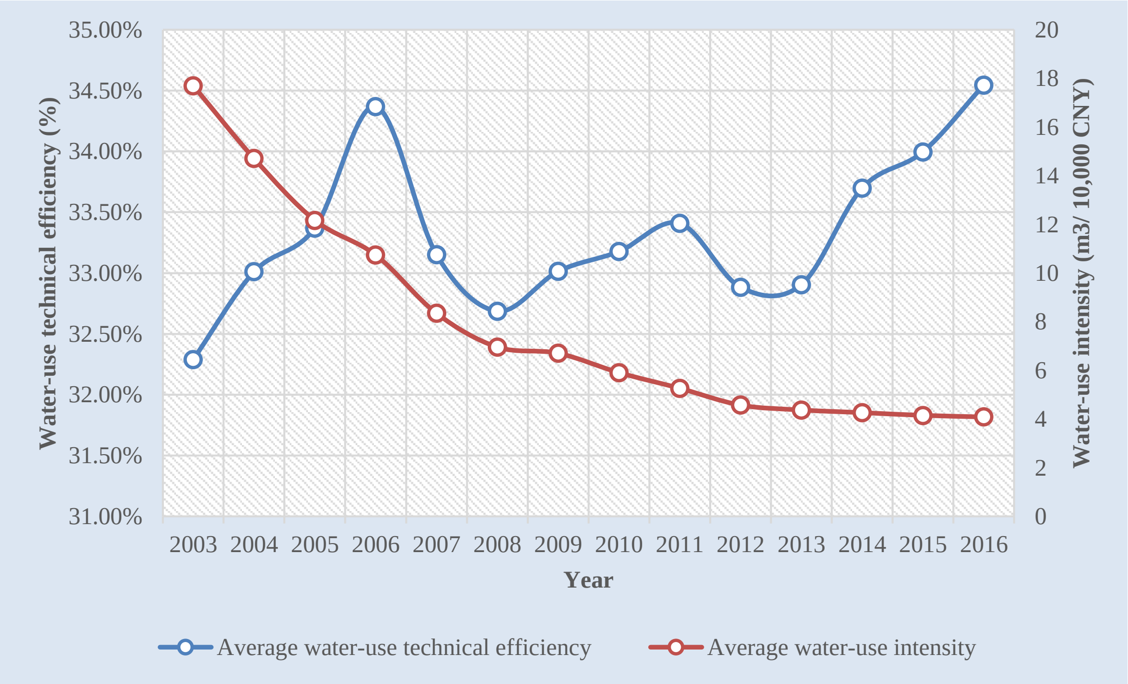
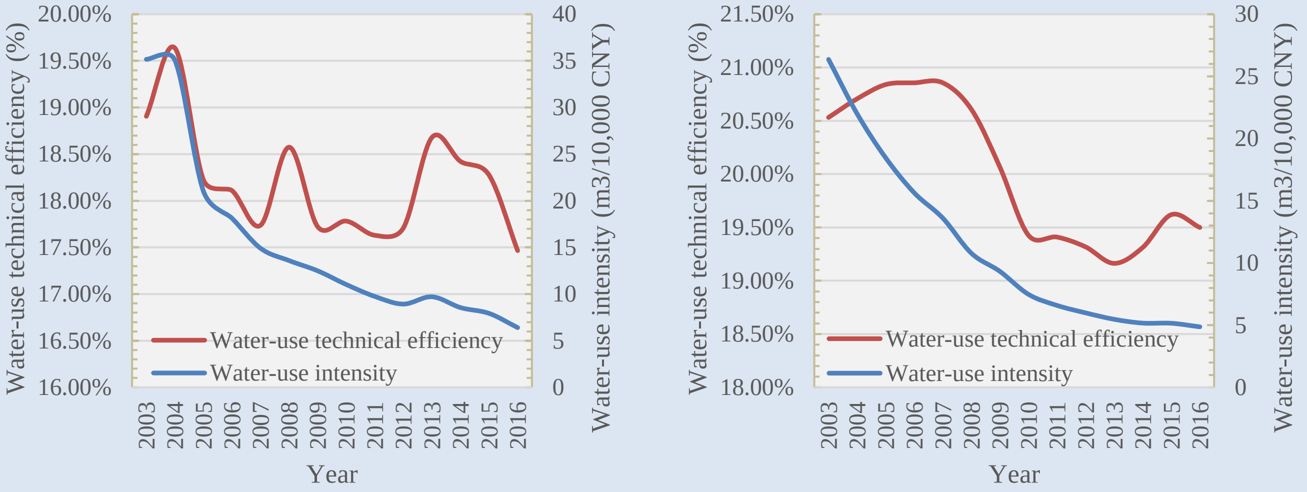
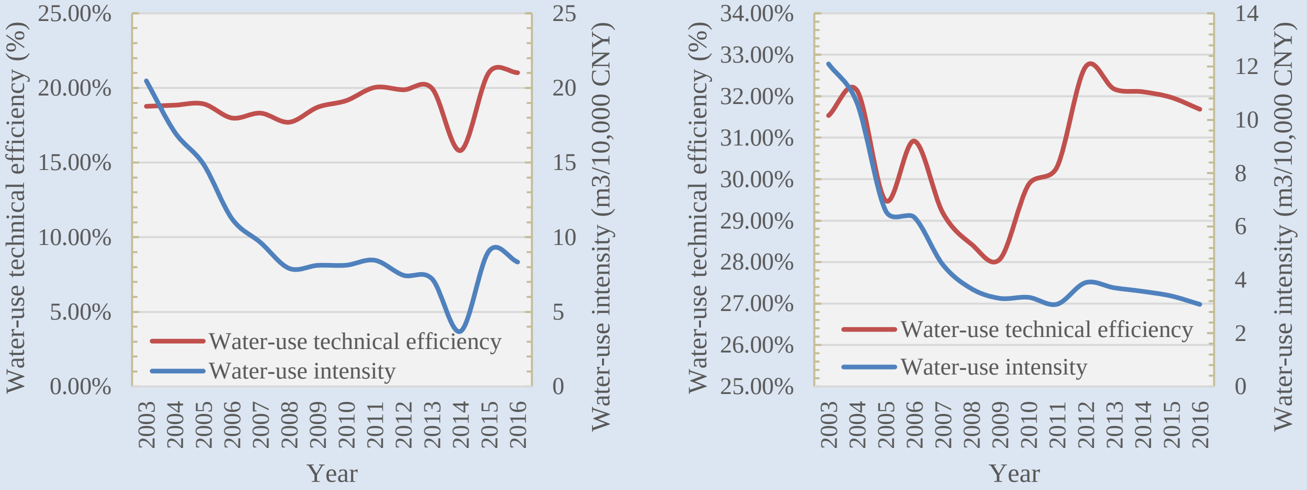


Fig. 4 Average water-use intensity and technical efficiency from 2003-2016

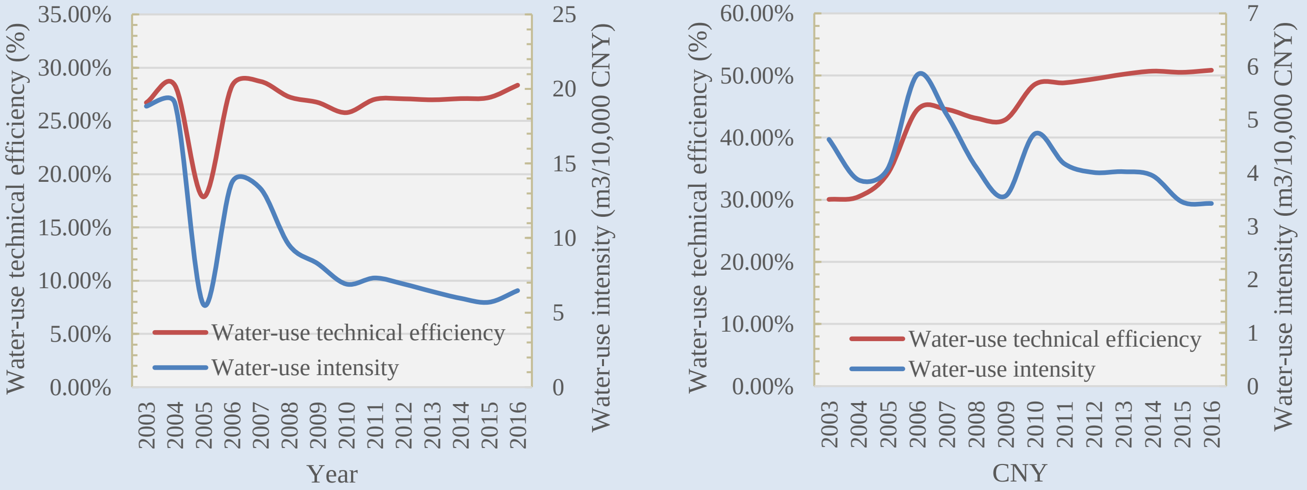
To examine the difference between WUI and WUTE, six large and medium water-receiving cities are selected for analysis: Beijing, Tianjin, Shijiazhuang, Nanyang, Jinan, and Suqian. The results are shown in Figure 5.



(a) Beijing **(b) Tianjin**



(c) Shijiazhuang **(d) Nanyang**



(e) Jinan **(f) Suqian**

Fig. 5 The water-use intensity and technical efficiency from 2003-2016 in (a) Beijing, (b) Tianjin, (c) Shijiazhuang, (d) Nanyang, (e) Jinan, and (f) Suqian igure 5 demonstrates that the WUI of the six cities showed a continuous downward trend during 2003-2016. However, despite the decline in WUI, only Shijiazhuang and Suqian showed an upward trend in WUTE. WUTE in Jinan and Nanyang did not show a clear trend during 2003-2016. WUTE in Beijing and Tianjin showed a significant downward trend even as WUI decreased. WUTE and WUI are totally unrelated. These results show that WUI cannot accurately reflect WUTE in water-receiving cities.

3.4 Water-saving potentials

The SNWTP's water-saving policies are oriented to reduce the WUI in water-receiving cities. It is, therefore, necessary to link WUI with WUTE. Since WUI is the ratio of water consumption to GDP, ln*gdp* is subtracted from both sides of Eq. (7) to obtain the following equation:

$$\ln WUI_{it} = \beta_0 + (\beta_1 - 1)\ln pop_{it} + (\beta_2 - 1)\ln pgdp_{it} + \beta_3 \ln manu_{it} + \beta_4 \ln serv_{it} + \beta_5 \ln t + \beta_6 (\ln t)^2 + \gamma_1 \overline{\ln pop_{it}} + \gamma_2 \overline{\ln pgdp_{it}} + \gamma_3 \overline{\ln manu_{it}} + \gamma_4 \overline{\ln serv_{it}} + \nu_{it} + \tau_{it} + \varphi_i \tag{8}$$

A reduction in WUI can be achieved by improving WUTE. Suppose that the maximum reduction in WUI due to WUTE improvement is $k_{it} \in [0,1]$. Then the association between water-use inefficiency and WUI is as follows:

$$\tau_{it} + \varphi_i = \ln WUI_{it} - \ln[WUI_{it} \cdot (1 - k_{it})] = \ln \frac{1}{1 - k_{it}} \tag{9}$$

By transformation of terms, the reduction frontier in WUI (k_{it}) can be expressed as follows:

$$k_{it} = 1 - e^{-\tau_{it} - \varphi_i} = 1 - WUTE_{it} \tag{10}$$

Suppose that the maximum reduction in WUI for the i-th city in the t-th year from efficiency improvement is k_{it}, then the water-saving potential for i-th city is:

$$\Delta cons_{it} = cons_{it} - cons_{it} \cdot WUTE_{it} = cons_{it} \cdot k_{it} \tag{11}$$

According to Eq. (11), the maximum average water-saving potential due to improved WUTE in water-receiving cities between 2003 and 2016 can be obtained (see Figure 6). The maximum average water-saving potential is determined by water consumption and WUTE. When there is similar water consumption, water-receiving cities with lower WUTE can save more water if there is no efficiency loss. For example, Luohe and Nanyang have similar annual average water consumption (79.43 million m^3 and 79.55 million m^3, respectively), while Luohe's average WUTE (0.1333) is less than Nanyang's (0.3076). Consequently, Luohe's water-saving potential (68.84 million m^3) is higher than Dongying's (55.09 million m^3). In addition, water-receiving cities with greater water consumption have higher water-saving potential when WUTE is similar. For example, Shijiazhuang and Anyang have similar average WUTE (0.1901 and 0.1910, respectively), while Shijiazhuang's annual average water consumption (302.60 million m^3) is much higher than Anyang's (101.11 million m^3). Consequently, Shijiazhuang's water-saving potential (245.07 million m^3) is also much larger than Anyang's (81.80 million m^3).

Figure 6 shows that the five cities with the highest water-saving potential from improved WUTE are Beijing, Tianjin, Qingdao, Zhengzhou, and Shijiazhuang, with a total water-saving potential of 2,626.84 million m^3. The water-saving potential of these five water-receiving cities accounts for 53.18% of the total water-saving potential of all cities (4,939.44 million m^3). The total water-saving potential of the five cities with the lowest water-saving potential (Cangzhou, Hengshui, Langfang, Zhoukou, and Xuchang) is 77.29 million m^3, accounting for only 1.56%.

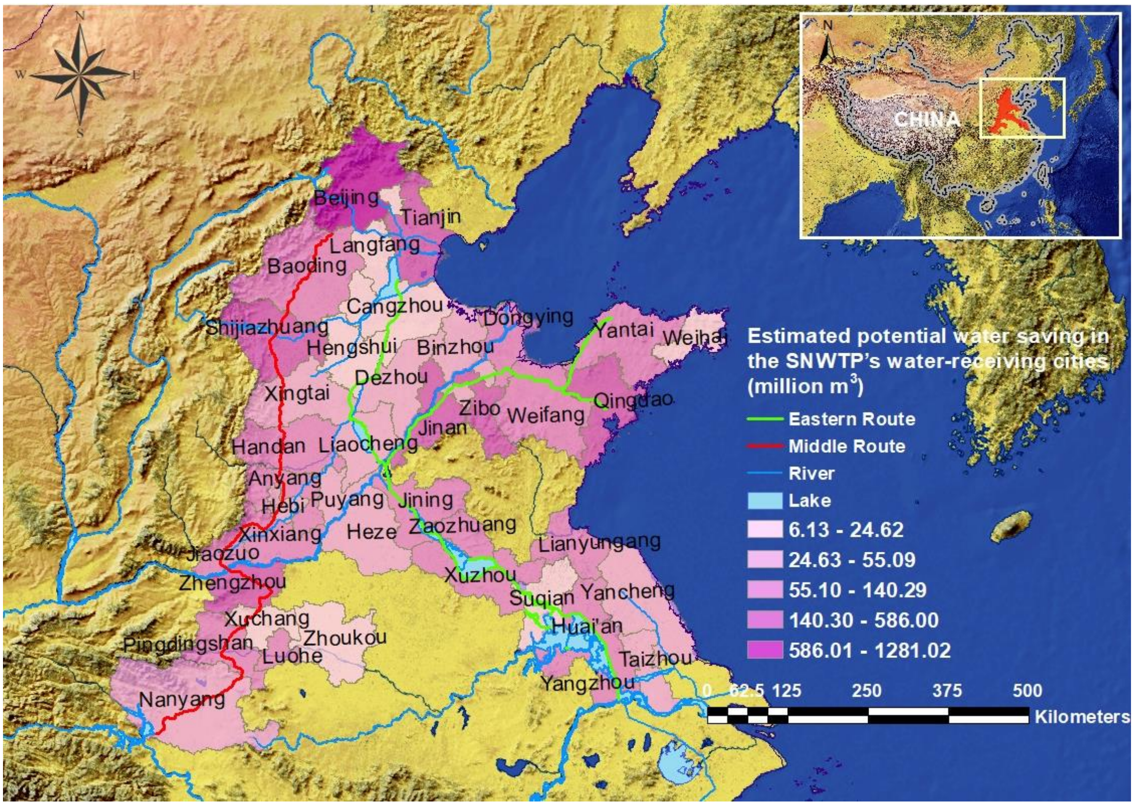


Fig. 6 Estimated potential water saving in the SNWTP's water-receiving cities

4 Discussion

There is no definitive link between improvements in WUTE and decreases in WUI, and thus water-saving policies oriented toward reducing WUI do not necessarily increase WUTE. The findings demonstrate that WUTE and WUI in water-receiving cities have deviated, indicating that WUI and WUTE are not equivalent. In fact, the intensity of resource use does not represent efficiency well, and the two are not interchangeable (Filippini & Zhang, 2016). Changes in WUI are determined by a combination of population size, per capita GDP, industrial structure, as well as exogenous and endogenous technological progress, while improvements in WUTE are mainly due to endogenous technological progress. The effects of Chinat's current water-saving policies are all assessed by WUI (State Council, 2012b). Therefore, the policies aimed at reducing WUI can be regarded as reducing water consumption rather than improving WUTE.

Achieving the goals of water-saving policies by reducing WUI alone remains challenging and requires improving the WUTE caused by endogenous technological progress. As shown in Eq. (11), the water-saving potential is determined by water consumption and WUTE. Therefore, the current water-saving policies of the Chinese government are all focused on limiting population growth and reducing industrial water consumption. However, the impact of these water-saving policies on endogenous technological progress is still uncertain; thus, its impact on WUTE and even the water-saving potential is unknown. For example, Beijing regards controlling population growth and encouraging the transformation of manufacturing to the service industry as an essential means of saving water (China Daily, 2018). However, the results indicate that Beijing's WUTE is lower than the median level of all water-receiving cities, and its WUI is higher than the median level. Since there is no inevitable link between reductions in WUI and improvements in WUTE, these water-saving policies, which are oriented towards reducing WUI, are not necessarily able to improve WUTE. The latter only depends on endogenous technological progress, which suggests improving WUTE through water-saving production technology innovation is necessary. Therefore, encouraging the innovation of water-saving production technology should also be an essential part of water-saving policies, which are a combination of taxes (negative incentives), subsidies (positive incentives), and enforcement (regulations) (Mohamed & Savenije, 2000).

Moreover, setting a unified target to reduce WUI leads to the unfair sharing of water-saving tasks between regions. The government's current water-saving policies are to form a unified reduction target of WUI for all cities. For instance, according to the most recent water-saving action plan, the WUI in 2020 and 2022 are required to be lowered by 23% and 30%, compared to 2015 (National Development and Reform Commission & Ministry of Water Resources, 2019). However, the WUTE of each water-receiving city is significantly different, and this difference has not been considered in the formulation of water-saving policies. Therefore, attempts to achieve water saving by setting a unified reduction target of WUI will lead to unfair sharing of water-saving tasks between cities. Furthermore, the fragmented, hierarchical, and authoritarian nature of China's top-down water management system (Lieberthal & Oksenberg, 1988) means that the unfair sharing of water-saving tasks is likely to prevent governments from coordinating and cooperating effectively (Moore, 2014).

In order to realize the fair sharing of water-saving responsibilities among cities, it is vital to consider the disparities between WUTE in various cities by establishing a fair responsibility-sharing mechanism for water-saving. A water monitoring system needs to be created to account for WUTE, and water-saving responsibilities should be fairly distributed among cities based on the accounting results (Gao & Yu, 2018). Since cities with low WUTE have high water-saving potential, a fair responsibility-sharing mechanism for water-saving will make them face more water-saving pressure. It would encourage those cities to choose efficient water-saving production technologies to achieve economic growth. Additionally, local officials need to compete for the achievements of water governance, in which only the winners can be promoted in China's water governance system; this is called the "cadre promotion tournament" (Sheng et al., 2018). When the fair responsibility-sharing mechanism for water-saving is included in such performance appraisal, local officials can be incentivized to save water for a job promotion. Therefore, they will compete to improve WUTE by adopting various feasible means.

5 Conclusion

Many parts of the world face water shortages because the water demand far exceeds the supply (Matete & Hassan, 2006). The situation in China reflects global concern in many ways, especially the water scarcity in northern China (Wu et al., 2015). In order to alter the association between the distribution of water resources and the distribution of economic activity, China uses the SNWTP to transfer water from the Yangtze River to the arid North and Northwest China. Furthermore, China is also trying to improve WUTE and reduce water demand by adopting various water-saving measures in the SNWTP's water-receiving cities (Miao et al., 2018). Since these numerous human activities have significantly affected water consumption, WUTE needs to be understood within the human-environment framework.

This study develops an extended human-environment framework for examining WUTE. Then, it uses the SNWTP as a case to estimate the WUTE of each water-receiving city by using an improved water-efficiency estimation model based on the stochastic frontier analysis. Moreover, the water-saving potential of each water-receiving city is computed according to the link between WUI and WUTE. After comparing the differences between the two, this study challenges the view that the government's current water-saving policies oriented to reducing WUI can improve WUTE. As has been shown previously, there is no definitive link between improvements in WUTE and decreases in WUI, and thus water-saving policies oriented toward reducing WUI do not necessarily increase WUTE. We draw attention to the fact that achieving the goals of water-saving policies by reducing WUI alone remains challenging and requires improving the wWUTE caused by endogenous technological progress. Finally, setting a unified target to reduce WUI leads to inequitable sharing of water-saving tasks between regions, resulting in conflicts of interest among government bureaucracies.

This study's careful observation of the complex association between WUI and WUTE in SNWTP reveals the limitations of the existing literature. WUI, which uses a univariate measure of productivity, does not consider other factors that may explain productivity changes. In turn, studies on WUTE do not consider the influence of various human activities on the resource consumption frontier in a human-environment framework. Therefore, the extended human-environment framework and the improved WUTE estimation method proposed in this study help to fill the above-mentioned research gaps and provide a feasible methodology for studying water-saving policies.

This study demonstrates a complex association between WUI and WUTE. However, as with any investigation, this study inevitably contains some limitations. First, this study focuses only on the differences between WUI and WUTE without considering the causal link between water-saving policies themselves and WUTE. An analysis of this causal association would help understand how water-saving measures affect and shape WUTE. Therefore, future studies could further focus on the causal association between water conservation policies and WUTE. Second, the issue of achieving water-saving goals by improving WUTE needs to be expanded with more case studies. This would not only increase our knowledge of WUTE estimation methods, but also broaden the cross-scale understanding of how water-saving policies are linked to WUTE. Since the way they are linked may vary depending on the socioeconomic context, observations of this process need to be analyzed in the context of the historical, cultural, and political environment. Therefore, future research could use more cases to verify the generalizability of the way water-saving policies are linked to WUTE.

Finally, these findings can contribute to understanding China and even global water-saving governance. Many water-saving policies aimed at reducing water demand by improving water-use efficiency were issued and implemented in parallel with the SNWTP's construction. China adopted " water saving before water transfer" as one of the three objectives of the SNWTP's water governance (State Council, 2014). Therefore, the SNWTP's water-receiving cities are the areas most affected by China's water-saving policies aimed at reducing WUI. Taking the SNWTP as a case can help reveal the connection between WUI and WUTE. We have confirmed no clear relationship between reductions in WUI and changes in WUTE. This finding matters for water-saving governance in China and the world. This suggests that the worldwide water-saving objective cannot be achieved just by depending on the decrease in water consumption brought on by the decrease in WUI. It is vital to encourage the endogenous innovation of water-use technologies to achieve global water saving by improving WUTE.

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