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Article

Analysis of the Economy-Wide Rebound Effect of Water Efficiency Improvement in China Based on a Multi-Sectoral Computable General Equilibrium Analysis

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Abstract: The effectiveness of water efficiency improvement is restricted by the water rebound effect by which anticipated water resource saving from improved water efficiency may be partly or wholly offset or even surpassed by an increase in water demand. The economy-wide rebound effect of water efficiency improvement in China is poorly understood. This study explored the economy-wide rebound effect of water efficiency improvement in China based on a multi-sectoral computable general equilibrium model. The results suggested that water efficiency improvement could effectively reduce water consumption in producing sectors and benefit economic growth and employment. However, the decrease in water consumption was much lower than the volume of water efficiency improvement, which indicated that the rebound effect partly offset water savings caused by water efficiency improvement. We observed a larger reduction in water consumption in the long run, which indicated a smaller rebound effect and a more significant effect in saving water resources in the long term. Notably, the total rebound effect in the short-run closure was much larger than that in the long-run closure, and the effect from the production side was much smaller. Hence, the economic-wide rebound effect is primarily derived from the incremental water consumption by households, investors, and governments.

Keywords: water efficiency; rebound effect; computable general equilibrium model; China

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1. Introduction

Owing to the limited water supply and increase in water consumption due to the growing population and rapid economic growth, China is facing severe water shortages. In 2019, China's total water utilization reached 602.12 billion m^3, accounting for 74% of its exploitable water resources [1]. The northern part of the country experiences the most severe water shortages with an average freshwater availability of 760 m^3 per capita per year, which is 25% less than the internationally accepted water scarcity level [2]. To address severe water shortages, China's government has adopted a series of policies that include improving water resource efficiency [3]. The Opinions on Implementing the Strictest Water Resources Management System issued in 2015 clearly stated the main objectives of the "three red lines" for water resource management. The policy clarified that China's water efficiency must reach or approach global advanced levels by 2030. The water volume of CNY 10,000 of industrial added value will be reduced to below 40 m^3, and the effective utilization coefficient of farmland irrigation water will increase to above 0.6.

Improvements in water efficiency are considered the most effective measures for reducing water consumption in different economic agents, including agriculture, industry, and households [4,5]. Water efficiency improvement can be achieved by installing new facilities, agricultural irrigation technologies, and cooling technologies for power generation industries [6]. Several studies have suggested that water efficiency improvement can effectively reduce water consumption [7,8]. Compared with surface irrigation, drip irrigation can improve irrigation efficiency by 30%, leading to significantly reduced water consumption [9]. Huang et al. [10] and Guo et al. [11] demonstrated that using water-saving technologies for irrigation could reduce crop water consumption and improve water productivity.

However, the effectiveness of water efficiency improvement is restricted by the rebound effect. The water rebound effect refers to the phenomenon by which water resource savings expected from improved water efficiency may be partly or wholly offset or surpassed (referred to as a ″backfire″ effect) by increased water demand [12–14]. The rebound effect had been empirically verified as a case of Jevons paradox, as suggested by Jevons [15], who observed that coal consumption increased rather than decreased in many industries, despite technological improvements in the study period. Numerous studies have focused on energy efficiency improvement and measured direct [16–18] and economy-wide rebound effects [19,20]. Direct rebound refers to an increase in demand for a service that has undergone efficiency improvements [21,22]. Economy-wide rebound implies changes in price, supply, and demand across regional economic systems [23,24].

An increasing number of studies have analyzed the rebound effects of water efficiency improvement. Wheeler et al. [25] suggested that water savings from efficiency improvement may be overestimated if the rebound effect is not considered. Gutierrez-Martin and Gomez [26] found that potential water savings from improving irrigation techniques were surpassed by increasing water demand in Spain, suggesting that attempts to improve water efficiency in agriculture were backfiring. Song et al. [3] estimated the magnitude of the agricultural water rebound effect in China from 1998 to 2014 to be 61.49%. However, these studies observed and measured the rebound effect at the micro-level, which was classified by Greening et al. [27] as being indicative of the direct rebound effect. Furthermore, most studies analyzed the effects of water efficiency improvements on agriculture and irrigation, while only few studies have determined the economy-wide rebound effect of water efficiency using the Computable General Equilibrium (CGE) model. For example, Freire-González [6] employed a dynamic water economy–computable general equilibrium model for Spain and found that the economy-wide water rebound effect is 100.74% in the case that overall water efficiency improves annually by 50%.

This paper examined the rebound effect of water efficiency improvement in China based on a multi-sectoral CGE model. In contrast to previous studies [28–30], we focused on the economy-wide rebound effect of water efficiency and calculated the rebound effect at the macro- and sector levels, as well as production and consumption sides. This study contributes to the literature in two ways: First, to the best of our knowledge, this is the first study to specifically measure the economy-wide rebound effect of water efficiency for China in a comprehensive CGE model. The CGE model is a suitable tool for measuring economy-wide rebound effects because it can incorporate different rebound effect mechanisms across different sectors and at different levels [31]. Second, due to the detailed modeling of the industrial sectors of China's economy (we incorporate 42 sectors), we can measure and decompose the economy-wide rebound effect and explore the mechanisms of this rebound effect at a large scale. Moreover, this study provides new and insightful implications in terms of water policies.

The remainder of this paper is organized as follows: Section 2 introduces the methodology for simulating water efficiency improvement; Section 3 describes the method of calculating the rebound effect at different levels; Section 4 discusses the simulation results; and Section 5 concludes this paper with several policy implications.

2. Methodology

Figure 1 shows the methodology of this study. We employed a multi-sectoral CGE model of China, the ORANIG model, to investigate the effect of water efficiency improvement. The model has five major modules, including production, investment, consumption, export, and equilibrium.

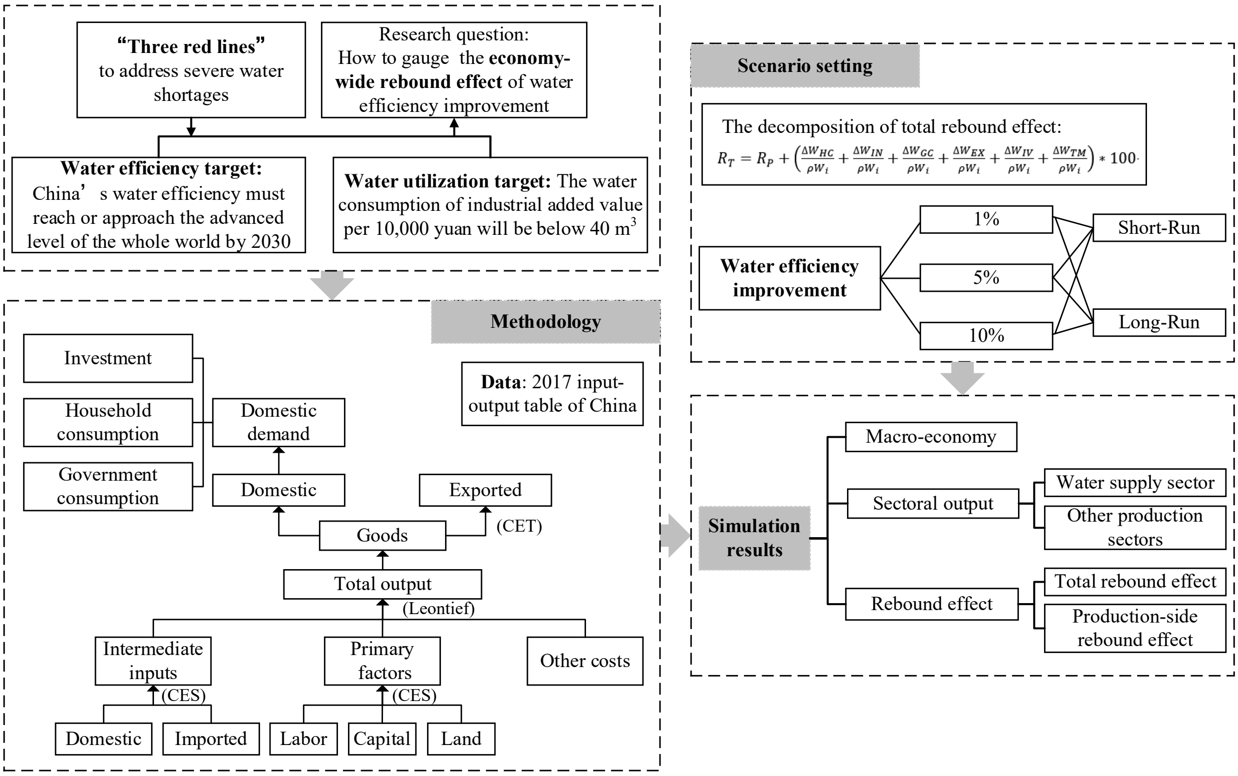

Figure 1. The flow chart for the methodology.

2.1. The ORANIG Model

(1) Production

The producing sectors' utilization of intermediate inputs and primary factors are determined by minimizing their costs. Outputs are allocated in the domestic and international markets according to the profit maximization. The input structure of each sector is illustrated in Figure 1. The total input is composited by intermediate inputs, primary factors, and other inputs, which are described by the Leontief function (Equation (1)).

$$X1TOT(i) = \frac{1}{G1(i)} \times MIN\left[All, c, COM{:}\frac{X1\_S(c,i)}{A1\_S(c,i)}, \frac{FAC(i)}{A1\_F(i)}, \frac{OCT(i)}{A1\_O(i)}\right], COM = \{1, \ldots, \mathrm{N}\} \quad (1)$$

$$X1TOT(i) = \frac{1}{G1(i)} \times MIN\left[All, c, COM{:}\frac{X1\_S(c,i)}{A1\_S(c,i)}, \frac{FAC(i)}{A1\_F(i)}, \frac{OCT(i)}{A1\_O(i)}\right], COM = \{1, \ldots, \mathrm{N}\} \quad (1)$$

where i, c, and s are the index industry, commodity, and source, respectively. $X1TOT(i)$ represents the output of the i-th sector. $X1\_S(c,i)$ represents the intermediate input c used by sector i, comprising the domestic and imported goods, which is depicted by a constant elasticity of substitution (CES) function (Equation (2)). $FAC(i)$ represents the primary factor used by sector i, comprising labor, capital, and land, which is depicted by the CES function (Equation (3)). $OCT(i)$ is the other cost. $G1(i)$ is a neutral technological parameter and $A1\_S(c,i)$ is the intermediate input-augmented technological parameter.

$$X1\_S(c,i) = CES\left[All, s, SRC{:}\frac{X1(c,s,i)}{A1(c,s,i)}\right], SRC = \{\text{dom}, \text{imp}\} \tag{2}$$

$$FAC(i) = CES\left[\frac{X1LAB(i)}{A1LAB(i)}, \frac{X1CAP(i)}{A1CAP(i)}, \frac{X1LND(i)}{A1LND(i)}\right] \tag{3}$$

(2) Investment

The investors determine the uses of investment commodities according to cost minimization. The investment in sector i is composited by different investment goods with the Leontief function (Equation (4)).

$$X2TOT(i) = \frac{1}{G2(i)} \times MIN\left[All, c, COM{:}\frac{X2\_S(c,i)}{A2\_S(c,i)}\right], COM = \{1, \ldots, \text{N}\} \tag{4}$$

where $X2TOT(i)$ is sector i's total investment, and $X2\_S(c,i)$ is the investment goods c purchased by sector i. Similarly, $G2(i)$ is the technological parameter, $A2\_S(c,i)$ is the technological parameter to investment goods c, and $X2\_S(c,i)$ is the composite of domestic and imported goods with the CES function (Equation (5)).

$$X2\_S(c,i) = CES\left[All, s, SRC{:}\frac{X2(c,s,i)}{A2(c,s,i)}\right], SRC = \{\text{dom}, \text{imp}\} \tag{5}$$

(3) Consumption

The residents maximize their utility subjected to the disposable income. The Klein–Rubin function describes the household consumption of different commodities (Equation (6)):

$$\begin{gathered} MAX\ U = \prod_{c=1}^{N}\left[\frac{X3\_S(c)}{Q} - A3SUB(c)\right]^{\beta(c)} \\ s.t.\ \sum_{c}\frac{X3\_S(c)}{Q} \times P3\_S(c) = \frac{Y}{Q} \end{gathered} \tag{6}$$

where U represents household utility, Y is per capita disposable income, and Q represents the population number. $X3\_S(c)$ is the consumption quantity. $X3SUB(c)$ and $A3SUB(c)$ represent the quantity and parameter for the subsistence consumption. $P3\_S(c)$ is the commodity price. $\beta(c)$ represents the marginal consumption propensity of commodity c. Through the maximation, we obtain the linear expenditure system (Equation (7)). The consumption of $X3\_S(c)$ is composited by domestic and import goods with the CES function.

$$X3\_S(c) = X3SUB(c) + \frac{\beta(c)}{P3\_S(c)} * \left[Y - \sum_{c=1}^{n} X3SUB(c) \times P3\_S(c)\right] \tag{7}$$

(4) Export

$$X4(c) = F4Q(c)\left[\frac{P4(c)}{PHI \times F4P(c)}\right]^{EXP\_E(c)} \tag{8}$$

The export for tradable commodities is negatively associated with the export price (Equation (8)). $X4(c)$ is the export quantity. $P4(c)$ is the export price in foreign currency and PHI represents the exchange rate. Two shift variables are included: $F4Q(c)$ and $F4P(c)$. The $EXP\_E(c)$ is the price elasticity of commodity c's exports.

(5) Equilibrium

As with most CGE models, the general equilibrium condition contains the clearance of all commodity and factor markets, the zero profit of producing sectors, and a balance between total saving and investment.

2.2. Data

China's recently published input–output table from 2017 with 149 original producing sectors was employed to construct the database for the ORANIG model. To simplify the data, the original producing sectors were aggregated into 42 sectors according to the National Industries Classification. The sectoral aggregation and concordance are provided in Appendix A. The behavior parameters, such as Armington elasticities, export elasticities, substitution elasticities of primary factors, and subsistence parameters of the Klein–Rubin function, have been taken from previous studies [32–34].

3. Measurement of Rebound Effect and Scenario Design

3.1. Measurement of Rebound Effect of Water Efficiency Improvement

There are several discussions on the methods to measure rebound effects. Following Greening et al. [27], this study focused on the economy-wide rebound effect at the macro-level rather than the micro-level effect. The measurement of macro-level rebound effects is defined by Saunders [13,35]. Following Turner [14,36] and Hanley et al. [37], the rebound effect of water resource efficiency is distinguished between that measured in physical units and efficiency units. The rebound effect is derived by the following equations:

$$R = [1 + \frac{\dot{W}}{\rho}] \times 100 \quad (9)$$

$$\dot{W} = \frac{\Delta W}{W} \quad (10)$$

where $\dot{W}$ is the changing rate of water utilization (W) benefiting from the rate of water-augmented technical progress, ρ. Specific to a certain sector, the economy-wide rebound effect is calculated by Equation (11):

$$R = [1 + \frac{\dot{W}}{\alpha_i \rho}] \times 100 \quad (11)$$

where $\alpha_i = \frac{W_i}{W}$ is the sector i's proportion of water utilization in the economy-wide water utilization.

Following Lecca et al. [38] and Koesler et al. [39], two levels of rebound effects are decomposed. The total water utilization contains the water consumption of the producing sectors and final users. The final users include households, investors, inventory, governments, and exporters. By substituting α_i into Equation (13), the term $\frac{\dot{W}}{\alpha_i * \rho}$ is re-written as follows:

$$\frac{\dot{W}}{\alpha_i \rho} = \frac{\Delta W}{\rho W_i} = \frac{\Delta W_1 + \Delta W_2 + \cdots + \Delta W_N + \Delta W_c}{\rho W_i} = \frac{\dot{W_i}}{\rho} + \frac{\Delta W_{OP}}{\rho W_i} + \frac{\Delta W_C}{\rho W_i} \quad (12)$$

The subscript "OP" represents other producing sectors, and C represents the final consumption. N is the number of producing sectors. Then, we calculate sector i's rebound effect with Equation (13).

$$R_i = [1 + \frac{\dot{W_i}}{\rho}] \times 100 \quad (13)$$

The rebound effect of all producing sectors is calculated as follows:

$$R_P = [1 + \frac{\dot{W}_p}{\rho}] \times 100 = R_i + \frac{\Delta W_{OP}}{\rho W_i} \times 100 \quad (14)$$

$\frac{\Delta W_C}{\rho W_i}$ is further decomposed in Equation (15).

$$\frac{\Delta W_C}{\rho W_i} = \frac{\Delta W_{HC}}{\rho W_i} + \frac{\Delta W_{IN}}{\rho W_i} + \frac{\Delta W_{GC}}{\rho W_i} + \frac{\Delta W_{EX}}{\rho W_i} + \frac{\Delta W_{IV}}{\rho W_i} + \frac{\Delta W_{TM}}{\rho W_i} \quad (15)$$

where HC, IN, GC, EX, IV, and TM are household consumption, investment, government consumption, exports, inventory, and transport margin, respectively.

The total rebound effect is defined as follows:

$$R_T = R_P + \left(\frac{\Delta W_{HC}}{\rho W_i} + \frac{\Delta W_{IN}}{\rho W_i} + \frac{\Delta W_{GC}}{\rho W_i} + \frac{\Delta W_{EX}}{\rho W_i} + \frac{\Delta W_{IV}}{\rho W_i} + \frac{\Delta W_{TM}}{\rho W_i}\right) \times 100 \quad (16)$$

Using Equation (16), we calculate the total rebound effect of water efficiency improvement in one sector and decompose the origins of the rebound effect. The rebound effect could be measured at the macro-level (R_T) and the sector level (R_i), as well as from the production side (R_P) and consumption side. Notably, the water utilization is measured in efficiency units rather than in physical units (such as tons), which indicates that we focus on the delivered water service more than physical water consumption.

3.2. Scenarios

In contrast to previous studies, we compared the rebound effect of water resource efficiency under short- and long-run closures. Both the effectiveness of water resource efficiency and the rebound effect differ significantly between the short and long term.

3.3. Closure

In this study, two model closures were used: short-run closure and long-run closure. Comparing the results under two closures will reveal distinct rebound effects of water resource efficiency in the short and long term. In the short-run closure, it assumes that wages are fixed. Laborers can move freely across sectors and the employment is determined endogenously. Capital stock is fixed in each sector, which suggests that the rate of capital returns differs across sectors. The amount of investment can vary from each sector due to differing investment return rates. Conversely, for a long-run closure, it assumes that capital has enough time to adjust such that it flows to higher-return sectors. This will equalize capital return rates across sectors in the long term. The employment level is usually fixed at the equilibrium level, and the demand for laborers is balanced by the endogenously determined wages.

We designed scenarios for the rebound effect considering different closures and different levels of water efficiency improvement. On the one hand, the comparison of simulation results between short- and long-run closures could highlight the differences in the effectiveness and rebound effects of water efficiency improvement in the short- and long-term, which is important for formulating water policies. On the other hand, although the macro-economic impact would change qualitatively, and the rebound effect increased with the water efficiency, most previous studies used a single shock for water efficiency improvement, primarily by 5%. Distinct from these studies, we simulated the rebound effect of water efficiency improvement by 1%, 5%, and 10%, respectively. A set of equations based on Equations (9)–(16) were constructed in the CGE model to measure the rebound effect at the macroeconomic level.

4. Simulation Results

4.1. Macroeconomic Impact

The simulation results showed that improving water efficiency in the producing sector would positively impact China's economic growth. In the short-run closure, the gross domestic product (GDP) would grow by 0.0052%, 0.0258%, and 0.0293% if the water efficiency increases by 1%, 5%, and 10%, respectively (Row 1, Table 1). In the long-run closure, the GDP would grow by 0.0022%, 0.0108%, and 0.215% if the water efficiency increases by 1%, 5%, and 10%, respectively. The water efficiency improvement would effectively reduce the water utilization of sectors and lower their production costs, stimulating sectoral production and increasing investment. Hence, improving water efficiency could increase China's GDP. However, we can also find that the GDP increases in the short-run closures are much larger than those in long-run closures. In the short-run closure, holding the capital stock unchanged, GDP growth is derived from an increase in employment. In the long-run closure, employment is fixed, and GDP growth is derived from an increase in capital stock. Additionally, employment in the short-run closure has a larger percentage increase than the changes in capital stock in the long-run closure. As a result, the GDP increases in the short-run closure are larger than those in the long-run closure.

Table 1. Macro-economic impact of water efficiency improvement (%).

	Short-Run Closure			**Long-Run Closure**		
	1%	**5%**	**10%**	**1%**	**5%**	**10%**
GDP	0.0030	0.0149	0.0293	0.0022	0.0108	0.0215
CPI	−0.0007	−0.0033	−0.0066	−0.0002	−0.0010	−0.0020
Investment	0.0052	0.0258	0.0505	0.0023	0.0113	0.0226
Household consumption	0.0035	0.0173	0.0341	0.0020	0.0101	0.0202
Exports	−0.0009	−0.0044	−0.0084	0.0012	0.0058	0.0116
Imports	0.0025	0.0120	0.0233	0.0006	0.0028	0.0055
Employment	0.0023	0.0114	0.0223	0.0000	0.0000	0.0000
Labor price	−0.0007	−0.0033	−0.0066	0.0030	0.0149	0.0298
Capital stock	0.0000	0.0000	0.0000	0.0013	0.0064	0.0128
Capital price	0.0048	0.0240	0.0473	−0.0006	−0.0031	−0.0062

Source: ORANIG model simulation.

Water efficiency improvement would also have a positive impact on household consumption and investment. Improving water efficiency could reduce the production cost of sectors; it also lowers the consumer price index (CPI), which stimulates households to increase their consumption. GDP growth would also increase households' disposable income, thus promoting household consumption. In the short-run closure, household consumption would increase by 0.0035%, 0.0173%, and 0.0341% if the water efficiency increases by 1%, 5%, and 10%, respectively (Row 4, Table 1). In the long-run closure, household consumption would grow by 0.0020%, 0.0101%, and 0.202% if the water efficiency increases by 1%, 5%, and 10%, respectively. We found that the impact of water efficiency improvement on household consumption is much larger in the short-term as the GDP growth in the short-run closure is also greater. Moreover, the decrease in sectors' production costs would expand their output and raise their demand for capital, which leads to an increase in investment. Furthermore, the increases in investment in the short-run closure are also more significant than those in the long-run closure. For example, if water efficiency increases by 10%, the investment would rise by 0.0505% in the short-run closure and 0.0226% in the long-run closure (Row 3, Table 1). Therefore, the water efficiency improvement would have a larger positive impact on household consumption and investment in the short-run closure than in the long-run closure.

The impacts of water efficiency improvement on the factor market are significantly different for short- and long-run closures. Regarding the labor market, the water efficiency improvement would increase employment and reduce the nominal labor price in the short-run closure; the long-run closure holds the employment unchanged and raises the nominal labor price. As for the capital market, the water efficiency improvement would raise the nominal capital price in the short-run closure, as it assumes that the capital stock is unchanged. The long-run closure holds the actual capital price fixed and increases the capital stock utilized by the producing sectors. Hence, the water efficiency improvement would expand employment in the short term but increase the capital stock in the long term.

Improving water efficiency could increase exports in the long run because water efficiency improvement could reduce the production cost of export-oriented sectors, as many of them are water-intensive in China (e.g., steel, textile, and chemical product sectors). In the long run, the water is saved in nonproducing sectors, and capital prices drop almost in all producing sectors, which lowers their cost and enhances their competitiveness in the global market. Such positive impacts have exceeded the negative shocks of rising labor prices. Moreover, exports would decline significantly as water efficiency improvement increases (Row 5, Table 1). The export would increase by 0.0116% if water efficiency increases by 10%, which is almost ten times larger than the export increase resulting from the 1% efficiency improvement. However, in the short term, exports would decline as capital becomes expensive in response to economic expansion, and this negative impact is larger than the benefit from decreasing labor prices. Similarly, exports would decrease considerably with the water efficiency improvement. If water efficiency increases by 10%, exports would decline by −0.0084 in the short run. Therefore, the water efficiency improvement would raise exports in the long term but limit exports in the short term.

Water efficiency improvement may promote imports in both the short and long terms. Improving water efficiency reduces the production costs of various sectors while also lowering the labor price in the short-run closure and capital price in the long-run closure, reducing domestic prices and limiting imports. However, the economic expansion caused by water efficiency improvement would also stimulate the demand for imported commodities. If the economic expansion effect exceeds the substitution effect between domestic and imported goods, imports may increase. Table 1 shows that imports would increase under both short- and long-run closures. Hence, the impact of economic expansion on imports exceeds the price decrease caused by the reduction in capital and factor prices. If water efficiency increases by 10%, imports would increase by 0.0233% and 0.0055% in the short-run and long-run closures, respectively. Hence, the import increase is much larger in short-run closures than in long-run closures. With the same level of water efficiency improvement, the GDP increases in the short-run closure are more significant than those in the short-run closure. Hence, the water efficiency improvement would cause a larger increase in the demand for imported commodities in short-run closures than long-run closures. As a result, the water efficiency improvement would raise the import by a more considerable amount in the short term, relative to in the long term.

To summarize, water efficiency improvement would have different impacts on the macro-economy from the following perspectives: (1) the positive impacts on the GDP in the short term are larger than those in the long term; (2) the positive impacts on household consumption and investment in the short term are greater than those in the long term; (3) the water efficiency improvement would expand employment in the short term, but increase the capital stock in the long term; (4) the water efficiency improvement would raise the export in the long term, but deteriorate the export in the short term; and (5) the water efficiency improvement would raise the import by a larger amount in the short term, relative to in the long term.

4.2. Impact on Producing Sectors' Output

In addition to the impact on the macro-economy, water efficiency improvement would reduce the demand for water resources in the producing sector and the output of the water supply sector. The output of the water supply sector is almost equal to the summation of water consumption by households and sectors, without considering the international trade of water resources. In the short-run closure, the output of the water supply would decline by 0.4873%, 2.4409%, and 4.8932% if the water efficiency improves by 1%, 5%, and 10%, respectively (Figure 2). Hence, the water efficiency improvement could effectively reduce water consumption. We find that the decrease in the water supply output is much smaller than the volume of water efficiency improvement. As water efficiency boosts economic growth and stimulates sectoral production and household consumption, it may raise the demand of producing sectors and residents for water resources, referred to as the rebound effect in previous studies. The rebound effect would partly offset the saving of water resources due to water efficiency improvement.

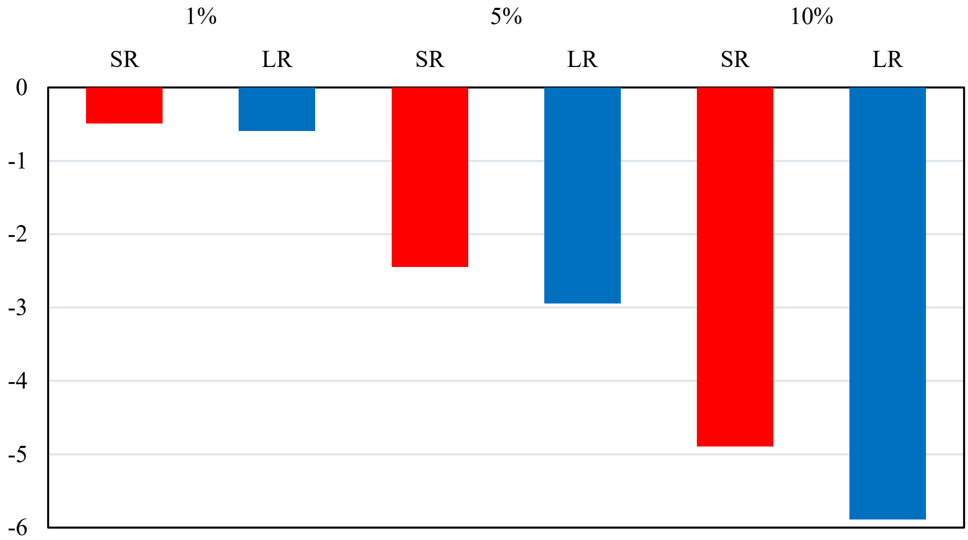

Figure 2. Impact of water efficiency improvement on the output of water supply sector (%). Note: The SR (LR) is short for the short-run (long-run) closure. Source: ORANIG model simulation.

In the long-run closure, the water supply output would decline by 0.5885%, 2.9426%, and 5.8856% if the water efficiency improves by 1%, 5%, and 10%, respectively (Figure 2). The larger reductions in water supply in the long-run closure indicate a smaller rebound effect of water efficiency improvement. Compared with the long-run closure, the water efficiency improvement would cause more significant GDP growth in the short-run closure. Thus, the demand for water resources would increase significantly, resulting in a more significant rebound effect and offsetting the saving of water resources more. Hence, in terms of saving water resources, the effectiveness of water efficiency improvement in the long run is more significant than in the short run.

In addition to the water supply sector, water efficiency improvement would benefit most producing sectors in the short closure. On the one hand, the water efficiency improvement would reduce the sectors' production costs and stimulate production. On the other hand, the water efficiency improvement would also increase sectoral employment and benefit more labor-intensive industries. As a result, most sectors would experience increased output (Figure 3). Among them, Construction (CON), Hotel and dining (HTD), Research (RSH), Non-metal products (NMP), and Technology service (TKS) exhibited the greatest production increase. All are downstream sectors of the water supply sector that are notably labor-intensive. Moreover, the Water and environment service (WPS) and Electricity supply (ELS) would experience a decrease in output. As these are the upstream sectors of the water supply sector, the water efficiency improvement would reduce the output of the water supply sector, consequently reducing the demand for water, environmental services, and electricity.

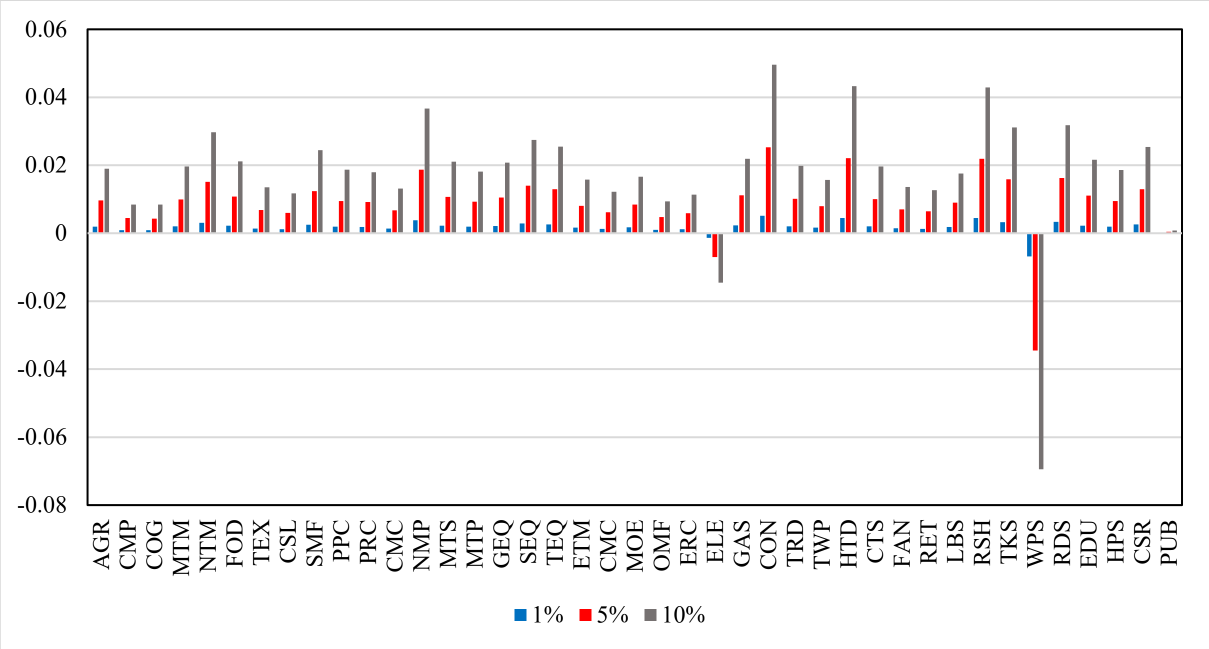

Figure 3. Impacts on the output of producing sectors excluding water supply under the short-run closure. Source: ORANIG model simulation.

Compared with the short-run closure, the positive impacts of water efficiency improvement are much smaller in the long-run closure (Figure 4). Although water efficiency improvement could stimulate sectoral production by reducing the production cost in the long run, the impact mechanism is significantly different. Assuming that employment is fixed, water efficiency improvement would increase the sectors' capital stock and raise their output. As capital accounts for a smaller share in the primary factor than labor in China, the increase in capital stock would lead to a smaller increase in the GDP for the long-run closure. Hotel and dining (HTD), Research (RSH), Other manufacturers (OMF), Construction (CON), and Culture, sport, and recreation (CSR) would have the greatest production increase. In addition to Water and environmental service (WPS) and Electricity supply (ELS), Coal mining products (CMP) would also experience a decrease in output as it is the downstream sector of Electricity supply (ELS), which is negatively affected by the decreasing output of the water supply sector.

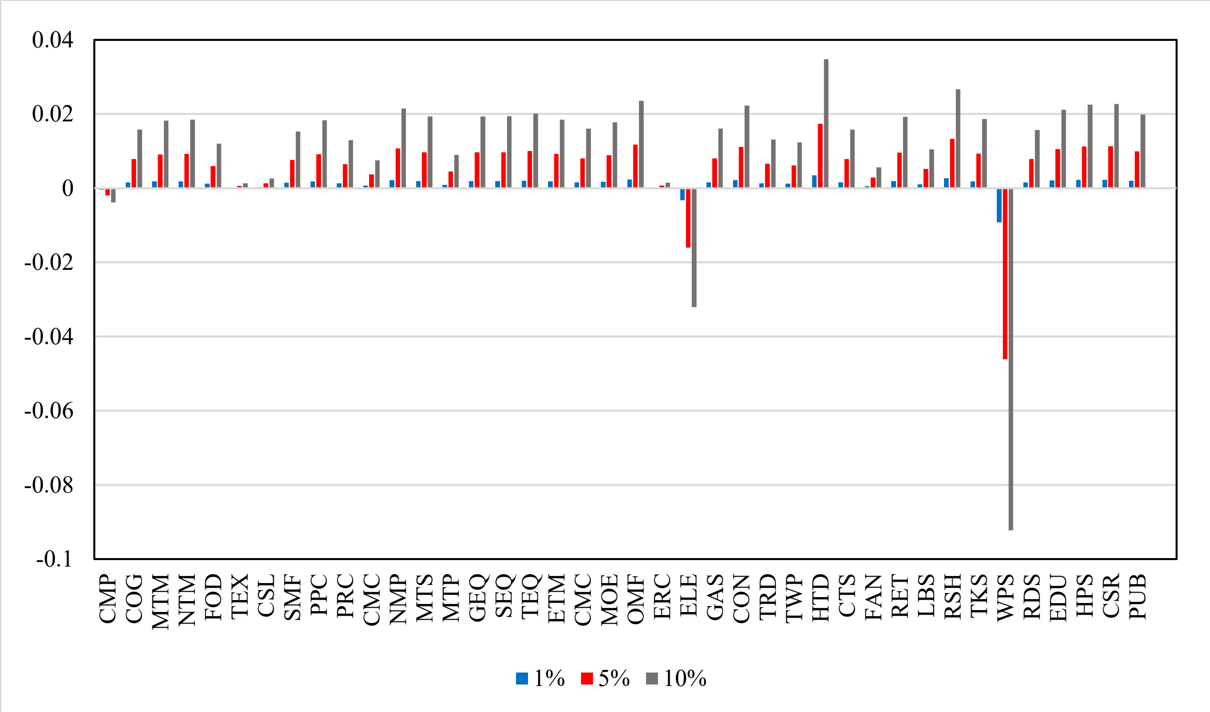

Figure 4. Impacts on the output of producing sectors excluding water supply under the long-run closure. Source: ORANIG model simulation.

4.3. Rebound Effect of Water Efficiency Improvement

The decrease in the output of the water supply sector indicates a significant rebound effect of water efficiency improvement. Table 2 shows the rebound effect of the water efficiency improvement calculated using Equations (9)–(16) with different closures and different efficiency improvement levels. We calculated two indicators for the rebound effect from the macro-level (R_T) and production side (R_P). The R_T exceeds 13 in the short-run closures and 5 in the long-run closures, suggesting that the total rebound effect is significant in both the short- and long-run closures. The total rebound effect increases as the water efficiency improves. It is worth noting that the total rebound effect in the short-run closure is much larger than in the long-run closure. This is because, as the positive impact on the macro-economy in the long-run closure is lower than in the short-run closure, the water demand stimulated by the economic expansion in the former is also smaller. Therefore, improving water efficiency would save more water resources in the long-run closure, generating a smaller total rebound effect.

Table 2. Rebound effect of water efficiency improvement under different closures.

	Short-Run Closure			**Long-Run Closure**		
	1%	**5%**	**10%**	**1%**	**5%**	**10%**
R_t	13.1096	13.6153	14.2236	5.1443	5.1502	5.1576
R_P	0.4310	1.1811	2.0868	0.1226	0.1296	0.1352

Source: ORANIG model simulation.

Compared with the total rebound effect, the rebound effect from the production side is much smaller. In the short-run closure, the R_P is estimated to be 0.4310, 1.1811, and 2.0868 if the water efficiency improves by 1%, 5%, and 10%, respectively. Although the total rebound effect is significant, the rebound effect from the production side is small. This is because the water efficiency improvement directly reduces the water consumption of the producing sectors. This result also suggests that the total rebound effect is primarily derived from the incremental water consumption from the demand side, including households, investors, and the government. The water efficiency improvement would reduce the demand of producing sectors for water resources and reduce the price of water resources, which would increase the water consumption by households, investors, and the government. Hence, the rebound effect of water efficiency improvement from the consumption side surpasses the rebound effect from the production side. Moreover, the rebound effect from the production side in the short-run closure is greater than in the short-run closure.

5. Discussion

Most of the existing studies estimated the direct rebound effect for agriculture and irrigation systems [3,40,41], while only few studies have evaluated the economy-wide rebound effect of water efficiency improvement. However, water efficiency improvement would reduce the water consumption of agriculture, consequently lowering the water price and raising the water consumption of nonagriculture sectors and residents. Hence, these studies may over- or under-estimate the economic-wide rebound effect from the production side. For example, Fei et al. (2021) found that for a water efficiency improvement by 1%, the rebound effect of agriculture is 0.4931 in the short term and 0.6601 in the long term, which indicated the larger rebound effect for agriculture in the long term [28]. Comparably, in our study, the economy-wide rebound effect from the production side was estimated to be 0.4310 in the short run and 0.1226 in the long run for a water efficiency improvement by 1%. While the previous studies did not estimate the total economy-wide rebound effect of water efficiency improvement in China, Freire-González [6] demonstrated that the total economy-wide rebound effect in Spain would be 100.74% if the water efficiency improves annually by 50%. Our study also found that the total rebound effect is much more significant in both the short- and long-run closures.

The circular economy is a sustainable development strategy that concentrates on the high-efficiency utilization and recycling of natural resources, transforming the traditional growth model to the one characterized with the low consumption, low emission, and high efficiency [42–48]. In 2021, China's National Development and Reform Commission (NDRC) issued the Circular Economy Development Plan during the 14th five-years (NDRC, 2021) and announced that the water consumption per unit GDP will decline by 16% toward 2025, compared with 2020, through recycling and sustainably utilizing water resources. The improvement of water efficiency would reduce the water consumption of producing sectors and effectively save water resources. However, the rebound effect would weaken the water-saving effect of water efficiency improvement. Therefore, the policymakers should promote the construction of the circular economy and reduce the rebound effect [49–53]. For example, the water recycling facilities should be invested largely, and the uses of reclaimed water should be encouraged to reduce the consumption of fresh water. Water-intensive firms, such as car washers, golf courses, and artificial skiing resorts, should equip advanced water recycling appliances and use reclaimed water and rainwater in priority.

6. Conclusions and Policy Implications

Water efficiency improvement is necessary for ameliorating the severe water shortages in China. However, its effectiveness is restricted by the water rebound effect, which refers to the effect that the anticipated water resource savings from improved water efficiency may be partly or wholly offset or surpassed (called "backfire") by the increase in water demand. However, the economy-wide rebound effect of water efficiency improvement in China is poorly understood. This study explored the economy-wide rebound effect of water efficiency improvement in China based on a multi-sectoral computable general equilibrium model. This study contributes to the literature in two ways: First, to the best of our knowledge, this is the first study to specifically measure the economy-wide rebound effect of water efficiency for China in a comprehensive CGE model. Second, we can measure and decompose the economy-wide rebound effect and explore the mechanisms of this rebound effect at a large scale.

Our results showed that (1) the water efficiency improvement has vastly different impacts on the macro-economy. The positive impacts on the macro-economy in the short term are larger than those in the long term. Water efficiency improvement would expand employment in the short term but increase the capital stock in the long term. (2) Water efficiency improvement would effectively reduce the consumption of water resources by producing sectors and limit the output of the water supply sector. However, the rebound effect partly offsets the water savings from the water efficiency improvement. (3) The reductions in water supply in the long-run closure are much larger, which indicates a smaller rebound effect of water efficiency improvement. In terms of saving water resources, the effectiveness of water efficiency improvement in the long term is more significant than in the short run. (4) The total rebound effect in the short-run closure is much larger than in the long-run closure. The effect of water efficiency improvement is more significant in saving water resources in the long-run closure. (5) Compared with the total rebound effect, the rebound effect from the production side is much smaller. Hence, the total rebound effect is principally derived from the incremental water consumption by households, investors, and the government.

Despite the economy-wide rebound effect, the improvement of water efficiency could still benefit the economic growth and the saving of water resources, especially in the long term. China's government should continuously support the development of highly efficient water-saving technologies and reduce the rebound effect from the consumption side. First, the government should put forward the reform of water prices and construct a flexible water price system that could efficiently reflect the demand and supply relation in the water market. The property rights of water resources should be clearly defined. Second, the government should implement multiple measures to optimize the structure of water uses and promote water saving from the consumption side. For example, the government should improve water saving from the current water supply network and greening irrigation system, extend water-saving technologies and processes, and raise the utilization of water-saving appliances. Third, to reduce water consumption effectively, the water uses in households, by investors, and by the government should be further studied. Policies to promote households' willingness to save water resources and reduce water waste are also important. Lastly, a circular economy should be established by recycling, treating, and utilizing water resources, which could simultaneously alleviate the rebound effect and promote the economic growth.

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Appendix A

Table A1. Sectors in the CHINAGEM model.

Number	Sector	Abbreviation	Number	Sector	Abbreviation
1	Agriculture	AGR	22	Other manufacturing	OMF
2	Coal mining product	CMP	23	Equipment repair and recycling	ERC
3	Crude oil and gas	COG	24	Electricity supply	ELE
4	Metal mining	MTM	25	Gas supply	GAS
5	Nonmetal mining	NTM	26	Water supply	WTS
6	Food processing	FOD	27	Construction	CON
7	Textiles	TEX	28	Trade	TRD
8	Clothes, shoe, and leather	CSL	29	Transportation, warehouse, and post	TWP
9	Sawmill and furniture	SMF	30	Hotel and dining	HTD
10	Paper, printing, and cultural products	PPC	31	Computer and communication service	CTS
11	Petroleum and coke	PRC	32	Finance and insurance	FAN
12	Chemical product	CMC	33	Real estate	RET
13	Nonmetal product	NMP	34	Lease and business service	LBS
14	Metal smelting	MTS	35	Research	RSH
15	Metal products	MTP	36	Technology service	TKS
16	General equipment	GEQ	37	Water and environment service	WPS
17	Special equipment	SEQ	38	Residential service	RDS
18	Transportation equipment	TEQ	39	Education	EDU
19	Electrical machine	ETM	40	Health and public service	HPS
20	Communication equipment and computers	CMC	41	Culture, sport, and recreation	CSR
21	Meters and office equipment	MOE	42	Public administration	PUB

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