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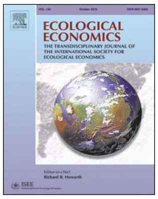

Analysis

The Agricultural Water Rebound Effect in China

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ABSTRACT

Although the water productivity of the agricultural sector in China continuously increased over the last twenty years, by improvements in irrigation technology, the total agricultural water use did not decline as expected, mainly due to continuous increases in agricultural output partially derived from technological progress. Thus, agricultural water use in China may experience a rebound effect. This study defines the water rebound effect (*WRE*) using macro-scale indicators of water use and water productivity, establishes a simplified direct comparison method using the contribution rate of technological progress, and evaluates the magnitude of the macro-scale water rebound effect in the Chinese agricultural sector using provincial panel data from 1997 to 2014. The magnitude of the agricultural *WRE* in China (1998–2014) is 61.49%. The northern and western regions of China experience a greater *WRE* than the southern and eastern regions, and the changes in the inter-annual *WRE* are distinct. These observations indicate that much of the expected water savings from efficiency improvement could be offset by increased water use for increased agricultural production due to technology enhancement. The control of water use growth is effective for reducing the water rebound effect. The study confirmed the existence of the agricultural *WRE* in China.

1. Introduction

Due to the limited supply, unbalanced distribution, and excessive consumption of water by the growing population and increasing economic development, China is facing severe water shortages. The northern part of the country has an average freshwater availability of 760 cubic meters per capita per year, 25% less than the internationally accepted threshold for water scarcity (Chai et al., 2014). As shown in Fig. 1, the agricultural sector accounts for > 60% of the water use in China. Improving the efficiency of water use is typically presented as an opportunity for large water savings, particularly in the agricultural sector (Dumont et al., 2013). The Chinese government strongly supports the development of irrigation technology and has implemented many water-saving irrigation measures with the objective of improving water productivity and reducing agricultural water use (Chai et al., 2014). Some progress has been made. As shown in Fig. 2, the water productivity of agricultural sector in China has increased continuously, from 2.93 Yuan/cu·m in 1997 to 5.77 Yuan/cu·m in 2014 (1990 prices). However, total agricultural water use did not decline as expected, mainly due to continuously increasing agricultural output (see Fig. 2). In an increasing number of places on Earth, water resources are used in a very efficient manner – with high agricultural water use efficiency – but water resources are also simultaneously being very quickly depleted (Hoekstra, 2013).

A concept used in energy studies, i.e., the "rebound effect", can help us more clearly quantify the effect of water productivity on water use. The "rebound effect" was first proposed by Jevons (1866), who found that more efficient steam engines not only reduced coal consumption but also resulted in a reduction in coal price, eventually increasing the demand for coal. This positive effect of energy efficiency on energy conservation has been questioned in economic circles (Binswanger, 2001; Sorrell and Dimitropoulos, 2008). The first scholars to study the rebound effect phenomenon in the economics literature were Brookes and Khazzoom (Brookes, 1990, 2000; Khazzoom, 1980). In the Khazzoom-Brookes hypothesis, they proposed that technological progress not only improves energy efficiency but also promotes economic growth and, thus, increases the demand for energy. This energy increment can partially offset the energy saved through improvement in energy efficiency. Following this proposal, theoretical and empirical research on energy rebound effects has developed rapidly and achieved

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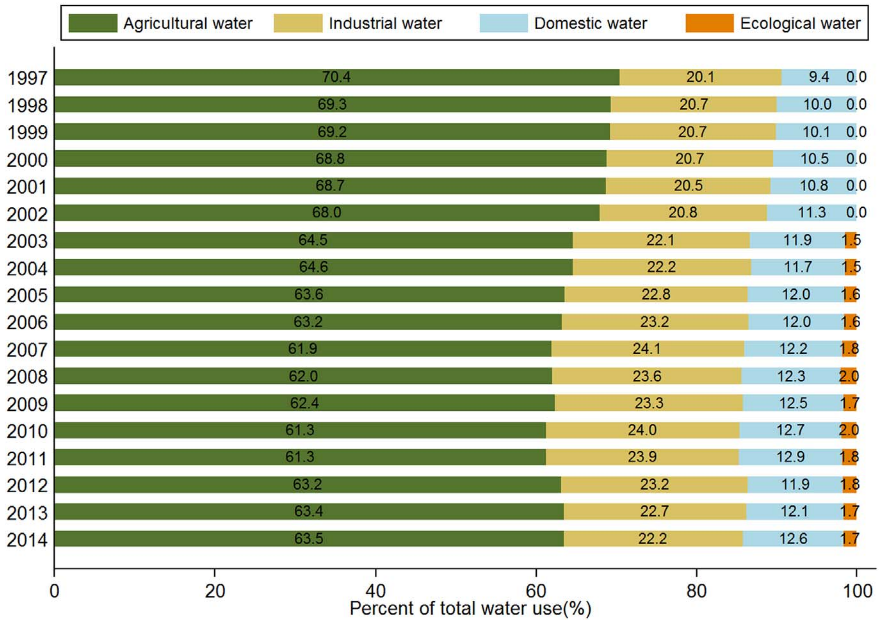

Fig. 1. Water use percentages in China from 1997 to 2014.
Data resources: China Water Resources Bulletin (1997, 1998, 1999) and China Statistics Yearbook (2006, 2015).

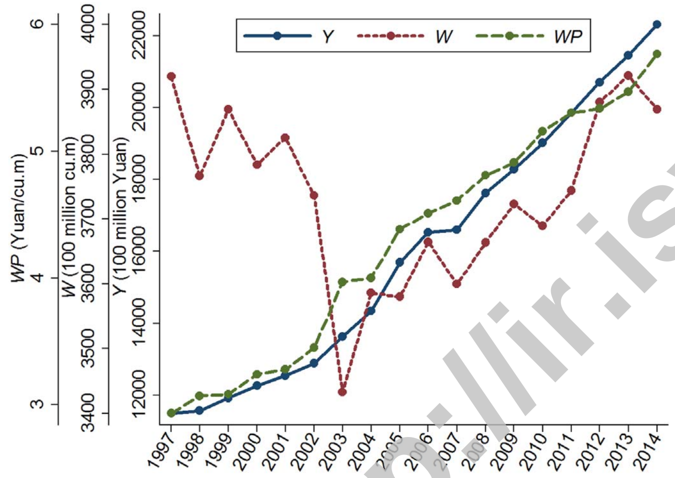

Fig. 2. Agricultural production and water use in China from 1997 to 2014.
Note: 1. *Y*: the gross output value of agriculture in 1990 prices (100 million Yuan); *W*: agriculture water use (100 million cu·m); and *WP*: agriculture water productivity (Yuan/cu·m), $WP = Y / W$.
2. Data resources: China Water Resources Bulletin (1997, 1998, 1999) and China Statistics Yearbook (1998–2015).

fruitful results (Alcott, 2005; Berkhout et al., 2000; Greening et al., 2000; Small and Van Dender, 2007). The energy rebound effect is estimated using various econometric methods and sample data. A common method is to estimate the energy rebound effect by estimating price elasticity or efficiency elasticity (Azevedo, 2014; Wang et al., 2012). For some countries or sectors where price does not truly reflect the supply and demand situation, some studies have estimated the energy rebound effect using the direct comparison method and the contribution rate of technological progress (Li and Han, 2012; Shao et al., 2014). Most of these studies confirm the existence of the rebound effect.

Agricultural water supply can also experience its own rebound effect (Berbel and Mateos, 2014). The European (2012) has recently identified this effect as a potential problem. Many researchers have analysed the effects of more efficient irrigation using theoretical model simulation or empirical comparative analysis, demonstrating that water use/consumption do not decrease or even increase following irrigation system improvement(Brinegar and Ward, 2009; Dagnino and Ward, 2012; Dinar and Zilberman, 1991; Ellis et al., 1985; García-Garizábal and Causapé, 2010; Huffaker, 2008; Huffaker and Whittlesey, 2000; Lecina et al., 2010; Peterson and Ding, 2005; Playán and Mateos, 2006; Qureshi et al., 2010; Rodríguez-Díaz et al., 2011; Scheierling et al., 2006; Ward and Pulido-Velazquez, 2008; Whittlesey, 2003). Although Dumont et al. (2013)query the usefulness of the rebound effect as a concept in the better management of water resources, some researchers have focused on water rebound effect in the past few years. Pfeiffer and Lin (2014) found that the shift to more efficient irrigation technology has increased groundwater extraction in western Kansas and indicated it is a rebound effect > 100%. Berbel and Mateos (2014) used a model to systematically analyse the conditions under which improved application uniformity of irrigation may yield increased water use and/or consumption. Water use has been found to decrease in all circumstances unless the irrigated area is expanded. Berbel et al. (2015) reviewed the literature regarding the water rebound effect and illustrate the conditions that may avoid the rebound effect with a case study in the Guadalquivir basin (southern Spain). They suggest that the keys for avoiding the rebound effect are (1) strict limitations placed on the size of the irrigated area, (2) the reduction of former water rights, and (3) the re-assignation of water savings to achieve environmental goals. Gomez and Perez-Blanco (2014) studied the conditions under which Jevons' Paradox in water use appears, building upon basic economic principles. The efficiency elasticity of water use contains three effects, namely the technical effect, cost effect and productivity effect. A positive elasticity indicates that Jevons' Paradox occurs. Loch and Adamson (2015) examined the anticipated impacts of the rebound effect on environmental and private irrigator water availability/use outcomes in the Murray-Darling Basin in Australia. Li and Zhao (2016) studied the role of water rights in limiting the rebound effect of LEPA irrigation in the High Plains Aquifer region of Kansas.

Research regarding the water rebound effect is ongoing; however, key issues remain unresolved. Although many previous researchers have observed the water rebound phenomenon in agriculture, empirical research regarding calculation of the magnitude of the water rebound effect is very limited. Examining and quantifying the agricultural water rebound effect are critical for confirming the existence and severity of the rebound effect in agricultural water use. The greatest difficulty in calculating the water rebound effect is the definition and measurement of the key variables – conservation and efficiency of water use are highly variable with both research purpose and scale. To allow a rough approximation of the agricultural water rebound effect, we define it using macro-scale indicators of water use and water productivity, establish a simplified direct comparison method, and valuate the magnitude of the agricultural water rebound effect in China at the macro scale using provincial panel data. The conclusions reported in this study could provide useful information for better understanding the role of water conservation technology improvement in the discussion of agricultural water in China.

The remainder of this paper is organized as follows. Section 2 presents a theoretical analysis, which consists of the definition and formulation of the agricultural water rebound effect. Section 3 introduces the estimation method and data resources used to calculate the water rebound effect in China. Section 4 describes and analyses the results of empirical research. Section 5 provides some discussion. In the final section, we provide the primary conclusions and relevant policy recommendations.

2. Theoretical Analysis of the Agricultural Water Rebound Effect

2.1. Definition of the Water Rebound Effect

Although water is significantly different from energy, some evidence now exists that the rebound effect also occurs in the context of water use, and some researchers have developed a model analysing why improved irrigation efficiency increases water use/consumption (Contor and Taylor, 2013; Gomez and Perez-Blanco, 2014; Huffaker, 2008). Previous studies have found that rebound water use in the irrigation sector may arise mainly from two mechanisms. One is the hydrological mechanism: increased efficiency frequently causes water consumption by crops to increase along with increased crop yield because the improved irrigation system more precisely and uniformly matches the water needs of a crop (Brinegar and Ward, 2009; Dagnino and Ward, 2012; Lecina et al., 2010; Lopez-Gunn et al., 2012; Perry, 2007; Qureshi et al., 2010; Scheierling et al., 2006; Ward and Pulido-Velazquez, 2008). The other mechanism is the economic mechanism, i.e., Jevons' Paradox in water use (Gutierrez-Martin and Gomez Gomez, 2011; Pfeiffer and Lin, 2014). The former is peculiar to water and focuses on the change in water consumption before and after irrigation system improvement, and the latter is similar to the energy rebound effect, focusing on farmer behavioural adjustment in response to improved efficiency.

The hydrological mechanism of the water rebound effect is technical, viz., due to the improved irrigation system's innate attributes, the yield increases. The economic mechanism of the water rebound effect is artificial: it depends on the irrigators' choices and can be controlled through water use policy. Water productivity is the key variable. Irrigators care about economic profits and their irrigation costs based on the quantity of water used rather than about water consumption. This study focuses on the water rebound effect arising from the economic mechanism and definite water rebound effect (*WRE*) as follows: More efficient irrigation technology generally increases the “efficiency” of a unit of water (water productivity: output obtained per volume of water use), but it also changes a farmer's profit maximization problem and can lead to changes in yields, crop choices, crop rotation patterns, and/or expanded irrigated acreage, i.e., more water use. The agricultural *WRE* measures rebound water use relative to the potential water savings from improving water productivity due to enhancement of irrigation techniques.

2.2. Formulation of the Agricultural Water Rebound Effect

Since the theory of the energy rebound effect was proposed, two different methods of estimating the magnitude of the rebound effect have been developed. One method is to directly compare the demand before and after the improvement of efficiency, and the other method focuses on demand elasticity and often uses price elasticity as a proxy variable (Berkhout et al., 2000; Freire-Gonz and Lez, 2011; Ouyang et al., 2010; Saunders, 2000; Sorrell and Dimitropoulos, 2008; Wang and Lu, 2014).

The agricultural *WRE* can be measured directly as the difference between expected and actual water savings from water productivity improvements, which can be defined as follows:

$$WRE = \frac{EWS - AWS}{EWS} \times 100\% = \frac{RWU}{EWS} \times 100\% \tag{1}$$

where *WRE* represents the agricultural water rebound effect, *EWS* represents the expected (calculated or anticipated) water savings after irrigation technique enhancement and *AWS* represents the actual water savings after irrigation technique enhancement. Thus, $RWU = EWS\text{-}AWS$ represents rebound (or additional) water use in response to increasing “efficiency” of a unit of water.

A *WRE* of 10% indicates that 10% of the expected water savings are offset by increased water use. In particular, a *WRE* of 0% indicates full achievement of water conservation, whereas a *WRE* of 100% represents complete failure of water conservation. Additionally, if the *WRE* is > 100%, irrigation efficiency improvement measures can even increase water use, which is called the “backfire effect”.

The other measurement of the water rebound effect is as follows:

$$WRE = 1 + \eta_{WP}(W) = 1 + \frac{\partial \ln W}{\partial \ln WP} \tag{2}$$

where *W* is water use, *WP* is water productivity, and $\eta_{WP}(W)$ is the water productivity elasticity of water use.

Under certain assumptions, measures of the rebound effect can be obtained from the estimation of price elasticity (Freire-Gonz and Lez, 2011; Saunders, 2000; Sorrell and Dimitropoulos, 2008; Wang and Lu, 2014):

$$WRE = 1 - \eta_{P_W}(W) - 1 = -\frac{\partial \ln W}{\partial \ln P_W} \tag{3}$$

where P_W is the water price, and $\eta_{P_s}(W)$ is the price elasticity of water use.

3. Methods and Data

3.1. The Agricultural Water Rebound Effect Estimation Method

As mentioned in Section 2.2, two different methods exist to estimate the rebound effect: performing a direct comparison and using price elasticity as a proxy variable; the latter method is the primary method used to calculate the energy rebound effect. The price elasticity method is based on a well-functioning market of agricultural water resources. Price elasticity can serve as a proxy for efficiency elasticity only when the agricultural water price can fully reflect the demand for agricultural water resources. However, the agricultural water price in China is determined by the government and has been very low and stable for many years. Therefore, the price elasticity method is inappropriate for estimating the agricultural water rebound effect due to the poorly functioning water resources market in China. Although the direct comparison method is not very precise, it is an alternative method for estimating the agricultural water rebound effect at the macro-economic level in China.

In Eq. (1), rebound estimation requires the estimation of the expected water savings (*EWS*) from efficiency enhancement and of the rebound water use (*RWU*) in response to a reduction in the cost of water use. The relationship between water use and water productivity is as following:

$$W = \frac{\mathrm{Y}}{WP} \tag{4}$$

where *W* is the total agricultural water use, *Y* is total agricultural output, and *WP* is agricultural water productivity at the macro-economic level.

Assume that agricultural water use, agricultural output and water productivity in year t are W_t, Y_t, and WP_t, respectively. According to Eq. (4), the change in agricultural water use from year t − 1 to year t (ΔW_t) can be decomposed as follows:

$$\Delta W_t = W_t - W_{t-1} = \frac{Y_t}{WP_t} - \frac{Y_{t-1}}{WP_{t-1}} = \frac{Y_t \Delta WP_t}{WP_t WP_{t-1}} + \frac{\Delta Y_t}{WP_{t-1}} \tag{5}$$

According to Eq. (5), the change in agricultural water use can be decomposed into two parts: the change in agricultural water use due to the change in water productivity ($\frac{Y_t \Delta WP_t}{WP_t WP_{t-1}}$) and the change due to agricultural growth ($\frac{\Delta Y_t}{WP_{t-1}}$). Changes in water use due to growth in agricultural outputs are caused not only by technological progress, i.e., improved input efficiency, but also by increases in input. ρ is assumed to be the proportion of change due to technological progress, rebound water use (*RWU*) to be equal to $\frac{\rho \Delta Y_t}{WP_{t-1}}$, and the expected agricultural water savings from water productivity improvement (*EWS*) to be equal to $\frac{Y_t \Delta WP_t}{WP_t WP_{t-1}}$. Thus, the estimation formula for the agricultural water rebound effect within t years can be expressed as follows:

$$WRE = \sum \frac{\rho \Delta Y_t}{WP_{t-1}} / \sum \frac{Y_t \Delta WP_t}{WP_t WP_{t-1}} \times 100\%. \tag{6}$$

According to Eq. (6), the water rebound effect is the increase in the ratio of the water use caused by agricultural output growth to the expected water savings resulting from water productivity improvement. Here, both the improvement in water productivity and the growth in agricultural output are caused by enhanced irrigation techniques.

According to Eq. (6), another important factor in estimating the rebound is to precisely estimate the contribution rate of technological progress (ρ). The Hicks-neutral Cobb-Douglas production function of agriculture is as follows:

$$Y_{it} = A_{it} W_{it}^{\alpha} X_{1it}^{\beta} X_{2it}^{\gamma} \cdots X_{nit}^{\eta} = A_i e^{rt} W_{it}^{\alpha} X_{1it}^{\beta} X_{2it}^{\gamma} \cdots X_{nit}^{\eta} \tag{7}$$

where $A_{it} = A_i e^{rt}$ is the Hicks-neutral technological parameter; r denotes the technological progress rate; Y_{it}, W_{it} and X_{1it}, X_{2it}, …, X_{nit} represent output, water input and other inputs, such as labour and land, respectively; and α, β, γ, …,η denote the output elasticities of W_{it}, X_{1it}, X_{2it}, …, X_{nit} respectively.

If we take the natural logarithm of Eq. (7), we obtain:

$$ln\, Y_{it} = ln\, A_i + rt + \alpha\, ln\, W_{it} + \beta\, ln\, X_{1it} + \gamma\, ln\, X_{2it} + \cdots + \eta\, ln\, Y_{nit}. \tag{8}$$

Thus, by using input-output data for China's agricultural production, *r* can be estimated. The contribution rate of technological progress can be expressed as follows:

$$\rho = \frac{r}{g_Y} \tag{9}$$

where g_Y is the growth rate of agricultural output.

Finally, using Eq. (6), we can calculate China's agricultural water rebound effect at the macro-economic level.

3.2. Data Resources

We use provincial panel data to estimate the rebound effect of agricultural water in China. Considering the consistency and availability of statistical data, Taiwan, Hong Kong and Macao are not included in this study. The employed data include 5 agricultural inputs, water (*W*), labour (*LB*), land (*LD*), machinery (*M*), fertiliser (*F*), and agricultural output (*Y*) of China's 31 provinces or autonomous regions from 1997 to 2014.

We adopt the real gross output value of agriculture (100 million Yuan) at the 1990 price level to represent agricultural output (*Y*). These data are calculated based on the gross agriculture output value at current prices and gross agriculture product deflators, i.e., the ratio of the gross agriculture product at current prices to the same variable at constant prices. Agriculture water use (100 million cu·m) represents the agricultural water input (*W*). The population of agricultural labourers (10 thousand people) is used to represent the agricultural labour input (*LB*). The total sown areas of farm crops (1000 ha) is used to assess the agricultural land input (*LD*). The total power of agricultural machinery (10,000 kw) represents the agricultural machinery input (*M*). The consumption of chemical fertiliser (10,000 tons) represents agricultural fertiliser (*F*).

Table 1
Descriptive statistics of the variables.

Variable	N	Mean	Sd	Min	Max
Y	558.00	517.38	403.78	19.37	2007.53
W	558.00	120.52	98.23	8.18	561.75
LB	558.00	960.99	749.35	37.09	3558.60
LD	558.00	5073.68	3521.94	196.10	14,378.30
M	558.00	2363.12	2479.63	77.55	13,101.40
F	558.00	158.49	131.59	2.50	705.75

This table presents the summary statistics of the variables in 31 provinces from 1997 to 2014. *Y* represents the real gross output value of agriculture (100 million Yuan). *W* represents agriculture water use (100 million cu·m). *LB* represents the population of agricultural labourers (10 thousand people). *LD* represents the total sown areas of farm crops (1000 ha). *M* represents the total power of agricultural machinery (10,000 kw). *F* represents the consumption of chemical fertiliser (10,000 tons).

Almost all the agricultural input-output data are from the China Statistics Yearbook (1998–2015). Part of the agriculture water use data is from the China Water Resources Bulletin. Part of the population data regarding agricultural labourers is from the Statistics Yearbook of the provinces, municipalities and autonomous regions. Table 1 shows summary statistics of the variables.

4. Results and Analysis

4.1. The Contribution Rate of Technological Progress

The first step to calculate the agricultural water rebound effect is to estimate the technological progress rate (*r*) and determine the contribution rate of technological progress (ρ). As described in Section 3, we estimate the agricultural production function model (8) to determine the *r* value. Eq. (8) was estimated with various specifications, and the results are presented in Table 2.

The first column of Table 2 presents the ordinary least squares estimation of the pooled model of Eq. (8). Most of the input variables have significant coefficients. (Only *lnM* has insignificant coefficients.) The coefficient estimate corresponding to the time t suggests that the technological progress rate (*r*) is 0.018. Although the pooled model estimates have some attractive features, they fail to recognize the panel characteristics of the data. A panel regression with fixed effects is more appropriate if the provinces have relatively stable, unobserved variables affecting their agricultural output. Column (2) of Table 2 reports a fixed effects panel regression, whose estimated coefficients on the determinants of output leverage are markedly different from their pooled model counterparts. The estimated coefficients of Variables *t* and *lnF* are different, although also significant at the 1% level, and the statistical significance of *lnM* is greater than the estimates in column (1). These results suggest that the technological progress rate (*r*), the coefficient estimate corresponding to the time t, is 0.024. The prominent difference between columns (1) and (2) in Table 2 are the estimated coefficients for *lnW*, *lnLB* and *lnLD*, which indicate that water and labour have negative effects (though insignificant) on agricultural output and that the output elasticity of land is positive (0.326) in the fixed effect panel model. Negative regressive coefficients of *lnW* and *lnLB* do not support the economic theory. However, they reflect the fact that in China, the agricultural water and labour input declined due to rapid economic development and the upgrading of the industrial structure during these years. The fixed effects on agricultural output are well justified: a F-test for the joint significance of the unobserved effects in

Table 2
Estimation of agricultural production function coefficients.

Variable	(1)	(2)	(3)	(4)
	Pooled model	Fixed Effects model	FE (robust standard errors)	FE (Driscoll-Kraay standard errors)
t	0.018***	0.024***	0.024***	0.024***
	(6.24)	(10.67)	(3.56)	(6.45)
lnW	0.113***	− 0.068	− 0.068	− 0.068*
	(5.33)	(− 1.63)	(− 0.69)	(− 1.74)
lnLB	0.205***	− 0.017	− 0.017	− 0.017
	(6.68)	(− 0.31)	(− 0.16)	(− 0.18)
lnLD	− 0.404***	0.326***	0.326*	0.326***
	(− 8.76)	(5.23)	(1.70)	(3.38)
lnM	0.014	0.117***	0.117	0.117***
	(0.48)	(3.95)	(1.04)	(4.95)
lnF	0.938***	0.366***	0.366***	0.366***
	(25.91)	(7.65)	(3.20)	(3.87)
Constant	− 33.188***	− 47.785***	− 47.785***	− 47.785***
	(− 5.73)	(− 9.88)	(− 3.44)	(− 6.15)
Observations	558	558	558	558
Adjusted R^2	0.927	0.849	0.857	
Within R^2		0.859	0.859	0.859

The dependent variable is *lnY*. *lnY*: natural log of agriculture output value; *t*: year; *lnW*: natural log of agriculture water use; *lnLB*: natural log of agricultural labourers; *lnLD*: natural log of crops sown areas; *lnM*: natural log of agricultural machinery power; *lnF*: natural log of chemical fertiliser consumption.

*** Represent significance at 1% level with *t*-values in parentheses.

* Represent significance at 10% level with *t*-values in parentheses.

column (2) rejects the hypothesis that these terms are equal across all provinces (F (30, 521) = 147.14; pr = 0.000).

A Modified Wald test for group-wise heteroscedasticity in fixed-effect regression models rejects the hypothesis that variances are equal for all provinces ($\chi^2(31) = 1882.38$; pr = 0.000). The robust standard errors are shown in parentheses under those for the fixed effects estimates in column (3) of Table 2. Because T (1997–2014) is not very large (18), we proceed under the assumption that serial correlation is not a significant effect in our study. Pesaran's test of cross-sectional independence rejects the hypothesis that cross-sections are independent (Pesaran's test = 3.235, Pr = 0.0012). The fourth column gives the fixed effects regression with Driscoll-Kraay standard errors. The coefficient estimates and Within-R^2 in columns (2), (3) and (4) are the same, but the standard errors are very different. In column (3), the robust standard errors are less than in column (2), which is a conservative estimate considering heteroscedasticity and serial correlation. In column (4), the Driscoll-Kraay standard errors, which consider heteroscedasticity, serial correlation and cross-sectional dependence, are very different from column (3). This suggests that cross-sectional dependence substantially affects the inferences one would draw. Therefore, we will use Eq. (5) to estimate the technological progress rate. Although the standard errors are different, the estimated coefficients for t are all statistically significant, < 1%, indicating that the estimated value of the technological progress rate, *r*, (0.024) is robust. After determining the *r* value, the technological progress contribution rate,ρ, can be calculated using Eq. (9).

4.2. Estimated Results of the Agricultural Water Rebound Effect

Using the contribution rate of technological progress, ρ, rebound water use and the agricultural water rebound effect could be calculated according to Eq. (6). The results are shown in Table 3 and Fig. 3. China's agricultural water rebound effect in 1998–2014 is 61.49%; viz., 61.49% of water savings initiated by efficiency improvement are offset by increased water use for agricultural production growth.

The agricultural water rebound effect in Shanghai Municipality (1998–2014) is highest at 165.71%. The second highest is Tianjin Municipality (149.17%). *WREs* are > 100% in several other provinces, including Jiangsu Province (133.82%), Chongqing Municipality (117.70%), Jiangxi Province (115.24%), and Anhui Province (110.33%). These results indicate that efficiency improvement measures can actually increase water use in those provinces; this phenomenon is called “Jevons' paradox” (rebound > 100%). Among these provinces, Shanghai Municipality is notable. The growth rate of agricultural output (*GY*) in Shanghai Municipality is negative (− 1.80%), however its growth rate of agricultural water use (*GW*) is also negative (− 2.84%), with much larger absolute values than *GY*. Therefore, the growth rate of agricultural water productivity ($GWP = GY - GW$) in Shanghai Municipality is positive, and the calculated *WRE* is positive. Tibet Autonomous Region is also notable because the agricultural *WRE* is negative (− 429.95). Negative *WRE* can have several causes, and we return to this issue in Section 5.2. The Tibet Autonomous Region is the only province in which *GW* (2.63%) is less than *GY* (3.69%), and therefore, its *GWP* is negative. That does not meet the hypotheses under which the agricultural water rebound effect is calculated. The expected water saving (*EWS*) is negative due to negative *GWP*, and thus calculated *WRE* is negative; however, this result is nonsensical. Except in these provinces, the agricultural *WRE* (1998–2014) in all of the other 24 provinces fell within the range of 0%–100%. The agricultural water rebound effect in the Ningxia Autonomous Region (1998–2014) is 28.29%, representing the lowest of all positive *WRE* values. These results indicate that a partial rebound effect is evident in these provinces. Water savings did not fully meet expectations; a portion of the expected water savings is offset by added water use to varying degrees.

The difference in the agricultural water rebound effects across these regions can be seen more clearly in Fig. 3, which shows that among the 7 large regions of China, East China's agricultural *WRE* is 74.79%, which is the highest value, and Northwest China's agricultural *WRE* is 46.49%, representing the lowest value. In addition to Northwest China, the agricultural *WREs* of North China (47.35%) and Central China (50.38) are much lower than the average level in China (61.49%). The agricultural *WREs* of the other regions, Southwest China (60.62%), Northeast China (61.49%) and Southern China (62.78%), are similar to the average level. These results are expected because western and northern China experience the most serious water scarcity; therefore, agricultural water use growth is limited and the agricultural *WRE* is lower. Irrigation water generally cannot be transferred, and thus supply shortages occur. This is one difference between the water and fossil-fuel rebound effects.

The variation in Chinese agricultural water rebound effects over time is shown in Table 4. From 1998 to 2014, *GW* was always less than *GY*, and *WP* maintained a positive growth rate. However, *GWP* was relatively low in some years (1999, 2001, 2004, 2007, 2009 and 2012), while *GW* was very similar to *GY*. Those are precisely the years in which a substantial water rebound effect or even a backfire was observed. The correlations among these variables are shown more clearly in Fig. 4, in which a strong negative correlation between *WRE* and the gap between *GW* and *GY* is clear. In addition, the lowest agricultural *WRE* appeared in 2003 because agricultural water use was greatly reduced in that year, as shown in Fig. 2. Indeed, annual *WRE* is sensitive to change in agricultural water use that partly depended on natural factors, such as large-scale rainfall. The changes in inter-annual *WRE* are very sharply illustrated in Fig. 4.

To observe the general trend of change in agricultural water rebound effects over time in China, we demonstrate the change in the total *WRE* for every 3 years in Fig. 5. From a holistic perspective, the agricultural water rebound effects in China demonstrate a periodic fluctuation. This trend is not very distinct due to the short time scale of this study. However, all three *WREs* (eastern, central and western regions) clearly experienced a minimum value in 2001–2003 and began to increase after 2003. The increasing trend lasted into 2007–2009 in the eastern regions and 2010–2012 in the western regions, later changing into a decline in both regions. Additionally, the *WRE* in the central

Table 3
Agricultural water rebound effect of provinces in China (1998–2014).

Region	*GY* (%)	*GW* (%)	*RWU* (100 million cu·m)	*EWS* (100 million cu·m)	*WRE* (%)
Beijing	0.81	− 4.67	5.60	13.70	40.83
Tianjin	1.92	0.39	5.01	3.36	149.17
Hebei	3.92	− 1.67	65.24	152.85	42.68
Shanxi	4.36	0.62	15.41	27.42	56.21
Inner Mongolia	5.74	− 0.37	61.29	156.37	39.20
Liaoning	4.85	− 0.32	37.84	80.14	47.21
Jilin	4.65	0.59	32.27	54.47	59.24
Heilongjiang	5.86	1.64	94.65	158.92	59.56
Shanghai	− 1.80	− 2.84	7.09	4.28	165.71
Jiangsu	2.97	1.24	115.60	86.39	133.82
Zhejiang	1.64	− 2.46	45.20	79.07	57.16
Anhui	2.79	0.58	57.51	52.13	110.33
Fujian	3.38	− 1.42	44.05	88.30	49.89
Jiangxi	2.84	0.60	61.84	53.66	115.24
Shandong	3.85	− 1.65	70.42	160.49	43.88
Henan	4.26	− 2.35	58.60	160.66	36.47
Hubei	4.22	0.85	61.48	84.65	72.63
Hunan	3.69	− 0.90	86.20	164.28	52.47
Guangdong	2.29	− 1.11	100.67	145.05	69.40
Guangxi	3.72	− 0.18	88.90	149.08	59.63
Hainan	5.39	− 1.06	15.21	41.71	36.46
Chongqing	3.03	1.03	8.63	7.33	117.70
Sichuan	3.99	0.52	53.53	76.19	70.26
Guizhou	5.07	0.03	21.40	45.21	47.32
Yunnan	5.37	− 0.50	45.37	109.78	41.33
Tibet	2.63	3.69	11.04	− 2.57	− 429.95
Shaanxi	5.98	− 0.07	23.73	59.20	40.08
Gansu	4.96	− 0.13	40.87	86.13	47.45
Qinghai	5.60	− 0.26	9.25	22.63	40.89
Ningxia	6.17	− 2.43	30.96	109.42	28.29
Xinjiang	5.82	1.38	202.97	409.53	49.56
China	3.90	− 0.08	1574.81	2560.94	61.49

GY: Growth rate of agricultural output (%); *GW*: Growth rate of agricultural water use (%); *RWU*: Rebound water use (100 million cu·m); *EWS*: Expected water saving (100 million cu·m); *WRE*: Water rebound effect (%).

regions maintains a fluctuating growth trend after 2003. Generally, over the last ten years, the agricultural *WRE* of eastern China has been the highest of the three regions in China and that of the western region has been the lowest. The main reason for this result is the uneven distribution of China's water resources, decreasing from southeast to northwest. Even so, the agricultural water rebound phenomenon is prominent in all three regions.

5. Discussion

5.1. Comparison of Results

Although there is no known research calculating water rebound effects at any scale, many researchers have analysed the effects of more efficient irrigation using model simulation or empirical comparative analysis and shown that efficiency improvements do not always reduce

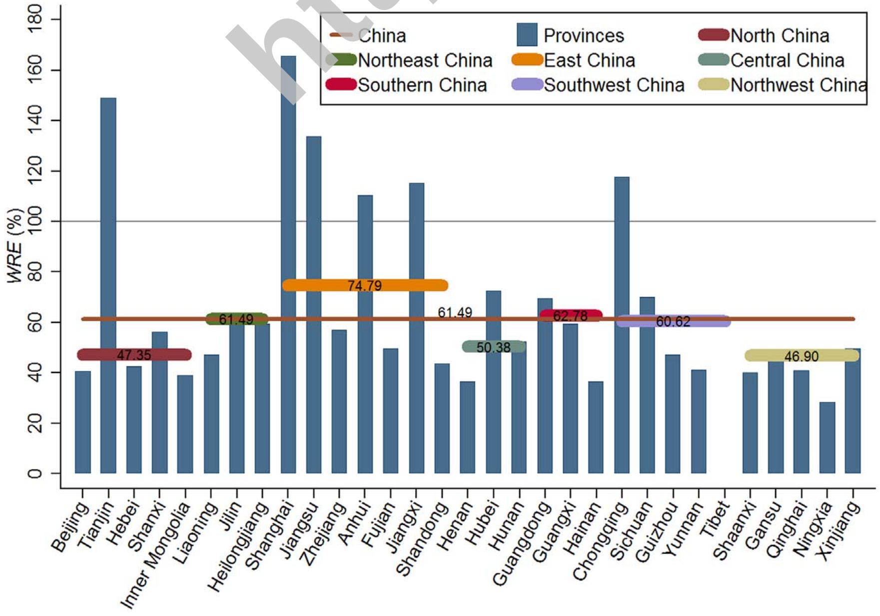

Fig. 3. Regional agricultural water rebound effects in China (1998–2014).
Note: 1. North China contains Beijing, Tianjin, Hebei, Shanxi and Inner Mongolia (*WRE* = 47.35%). Northeast China contains Liaoning, Jilin and Heilongjiang (*WRE* = 61.49%). East China contains Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi and Shandong (*WRE* = 74.79%). Central China contains Henan, Hubei and Hunan (*WRE* = 50.38%). Southern China contains Guangdong, Guangxi and Hainan (WRE = 62.78%). Southwest China contains Chongqing, Sichuan, Guizhou, Yunnan and Tibet (*WRE* = 60.62%). Northwest China contains Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang (*WRE* = 46.90%).
2. The agricultural *WRE* of Tibet is negative, which is not shown in the figure.

Table 4
Agricultural water rebound effect in China over time.

Year	*GY* (%)	*GW* (%)	*RWU* (100 million cu·m)	*EWS* (100 million cu·m)	*WRE* (%)
1998	0.58	− 3.99	95.79	176.35	54.32
1999	3.09	2.70	93.21	15.40	605.27
2000	2.80	− 2.24	95.61	195.53	48.90
2001	2.26	1.11	93.24	44.40	210.02
2002	2.70	− 2.37	94.49	194.40	48.61
2003	5.55	− 8.47	93.61	516.77	18.12
2004	5.18	4.36	85.85	29.56	290.40
2005	9.00	− 0.16	91.43	343.53	26.61
2006	5.17	2.33	89.53	105.47	84.88
2007	0.40	− 1.79	89.47	79.63	112.36
2008	6.00	1.76	90.39	158.62	56.99
2009	3.66	1.61	90.92	77.10	117.94
2010	3.98	− 0.92	92.55	185.39	49.92
2011	4.28	1.46	91.84	106.82	85.97
2012	4.20	3.59	93.16	23.82	391.06
2013	3.55	1.06	96.25	98.94	97.28
2014	3.91	− 1.35	97.45	209.18	46.59

GY: Growth rate of agricultural output (%); *GW*: Growth rate of agricultural water use (%); *RWU*: Rebound water use (100 million cu·m); *EWS*: Expected water saving (100 million cu·m); *WRE*: Water rebound effect (%).

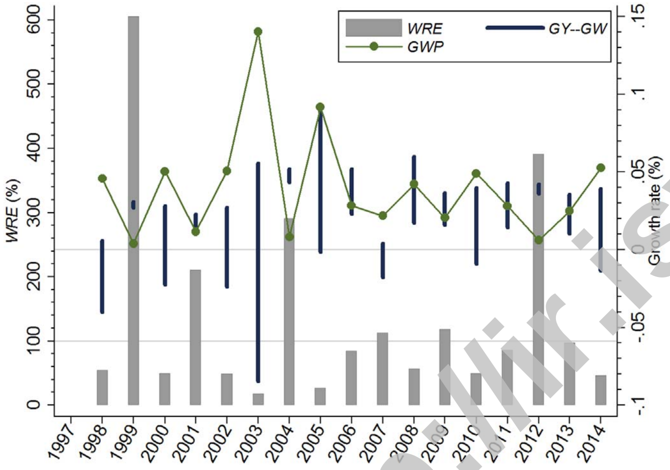

Fig. 4. Annual agricultural water rebound effects in China (1998–2014).
Note: 1. *WRE*: Water rebound effect (%); *GY*: Growth rate of agricultural output (%); *GW*: Growth rate of agricultural water use (%), and *GWP*: Growth rate of agricultural water productivity (%), $GWP = GY - GW$.
2. The upper end of the navy vertical bar represents *GY* and the lower end represents *GW*.

overall water use. These studies are summarized in Table 5.

We extend the past work as follows: 1) unlike previous researchers who empirically investigated the effect of irrigation system improvement on water use/consumption/depletion/extraction at the farm or basin scale, we evaluate the performance of agricultural water conservation practices as a whole at the macro scale. 2) We consider not only increase in water use but also non-realized water savings following improvements in irrigation efficiency. Most previous studies that have observed the rebound phenomenon have found, primarily at the basin scale, that water consumption, water use, both of those, or water demand increase (or do not decrease) following implementation of more efficient technology (Brinegar and Ward, 2009; Contor and Taylor, 2013; Dagnino and Ward, 2012; Ellis et al., 1985; Fernandez Garcia et al., 2014; Lecina et al., 2010; Pfeiffer and Lin, 2014; Rodríguez-Díaz et al., 2011; Ward and Pulido-Velazquez, 2008). Although those results are thought-provoking, they suggest that water use does decrease, but part of this water savings is offset because various aspects of efficiency improvement are not ideal. In addition, some previous studies found that water use/consumption decreases after improvements to irrigation

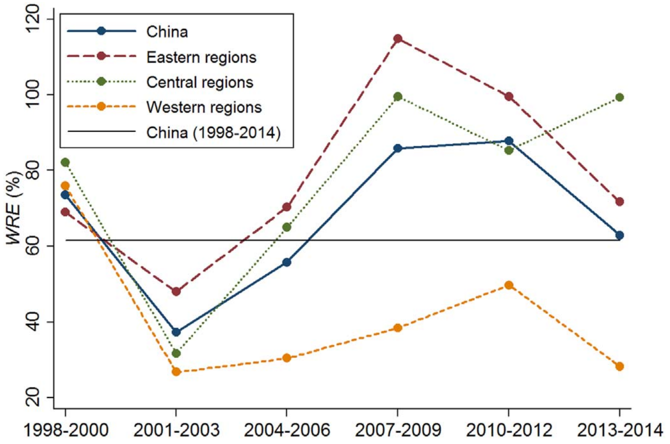

Fig. 5. The change in the agricultural water rebound effects in China over time.
Note: 1. The eastern regions contain 12 provinces or autonomous regions, viz., Liaoning, Beijing, Tianjin, Hebei, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, Guangxi and Hainan. The central regions contain 9 provinces or autonomous regions, viz., Shanxi, Inner Mongolia, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei, and Hunan. The western regions contain 10 provinces or autonomous regions, viz., Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang, Chongqing, Sichuan, Yunnan, Guizhou, and Tibet.

system efficiency but that actual water savings are less than expected (Gutierrez-Martin and Gomez Gomez, 2011; Lopez-Gunn et al., 2012). 3) We defined *WRE* as non-realized savings in resource use relative to the potential savings from efficiency improvements and calculated its magnitude in China. Although the rebound phenomenon in the context of agricultural water use has been observed across the globe, few studies have related the effect of improved irrigation efficiency to water savings in terms of the rebound effect and many of them are theoretical research (Berbel et al., 2015; Berbel and Mateos, 2014; Contor and Taylor, 2013; Gomez and Perez-Blanco, 2014; Pfeiffer and Lin, 2014). In addition, some studies conclude that water use decreases following the adoption of water conservation technology (Jackson et al., 2010; Törnqvist and Jarsjö, 2012; Xu et al., 2011). This paper provides another research perspective regarding this new, uncommon, ambiguous and debatable research.

5.2. Magnitude of the Rebound Effect and Its Connotation

Agricultural *WRE* is generally expressed as a percentage, which is usually between 0% and 100%. We can classify *WRE* according to its magnitude (see Table 6), and after rearranging Eq. (6), we generate another formula for *WRE* using growth rate.

$$WRE_t = \frac{\rho \Delta Y_t}{Y_t} / \frac{\Delta WP_t}{WP_t} = \rho GY_t / GWP_t = \rho GY_t / (GY_t - GW_t) \times 100\% \tag{10}$$

The magnitude of *WRE* and the corresponding relations among these variables can be seen in Table 6. As noted, if water savings did not fully meet expectations, a portion of the expected water savings are offset by added water use. As such, *WRE* values are between 0% and 100%, and a partial rebound is said to occur. This assumes that ρ*GY* is less than *GWP and* (1 − ρ)*GY* is less than *GW*, where ρ*GY* is with respect to the growth rate of the agricultural output derived from technology progress, which also improves water productivity. As discussed in Section 3.1, agriculture output growth is caused not only by technological progress but also by other factors, such as the growth of labour, machinery and fertiliser input. (1 − ρ)*GY* is with respect to the growth rate of agricultural output derived from the growth of other input factors besides technology progress. And if it is equal to the growth rate of agricultural water use, while the growth rate of agricultural output derived from technology progress (ρ*GY*) is equal to the growth rate of water productivity (*GWP*), a water rebound effect of 100% (Full rebound) will occur, indicating complete failure of water savings. In

Table 5
Summary of the results of previous research.

Literature	Location	Method	Measures	Water-saving effects
Ellis et al. (1985)	Texas High Plains	Alinear programming framework	Adoption of new technologies	Annual water use changes very little.
Ward and Pulido-Velazquez (2008)	Upper Rio Grande Basin of North America	An integrated basin-scale analysis	A series of water conservation policies	Water use unlikely reduce and water depletions can actually increase.
(Brinegar and Ward, 2009)	Upper Rio Grande Basin of Colorado, New Mexico, and Texas, USA.	A dynamic, nonlinear programming model	Several potential public subsidies of drip irrigation	Less water applied to crops and more water consumed by crop.
(Lecina et al., 2010)	Riegos del Alto Aragón in interior Spain	A conceptual approach, based on water accounting and water productivity	Irrigation modernization	Water depletion and water use increase.
Gutierrez-Martin and Gomez Gomez (2011)	GenilCabra irrigated area in the Guadalquivir valley (South Spain)	A preference revelation model	Efficiency in the use of water is improved under different scenarios	The potential water savings are overcome by increasing water demand.
Rodríguez-Díaz et al. (2011)	A typical Andalusian irrigation district in southern Spain	Performance indicators	Irrigation modernization	The amount of water diverted for irrigation to farms reduced, consumptive use increased.
Dagnino and Ward (2012)	A sub-basin in North America's Rio Grande	A programming model	Conversion from surface to drip irrigation.	The demand for water depleted by crops increase.
Lopez-Gunn et al. (2012)	Alicante and Almería in Spain	Comparison	Irrigation system improvement	Real saving is less than theoretical saving.
Contor and Taylor (2013)	Eastern Snake River Plain of Idaho, USA	A mathematical demand function	Irrigation efficiency improvement	Field delivery of irrigation water reduces but consumptive use increases.
Pfeiffer and Lin (2014)	Western Kansas	Econometric analysis	Irrigation system improvement	Groundwater extraction has increased
Fernandez Garcia et al. (2014)	Five irrigation districts of Andalusia, Southern Spain	Performance indicator comparison	Irrigation system improvement	Water diverted for irrigation reduce, but irrigation water demand increase.

contrast, a 0% water rebound effect will arise when the growth rate of the agricultural output is zero and full achievement of expected water savings is achieved. Additionally, if a water rebound effect is > 100%, water productivity improvement measures can even increase water use; this phenomenon is called the backfire effect. Although several researchers have indicated that overall water use may increase after efficiency improvements, and Pfeiffer and Lin (2014) clearly state that a rebound effect of over 100% occurs, estimating rebound by comparing water use change before and after efficiency improvement is not reasonable. Because efficiency improvements only contribute a portion of the growth in agricultural output, water use growth for other reasons should not be defined as rebound water use derived from efficiency improvements.

In special cases, the *WRE* value is negative; this can be called 'super conservation'. Thus, the actual amount of water savings is greater than the expected savings. Theoretically, this phenomenon should occur only when agricultural output decreases with efficiency improvements. If the agricultural product has the same properties as the Giffen good,[1] for which a decrease in price yields a reduction in demand, or other factors have a greater and opposite influence on the agricultural product, such as industrial structure upgrading and transformation from agriculture to another industry in the area, the agricultural output decreases when water productivity improves and *WRE* is less than zero. As discussed in Section 4.2, agricultural *WRE* in the Tibet Autonomous Region is calculated as −429.95; however, that estimate does not represent super conservation. The estimate is instead nonsensical because when $EWS \le 0$ or $GWP \le 0$ or $GY \le GW$, as shown in Table 6, the *WRE* can be calculated to have any value. In this case, the implied hypothesis of the water rebound effect calculation, that water productivity has been improved, is not met, so the calculated result is meaningless. This judgement is consistent with empirical research regarding the energy rebound effect.

6. Conclusion

This paper defines the macro-scale agricultural water rebound effect and uses the direct comparison method to measure the magnitude of the agricultural water rebound effect in China. This study focuses on the water rebound that arises from farmer behaviour adjustment in response to improved efficiency and on the definite water rebound effect (*WRE*) at the macro scale as rebound water use relative to the potential water savings from improving water productivity due to irrigation technique enhancement. Considering the irrigation water market situation in China, where water price does not truly reflect the supply and demand situation, we establish a simplified direct comparison method based on the contribution rate of technological progress to the calculated macro-scale agricultural water resource rebound effect in China from 1998 to 2014 using provincial panel data. The empirical results indicate a partial rebound effect in Chinese agricultural water use, with a magnitude for the entire nation (1998–2014) of 61.49%, indicating that 61.49% of the expected water savings from efficiency improvement could be offset by increased water use for agricultural production growth due to technology enhancement. The northern and western regions of China experience a greater water rebound effect than the southern and eastern regions, likely because water scarcity is more serious and water use growth more limited in the northern and western regions.

The results reveal the existence of the agricultural water rebound effect in China, its differences among regions, and its variation over time. This study extends past work as follows: 1) We estimate the magnitude of the water rebound effect on the macro scale and reveal

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[1] For some goods, the demand decreases when the price is reduced. Such goods are referred to as Giffen goods, after the nineteenth-century economist who first noted this phenomenon.

Table 6
Types of agricultural water rebound effect.

Type	*WRE* (%)	*AWS* vs *EWS*	*GY* vs *GWP* (%)	*GY* vs *GW* (%)
Backfire	$WRE > 100$	$AWS < 0$	$\rho GY > GWP > 0$	$(1-\rho)GY > GW > 0$
Full rebound	$WRE = 100$	$AWS = 0$	$0 < \rho GY = GWP$	$0 < (1-\rho)GY = GW$
Partial rebound	$0 < WRE < 100$	$0 < AWS < EWS$	$0 < \rho GY < GWP$	$0 < (1-\rho)GY < GW$
Zero rebound	$WRE = 0$	$0 < AWS = EWS$	$\rho GY = 0$	$\rho GY = 0$
Super conservation	$WRE < 0$	$AWS > EWS > 0$	$\rho GY < 0$	$\rho GY < 0$
nonsense	–	$\mathrm{EWS} \leq 0$	$GWP \leq 0$	$GY \leq GW$

WRE: Water rebound effect (%); *AWS*: Actual water saving (100 million cu·m); *EWS*: Expected water saving (100 million cu·m); *GY*: Growth rate of agricultural output (%); *GWP*: Growth rate of agricultural water productivity (%); *GW*: Growth rate of agricultural water use (%).

the severity of agricultural water rebound in China. 2) We examine the magnitude of the water rebound effect and reveal that even if the rebound does not rise to the level of a backfire or Jevons' Paradox, a rebound effect of 0%–100% is also a matter of concern. 3) We clarify the connotation of water rebound effect, viz., that only a portion of the increase in water use derived from agricultural output growth can be seen as rebound water use due to irrigation technology enhancements.

The results obtained from this study may have important policy implications. They indicate that water saving policies aimed at improving water productivity are not as effective as expected. China cannot consider water-saving irrigation technological enhancement as the only approach to achieve water-savings targets or solve water scarcity problems. In assessing the role of irrigation system improvement in reducing agricultural water use, the rebound effect should be considered. Additionally, the Chinese government may consider developing and implementing some accompanying policies to mitigate the agricultural water rebound effect. On the one hand, to support rapid economic growth and maintain social stability, China has implemented water pricing reforms relatively slowly. China's low, fixed agricultural water price policies conflict with its water conservation efforts and add to the difficulty in achieving agricultural water-savings targets. The government should promote the development of the agricultural water market so that the agricultural water price could reflect its real costs and scarcity. On the other hand, comparing with the water-savings strategy focusing on promoting water productivity, an agricultural water quota control policy is fundamental for sustainable water use in China. If quotas were in place, legally, the increases in ‘water productivity’ would automatically follow. According to the analysis in Section 4.2, the agricultural *WRE* is lower in regions with more serious water scarcity. Water quotas can limit the agricultural water rebound effect and guarantee water savings achievement through irrigation efficiency improvement.

Finally, we have applied the direct comparison method at the macro scale, a method that can be applied to estimate the water rebound effect when the price of water is unknown or shows non-market characteristics. The contribution rate of technological progress is used in this method to represent the proportion of rebound water use from technological progress. This method results in two issues: the effectiveness of the estimate of the contribution rate of technological progress and the rationality of using technological progress to represent water productivity improvement. Hence, future studies should develop a more reasonable methodology to estimate the water rebound effect. In addition, this study only considers the direct water rebound effect of the agricultural sector in China. Given data availability, this study could be extended by estimating the indirect and economic range water rebound effects. Research on decomposing the water rebound effects, observing the main path by which water use rebounds, and providing specific policy advice for controlling the water rebound effect and guaranteeing water sustainability are also necessary.

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