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Economic size and water use efficiency: an empirical analysis of trends across China

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ABSTRACT

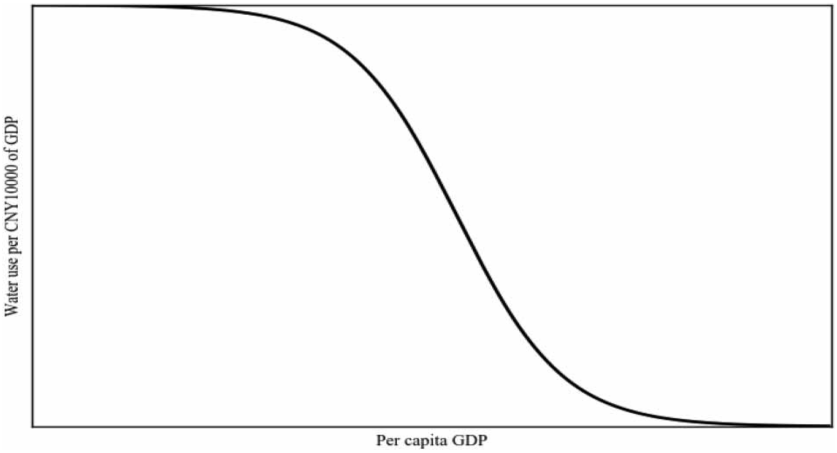
Water shortage is a global risk that could arguably be mitigated using water more efficiently. However, the profound relationship between water use efficiency and regional economic size has not been empirically tested. The research design employed an exploratory empirical analysis done through non-linear curve function and attempted to analyze the evolution of water use efficiency over economic growth. First, the water use efficiency change was decomposed into pure technical efficiency change, scale efficiency change, and technological advance change. Second, the scale efficiency is generally less than 1, revealing that it is the main reason for the decreased water use efficiency by the empirical analysis of trends across China. Third, the fitting function between water use efficiency and economic development was constructed. The results supported the existence of an inverted-S shape between water use efficiency and regional economic growth. This analysis will be the reference to formulate scenarios for economic and demographic growth coupled with water use, particularly for planning and managing future water provision and demand.

Key words: China's provinces, Economic size, Efficiency changes, Per capita GDP, Water use efficiency

HIGHLIGHTS

- Water use efficiency was decomposed into three parts.
- The inverted-S shape between water use efficiency and economic growth was simulated.
- The cubic curve model can be used to simulate and predict the future water demand.

GRAPHICAL ABSTRACT



INTRODUCTION

Globally, from 1980 onwards, water was no longer cheap and plentiful but had become a costly and scarce resource (Duarte *et al*., 2014). Water stress is dominated by socio-economic variables, with climate change acting to exacerbate water stress even further (Distefano & Kelly, 2017; Maja & Ayano, 2021). Water remains a significant obstacle to growth in both developed and developing countries. This is true even for abundant water countries, such as Russia, Canada, and Brazil under the business as usual (Distefano & Kelly, 2017). At the developed European scale, they are also facing varying degrees of water pressure (EEA, 2018). A possible alternative to these pessimistic scenarios is to boost technological progress via investment in water use efficiency (Distefano & Kelly, 2017). The '2030 Agenda for Sustainable Development' also called for a focus on water use efficiency to use freshwater resources sustainably and reduce water stress (UN, 2015). Water use efficiency – wasting less water and increasing productivity per volume are essential for building resilience into our systems and adapting to climate change (EEA, 2018). Improving water use efficiency is an economic and environmental opportunity that serves water sectors, helps economic growth, and safeguards the environment (EEA, 2018). During the past decades, China has undergone a dramatic economic boom, together with the demand for water has been increasing due to extensive urbanization, industrialization, and the rise in the standard of living. Especially, since 2012, China's total annual water use has remained at around 610 billion m^3, and its gross domestic product (GDP) has increased from 54 trillion yuan to 90 trillion yuan (China Daily, 2019), owing to improved water use efficiency. Hence, most of the existing literature has focused on the link between total water use quantity or industrial water use and economic growth (Wu, 2014; Wang & Wang, 2020), including looking for inflection points of water consumption by this linkage relation between water use quantity and economic growth (GDP growth) (Zhao *et al*., 2017). In spite of water use efficiency or water use intensity was widely identified as a driver responsible for a significant reduction in the growth of total water use (Distefano & Kelly, 2017; EEA, 2018). The deep relationship between water use efficiency and economic size has nevertheless traditionally attracted little attention by analysts.

Therefore, take China, a developing country, as an example. This work investigates the deep relationship between water use efficiency and regional economic size – this study attempt to analyze the evolution of water use efficiency over economic growth. By understanding the evolution rules between water use efficiency and economic development, water-related conflicts related to human needs can better be addressed without under-supplying. Some policy enlightenments on future water resources management and economic development goals can be obtained through the evolution rules to alleviate water resources pressure and reduce the utilization of freshwater resources.

LITERATURE REVIEW

The review of water resources utilization

The causes of water use change can be explained from an economic perspective with two aspects of input and output. On the one hand, the contributing factors of increasing water use volume can be viewed as input elements, and economic size can be considered as final output. On the other hand, the joint effect of many contributing factors to final output variation was expressed as water use efficiency. The change of water use was reviewed from contributing factors and water use efficiency, respectively, below.

Cosgrove & Cosgrove (2012) summarized 10 drivers with varying influences and impacts in different world regions: agriculture, climate change, variability, demography, economy and security, ethics, society and culture, governance and institutions, infrastructure, politics, technology, and water resources. In China, at present, the population shows a slow increase trend (MWR, 2003–2019; Zhou *et al.*, 2020). Over the past decades, the economy presented an exponential growth trend, and so is the future (World Bank & DRCSC, 2013; World Bank, 2020). To date, in terms of water supply infrastructures, they have a great improvement that had already met the human activities demand for water in 2008, while the water supply during 2008–2019 was almost stable (Jia & Zhu, 2020). To mitigate and improve ever-increasing ecological environment deterioration induced by water shortage, China government enacted the Most Stringent Water Resources Management System in 2011. Subsequently, a series of policies were issued, including ‘the Action Plan to Control the Total and Intensity of Water Resources Consumption during the 13th Five-Year Plan period’ in 2016 and ‘National Action Plan for Water Conservation’ in 2019 and the like. In the case of climate, generally, socio-economic factors have more enormous impacts on the future water demand/supply situation than climate (Shen *et al.*, 2014; Veldkamp *et al.*, 2015; Fant *et al.*, 2016; Wad *et al.*, 2016). These facts point to the strong role played by upwards and unlimited economic growth as determinants of water scarcity.

In terms of water use efficiency, Doeffinger & Hall (2020) and Zhou *et al.* (2020) depicted that the water use change largely depends on water use efficiency. Improving water use efficiency can play an essential role in reducing the increase in demand for water (Molden *et al.*, 2007). In particular, as is well known, agricultural water accounts for a large proportion of total water use volume all the time in regions of the world (Borrelli *et al.*, 2020). Molden *et al.* (2007) projected that with no improvements in water use efficiency, global water consumption for agriculture would need to increase by 70–90% by 2050 (Molden *et al.*, 2007). By 2050, compared to current demand, agricultural water for demand will be reduced 20–25% with productivity improvements (Molden *et al.*, 2007). Improving water use efficiency, an effective way to address water shortage, is the principal alternative to sustainable governance of water resources globally for effectively reducing net water withdrawal (Zoebl, 2006; Alcamo *et al.*, 2007; Shen *et al.*, 2014; Doeffinger & Hall, 2020). As far as China is concerned, despite the deceleration of China’s human water use and its key driver was water use efficiency in the past decades (Zhou *et al.*, 2020), yet it is still far below developed countries’ efficiency. The water use per CNY10,000 of industrial added value is 45.6 m^3, twice that of the advanced world level.

On the whole, water use per US$10,000 of GDP is about 500 m^3, while that of developed countries is basically below 300 m^3, 40% higher than that of developed countries (Economic Daily, 2020). Water use efficiency rise fuels total withdrawals stabilize quickly or decline in developed countries (Alcamo *et al.*, 2007). As we have stated above, one of the biggest challenges for human society is to improve water use efficiency globally for effective reduction of net water withdrawal, which is the consensus of most people (Shen *et al.*, 2014).

Water use and economic growth

It is a prevailing viewpoint that population, economic development, and growth leading to increasing water demand and socio-economic drivers become more important in the coming decades (Veldkamp *et al.*, 2015; Fant *et al.*, 2016; Wad *et al.*, 2016; WWAP, 2020). Whereas with technical progress and innovation even policies implemented, the decoupling relationship between water resources utilization and economic growth is gradually transitioning from weak decoupling to strong decoupling in developing countries (Duarte *et al.*, 2014; Wang & Wang, 2020). What the so-called decoupling is the degree of dependence between economic growth and water resource consumption decreases gradually from strong correlation to weak correlation, and finally presents a state potential of reverse change or no correlation in the course of economic development (Wu, 2014). Specifically, the total consumption and utilization of water resources come true zero growth or negative growth with keeping economic growth at the same time (Wu, 2014). The decoupling evaluation of economic development and water resource utilization is mainly based on the changes in total water consumption and water use efficiency together with economic output (GDP) to distinguish whether economic development and water consumption and utilization have changed from weak decoupling to strong decoupling or not (Wang & Wang, 2020). Because of water resources' irreplaceable attributes, complete decoupling (absolute decoupling) between water use and economic development seems impossible. Hence, the relationship can be summarized as shown in Table 1 cited from Wu's (2014) study.

Similarly, the other description adopted the Kuznets curve between economic growth and total water volume or water use by sector was widespread, namely inverted U-shape, which elucidated the connection between per capita GDP and water consumption by non-linear model. Rock (1998), Duarte *et al.* (2013), and Zhao *et al.* (2017) stated that the relationship between water resources and economic development appears to follow an inverted U-shape. Goklany (2002) and Duarte *et al.* (2013) showed that agricultural water use and per capita GDP in the United States were likely to be an inverted U-type. Jia (2001) presented the Kuznets curve for industrial water use in most member countries of the Organization for Economic Cooperation and Development. Hemati *et al.* (2011) supposed that income elasticity and industrial water withdrawal have a bell-shaped curve. Hao *et al.* (2019) found that the relationship between per capita water consumption and per capita GDP in China is 'N' shaped, building on the theoretical framework of the environmental Kuznets curve.

Table 1. | The decoupling states between economic development and utilization of water resources.

Decoupling class	Economic development	Water stress	Water use efficiency	Decoupling coefficient	Decoupling judgment
Decoupling	Growth	Decrease	Advance	≤0	Strong decoupling
	Growth	Increase	Advance	(0,0.8)	Weak decoupling
	Recession	Decrease	Advance	≥1.2	Recessionary decoupling
Negative decoupling	Recession	Increase	Decrease	≤0	Strong negative decoupling
	Recession	Decrease	Decrease	(0,0.8)	Weak negative decoupling
	Growth	Increase	Advance	≥1.2	Expansionary negative decoupling
Connection	Growth	Increase	Decrease	–	Growing connection
	Recession	Decrease	Decrease	–	Declination connection

Note: The decoupling coefficient mainly refers to the ratio of the growth rate of the water stress to the growth rate of economic, aiming to distinguish the decoupling tense between economic development and water resource consumption and utilization.

The decoupling effect and Kuznets curve used to test the overall correlations between water use and economic growth emphasized that water use quantity (including sectoral water) decreased accompanying economic growth. They solely revealed the relationship between water consumption and economic growth without further discussing the correlation between economic size and water use efficiency.

Water use efficiency decomposition

Usually, water use efficiency refers to the ratio of production output relative to water use (in terms of water withdrawn, applied). Water intensity equals total water use divided by gross value added, a metric of water use efficiency (EEA, 2018). Water productivity indicates how much economic output (in terms of the gross or net value of the product) is produced per m^3 of freshwater, which serves as a measure of the efficiency of water use (EEA, 2018). In fact, they share a nature consistency of efficiency, namely less input more output. Customarily, they are expressed in dollars per cubic meter (US$/$m^3$). We collectively defined them as water use efficiency in this study. As detailed previously, increasing water availability through enhancing water use efficiency could positively influence society. Water use efficiency is a composite index that can be decomposed further. The dynamic change and variation trend of water use efficiency were decomposed into technological progress change, pure technical efficiency change, and scale efficiency change (Ma *et al*., 2012; Ali & Klein, 2014; Pan *et al*., 2020). Existing research results appeared that technological progress is more beneficial for enhancing water use efficiency. Inversely, ineffective scale efficiency hindered the improvement of water use efficiency. Ineffective scale efficiency means optimal output is not achieved.

Pure technical efficiency change indicates the relative production efficiency change in two adjacent periods when the technology and scale remain constant. That reflects the management level of decision-makers, in what follows, it is out of our consideration. Laspeyres index of complete decomposition method was introduced to decompose change of water use per CNY10,000 of GDP into technological progress, and industrial structure effect, with getting technological progress contributes more to efficiency change than to industrial structure (Tong *et al*., 2011). As mentioned above, water use efficiency (or water use per CNY10,000 of GDP) can be expressed as the ratio of GDP to water use volumes, which also equals the product of population and per capita GDP divided by water use volumes. Building on the expression, combined experience in both developed and developing countries, the rise in population and water use is below the per capita GDP rate. That is, per capita GDP representing scale output has a more significant impact on water use efficiency than population and water resources. Moreover, according to existing research, industrial structure indirectly reflects the economic scale of a country or region (Tong *et al*., 2011). To sum up, technological progress leads to efficiency improvement without any doubts. Nevertheless, the following study focused on potential water use change through water use efficiency variation from an economic scale perspective building on previous efforts.

MATERIALS AND METHODOLOGY

Data envelopment analysis-Malmquist

According to available studies, technical progress, decision-maker management level, and return to scale together affect water use efficiency (Ma *et al*., 2012). To support this viewpoint, further verification has been done. The Malmquist index (change in total factor productivity (*Tfpch*)) is the previous and current water use efficiency ratio. Hence, when the Malmquist index is greater than 1, the efficiency increases; conversely, when less than 1, the efficiency decreases; when it equals 1, the same efficiency. Similarly, pure technical efficiency change, scale efficiency change, and technological progress change follow the same evaluation criteria. Usually, the

Malmquist index is quantified by the distance function.

$$M_t(x^t, y^t, x^{t+1}, y^{t+1}) = \frac{D_c^t(x^{t+1}, y^{t+1})}{D_c^t(x^t, y^t)} \tag{1}$$

$$M_{t+1}(x^t, y^t, x^{t+1}, y^{t+1}) = \frac{D_c^{t+1}(x^{t+1}, y^{t+1})}{D_c^{t+1}(x^t, y^t)} \tag{2}$$

where x and y are the input and output, coupled with the superscript t and $t+1$ denote certain period, respectively. The change of the relationship between input and output from (x^t, y^t) to (x^{t+1}, y^{t+1}) can be depicted as the change in total factor productivity. Here, it means water use efficiency. Moreover, $D_c^t(x^t, y^t)$ and $D_c^{t+1}(x^{t+1}, y^{t+1})$ are the distance function of time t to $t+1$ on the fixed-scale benefit. $D_v^t(x^t, y^t)$ and $D_v^{t+1}(x^{t+1}, y^{t+1})$ are the distance function of time t to $t+1$ based on the changeable-scale benefit. The Malmquist index reflects the change of productivity of one decision-making unit (also called sample) from time t to $t+1$. According to the Fisher indices definition, the geometric average productivity index of the two periods is the total factor productivity index.

$$\begin{aligned} M(x^t, y^t, x^{t+1}, y^{t+1}) &= (M_t \times M_{t+1})^{1/2} = \left[\frac{D_c^t(x^{t+1}, y^{t+1})}{D_c^t(x^t, y^t)} \times \frac{D_c^{t+1}(x^{t+1}, y^{t+1})}{D_c^{t+1}(x^t, y^t)}\right]^{1/2} = \frac{D_v^{t+1}(x^{t+1}, y^{t+1})}{D_v^t(x^t, y^t)} \\ &\times \left[\frac{D_v^t(x^t, y^t) D_v^t(x^{t+1}, y^{t+1})}{D_v^{t+1}(x^t, y^t) D_v^{t+1}(x^{t+1}, y^{t+1})}\right]^{1/2} \left[\frac{D_c^t(x^{t+1}, y^{t+1})/D_v^t(x^{t+1}, y^{t+1})}{D_c^t(x^t, y^t)/D_v^t(x^t, y^t)}\right. \\ &\times \left.\frac{D_c^{t+1}(x^{t+1}, y^{t+1})/D_v^{t+1}(x^{t+1}, y^{t+1})}{D_c^{t+1}(x^t, y^t)/D_v^{t+1}(x^t, y^t)}\right]^{1/2} \\ &= Pech \times Techch \times Sech \end{aligned} \tag{3}$$

In this study, x is the input including water use quantity, fixed assets, and employment-population for every province, as well as y is the GDP of each province. *Pech* is the pure technical efficiency change, *Sech* is the scale efficiency change, and *Techch* is the technological advance change.

Cubic curve model

Building upon previous studies, including decoupling effect, Kuznets curve theory, and sigmoid curve function, through the historical time series, we find that water use efficiency (water use per CNY10,000 of GDP change shown an inverted-S shaped curve with the change of per capita GDP (see Figure 1). Here, we adopted per capita GDP representing economic size to highlight the better economic growth of a country or a region. And then, the fitting function between per capita GDP and water use efficiency can be expressed below.

$$z = d/[m \cdot \ln y' + n \cdot (\ln y')^2 + p \cdot (\ln y')^3 + q] \tag{4}$$

In which, z is the water use per CNY10,000 of GDP, y' is the per capita GDP at 2019 constant price, and the coefficients d, m, n, p, and q are all constant.

Technical validation

In this study, to make the analysis robust and scientific, we employed water use efficiency estimates of each province or region from 2003 to 2019 and their actual water use efficiency to examine the fitting regression model accuracy with a couple of criteria, including the mean absolute percentage error (*MAPE*), the coefficient of

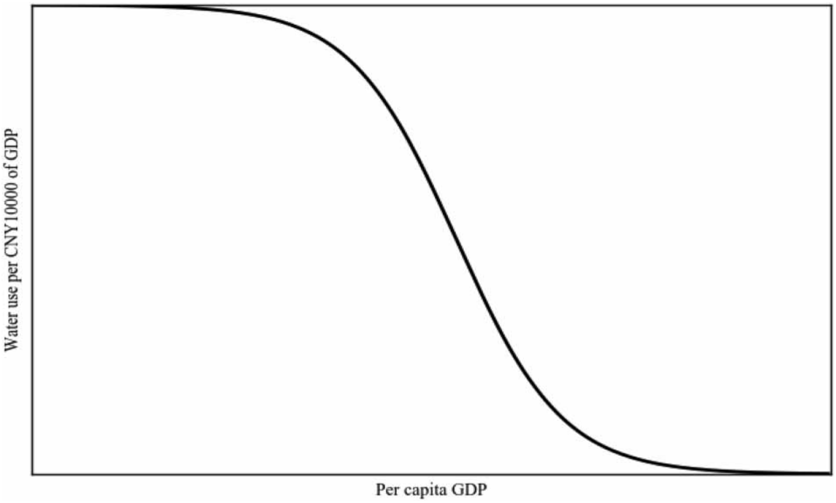


Fig. 1. | The curve of water use efficiency over per capita GDP.

determination of R^2, and the root mean square error (*RMSE*). Independent-samples *t*-test is also used to analyze the different cases of the estimated and actual values.

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{T\hat{W}_i - TW_i}{TW_i}\right| \tag{5}$$

$$R^2 = 1 - \frac{\sum_i (T\hat{W}_i - TW_i)^2}{\sum_i (T\bar{W}_i - TW_i)^2} \tag{6}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(TW_i - T\hat{W}_i)^2} \tag{7}$$

where TW_i is the measured total water use, namely actual total water use quantity, $T\hat{W}_i$ is the estimated water use, n is the sample size, and $T\bar{W}_i$ is the mean of actual water use quantity. Among the above statistical measures, when $MAPE = 0\%$, the constructed model indicates a fully perfect model, while when $MAPE > 100\%$, it represents an inferior model. The range of R^2 is [0, 1], the bigger, the better, rather *MAPE* and *RMSE* the smaller, the better. In addition, the t-test was performed at the significance level of 5%.

Materials and data processing

Due to a lack of data, the selected decision-making units are 31 provinces across China, excluding Hong Kong, Macao, and Taiwan. The original data of water use quantity, fixed assets, and employment-population indicated by x come from the China Statistical Yearbook (2002–2020) (BSC, 2002–2020) or Statistical Bulletin on each province's National Economic and Social Development. The data of per capita GDP (y') (see Supplementary Material) and total GDP (y) of each province are also selected from China Statistical Yearbook (2002–2020) (BSC, 2002–2020), which are converted into 2019 constant price to eliminate inflation factor. It is worth noting that water use efficiency (z) in this paper is calculated by dividing the productive water use (including industrial and agricultural water use) by the GDP (see Supplementary Material), which is closer to truth, rather than employing official statistics from China Water Resources Bulletin directly. Mainly because domestic and ecological water use does not have a contribution to GDP. Therefore, the official statistics, which has both elements under consideration in the calculation except for production water use, would lead to exaggerated results.

RESULTS AND DISCUSSIONS

In what follows, we try to delve deeper into the discussion of the historical facts underlying the different effects driving the evolution of water demands from the perspective of the technical economy.

Efficiency change decomposition

According to the above evaluation criteria of data envelopment analysis-Malmquist, when the efficiency change value is greater than 1, it means positive; when less than 1, it means negative. Decomposed water use efficiency change for every province is illustrated in Table 2. The results show that the *Techch* is all greater than 1 (Table 2), which is indisputable and consistent with reality. On the contrary, all *Pech* and *Sech* are not greater than 1. Then, on the ground of Equation (3) $Techch > 1$ means technical progress and innovation induced advance in water use efficiency that is $Tfpch > 1$. $Pech < 1$ and $Sech < 1$ will result in $Tfpch < 1$ that indicated no increase in water use efficiency relative to the former period.

On the economic level, the value of efficiency change is less than 1, which means low-quality economic growth and vice versa. Among them, *Sech* reflects the change of scale returns in two adjacent periods, including increasing scale returns, decreasing scale returns, and unchanged scale returns. *Pech* is to measure the ability of the decision-making subject to provide corresponding output with the given input resources, which is directly related to the management level of the decision-making subject. From the perspective of decreased water use efficiency, due to lack of control on management standard of decision-maker or manager, under no consideration about the change of pure technology efficiency, the decrease in water use efficiency is dependent upon mainly scale efficiency variation. Alternatively, put another way, in terms of water use efficiency decline, *Sech* generally carries a higher weight than *Pech* (Table 2).

Analysis for scale efficiency change

$Sech < 1$ signified that it is not reached the optimal output under given resources input. In other words, the change of scale efficiency is determined by output size under a given certain amount of input. It can be seen from Table 2 that *Sech* is lower than 1 in most of the provinces and regions except Beijing, Tianjin, Liaoning, Jilin, and Xinjiang. The regions and provinces for increasing scale returns are also rare. It simply means that the increase in output is less than the increase in factors of production. Actually, in the past few decades, the whole China's economic growth pattern has extensive economic growth, which is an uneconomical pattern to grow.

It is precisely because of this kind of extensive economic growth mode that leads to blindly input too many production factors but not the optimal output. That means the input resources, including water resources, have not been utilized fully. And then, China's water crisis and water shortage were exacerbated. The most important driver of water scarcity is economic size growth, which greatly overcomes any expected water saving due to technological progress (Distefano & Kelly, 2017). As a result, the Chinese government calls for a shift from high-speed and extensive economic growth to a stage of high-quality economic development (Zhang, 2017). Regarding water resources utilization, the principle of water determined city size, water determined cultivated land scale, water determined population size, and water determined output scale should be followed (China Daily, 2020). In general, the relationship between water resources and economic scale is the relationship between input and output.

Table 2. | Malmquist index summary of every province means.

Region	*Techch*	*Pech*	*Sech*	*Tfpch*
Beijing	1.052	1.000	1.000	1.052
Tianjin	1.062	1.000	1.000	1.062
Hebei	1.034	0.981	0.974	0.988
Shanxi	1.028	0.980	0.993	1.001
Inner Mongolia	1.039	0.968	0.993	0.998
Liaoning	1.041	1.000	1.000	1.041
Jilin	1.039	0.963	1.000	1.001
Heilongjiang	1.019	0.962	0.986	0.966
Shanghai	1.052	1.000	1.000	1.052
Jiangsu	1.035	1.007	0.976	1.017
Zhejiang	1.043	1.000	0.988	1.031
Anhui	1.040	0.945	0.972	0.955
Fujian	1.037	0.975	0.979	0.990
Jiangxi	1.030	0.954	0.983	0.966
Shandong	1.022	1.000	0.976	0.997
Henan	1.034	0.968	0.969	0.970
Hubei	1.036	0.976	0.975	0.986
Hunan	1.027	0.961	0.975	0.962
Guangdong	1.040	1.000	0.967	1.005
Guangxi	1.017	0.927	0.976	0.921
Hainan	1.033	0.955	0.982	0.969
Chongqing	1.037	0.985	0.990	1.011
Sichuan	1.039	0.982	0.972	0.992
Guizhou	1.031	0.948	0.992	0.970
Yunnan	1.035	0.943	0.984	0.960
Tibet	1.035	1.000	0.948	0.981
Shaanxi	1.033	0.973	0.985	0.989
Gansu	1.031	0.951	0.996	0.977
Qinghai	1.029	1.000	0.978	1.007
Ningxia	1.036	0.993	0.972	0.999
Xinjiang	1.037	0.951	1.005	0.991

Fitting model verification

Based on the foregoing, the relationship between water resources and economic output can be reflected in water resources efficiency and output per capita. As a result, Equation (4) was constructed. The statistical test results of the cubic curve model through the above traditional criteria are shown in Table 3. The values of *MAPE* and *RMSE* are mostly around 3–4%, coupled with the values of R^2 are greater than 0.95, and p-values are much

Table 3. | Test statistical results.

Region	*MAPE*	*RMSE*	R^2	*p*
Beijing	4.73%	4.87%	0.9954	0.9875
Tianjin	8.71%	9.00%	0.9891	0.9835
Hebei	1.48%	1.48%	0.9990	0.9996
Shanxi	3.54%	3.56%	0.9922	0.986
Inner Mongolia	5.03%	5.16%	0.9973	0.9954
Liaoning	4.49%	4.52%	0.9942	0.9964
Jilin	3.32%	3.29%	0.9961	0.9998
Heilongjiang	1.92%	1.90%	0.9947	0.9993
Shanghai	3.73%	3.73%	0.9949	0.9986
Jiangsu	4.24%	4.24%	0.9817	0.9977
Zhejiang	2.07%	2.06%	0.9992	0.9986
Anhui	4.59%	4.56%	0.9711	0.9991
Fujian	1.42%	1.41%	0.9994	0.9998
Jiangxi	4.03%	3.99%	0.9747	0.9983
Shandong	2.87%	2.85%	0.9962	0.9986
Henan	5.18%	5.17%	0.9826	0.9972
Hubei	2.41%	2.43%	0.9983	0.9983
Hunan	4.69%	4.75%	0.9930	0.9932
Guangdong	1.11%	1.11%	0.9992	0.9994
Guangxi	3.97%	3.99%	0.9923	0.9965
Hainan	5.00%	5.09%	0.9939	0.9934
Chongqing	4.42%	4.59%	0.9963	0.9909
Sichuan	3.13%	3.14%	0.9971	0.998
Guizhou	4.93%	4.98%	0.9948	0.9942
Yunnan	2.53%	2.54%	0.9980	0.9974
Tibet	10.08%	9.91%	0.9475	0.9814
Shaanxi	3.73%	3.76%	0.9945	0.9978
Gansu	0.93%	0.93%	0.9997	0.999
Qinghai	6.05%	6.24%	0.9922	0.9885
Ningxia	4.30%	4.27%	0.9746	0.9999
Xinjiang	1.94%	1.95%	0.9978	0.9991

larger than 0.05 at the significance level of 5%. As a consequence, we can conclude that the cubic curve model is feasible and practical.

Moreover, to reflect the effectiveness of the fitting model intuitively, the comparison diagrams (see Figure 2) from four significantly different provinces were drawn, including Hebei, Shanghai, Hunan, and Xinjiang. They have different socio-economic environments and development as well as resources endowment (Guo & Wang, 2021). It can be obtained from the parameters in the fitting model that regional development level (per capita

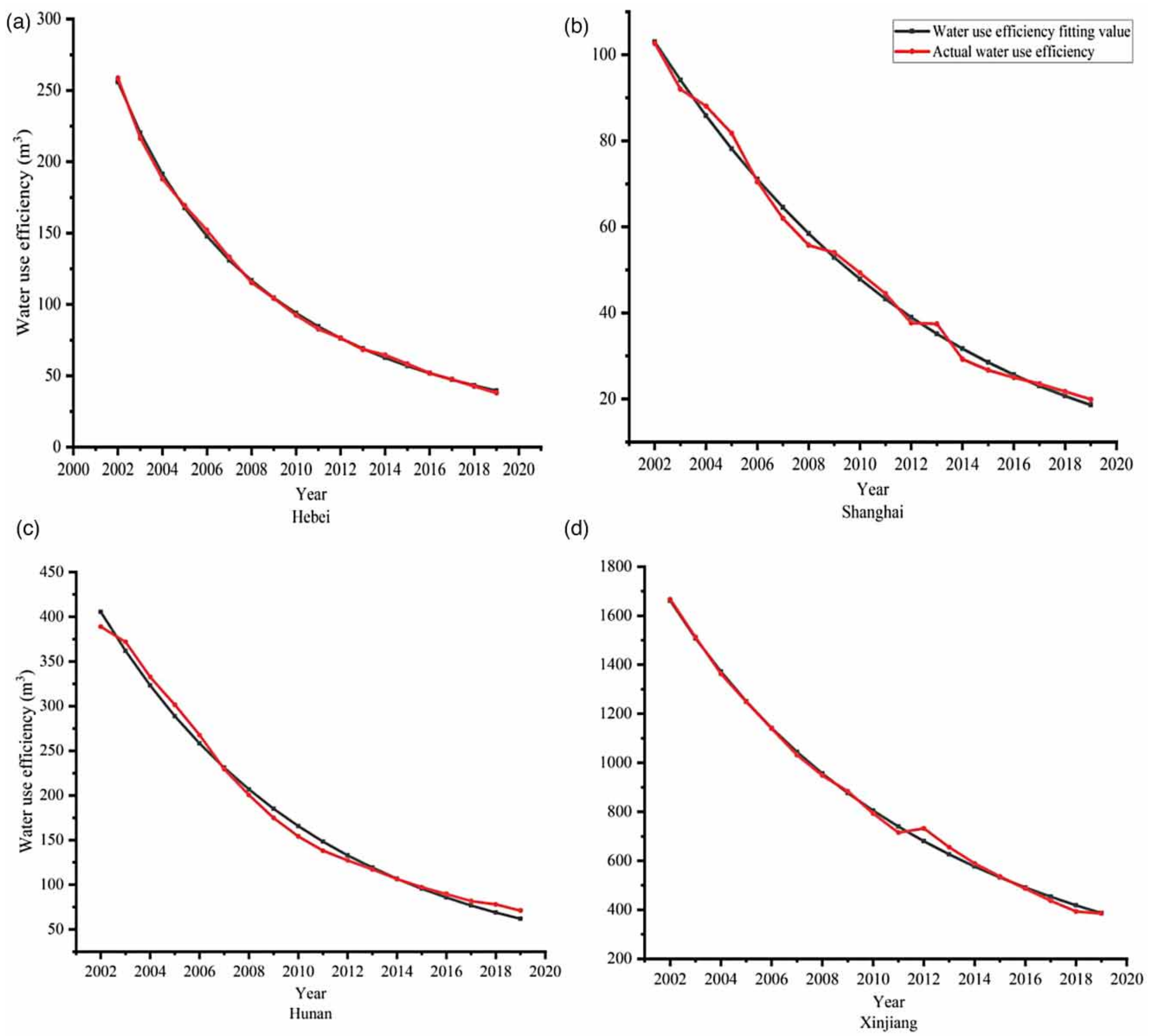


Fig. 2. | Actual water use efficiency and water use efficiency fitting value of 2003–2019 at the provincial level.

GDP) is responsible for water use efficiency. Similarly, according to developed countries' experience, during the first half of the twentieth century, the per capita income improvement is the driving force behind water withdrawal in developed countries, such as Europe (Duarte *et al.*, 2014). Furthermore, water resources endowment denoting certain regions' available water should not be ignored, owing to irreplaceable attributes and water transfer cost. Hence, the above four provinces with significant geographical distribution differences and vast economic levels were chosen as examples. Figure 2 also shows the perfect goodness of fit of the cubic curve model. In conclusion, the cubic curve model can be used to estimate and forecast water use efficiency by the per capita GDP level.

Limitations of the cubic curve model

The inverted-S shape in Figure 1 shows that the fitting model is applied to per GDP continuing growth and water use efficiency persistent improvement, that is, most developing countries like China. Meantime, the potential premise is economic expansion progress with steady reforms and no major shock. Throughout our study, we have side-stepped certain important issues such as the role of agricultural and industrial water use coupled with the industrial structure on water use efficiency was not involved. Although some of these issues lie behind the changes we have discussed, they have not been considered directly in our model. The results only reflect the linkage between economic development and water utilization at the macro-level and do not explore the micro-level in depth. Therefore, it is suitable for the states or regions in the process of industrialization.

CONCLUSION AND IMPLICATIONS

Conclusions

As stated earlier, future water demand estimates are sensitive to the underlying assumptions regarding socio-economic drivers such as economic growth, and the most important driver of future water scarcity is still economic growth. Advance in water use efficiency is the critical pathway in response to ever-increasing threats and challenges from water shortage. As such, to some extent, knowing the extent of per capita GDP representing the economic development scale on the water use efficiency is essential for the sustainability of freshwater resources.

Our research sheds light on the inverted-S shape relationship between water use efficiency and per capita GDP in 31 provinces of China from the early twenty-first century by decomposing water use efficiency and economic size, respectively. It contributes to the literature in two aspects. First, water use efficiency changes were decomposed, with getting scale efficiency change restricted advance in water use efficiency, technical progress change, and pure technical efficiency change. Second, variation trends of both per capita GDP and water use efficiency show an inverted-S shape. And the constructed fitting model can serve as a good basis for understanding the profound relationship between per capita GDP and water use efficiency and providing valuable guidance for decision-makers in making the right policies for water resources assessments.

Implication and future research

1. Forecasting future water demand facilitates water resource planning and management.

From a holistic perspective, the constant improvement in water use efficiency at the national scale prevented a greater water use increase. The inverted-S shape relationship between water use efficiency and per capita GDP can be a foundation for future water demand management. It was of global significance, especially regarding developing countries with water shortages. Brown *et al.* (2015) pointed out that the prediction of the future of water resources is the basis of the scientific implementation of sustainable management to cope with the global water challenges in the twenty-first century. Water resources planning is ultimately the prediction of the implementation of plans and policies. In detail, from an economic point of view, the constructed simulation function can serve to predict water use efficiency based on pre-planned goals of per capita GDP growth indicating the per capita welfare level in the meantime representing economic scale. Then, future water demand with relative accuracy can be projected through water use efficiency that is beneficial to water resources management, keeping enough water needs, and avoiding water crisis paired with alleviating water stress.

2. Promoting the coordinated development of water resources and social economy.

In terms of scale efficiency change, at the economic level, excessive resources input will lead to decreasing scale returns which is a sign of under-utilized resources. At the resource acquisition level, resources are wasted. At the environmental level, it has intensified the destruction of the ecosystem. To sum up, to use water resources as its capacity permits, the principle of water determined population size, water determined output scale, water determined city size, and water determined cultivated land scale should be followed while keeping economic development. Exploring the relationship between per capita GDP and water use efficiency offers a reference to reconcile economic boom with water resources sustainability. It is conducive to avoiding excessive economic growth induced by extensive economic growth, causing natural resources exhausting and environmental polluting.

In the following work, we will use the cubic curve model in this paper to simulate and predict the future water demand and peak water in China, coupled with determining whether the water use limit of 700 billion m^3 will be breached by 2030 (Jiao, 2011; Guo & Wang, 2021).

CONFLICTS OF INTEREST

There are no conflicts to declare.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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