Will Technological Progress Lead to the Rebound Effect of Agricultural Water: A Case Study of Groundwater Over-Exploitation in North China Plain

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This research is financed by Projects of the National Social Science Foundation of China (19BGJ171).

Abstract. Water-saving technology is an important measure to alleviate water shortage, but technical efficiency may lead to the increase of agricultural water by promoting economic development, resulting in the rebound effect of agricultural water. Taking the groundwater over-exploitation area in the North China Plain as an example, the DEA model was used to calculate the technical efficiency and calculate the rebound effect of agricultural water caused by technological progress. The Tapio decoupling model was used to estimate the decoupling state of agricultural water and agricultural output value. The results show that there is a rebound effect of agricultural water in the groundwater over-exploitation area of the North China Plain from 2010 to 2020, with an average value of 64.1%. Beijing has the most positive water-saving effect, while Tianjin, Shandong and Henan have a "backfire effect", and Hebei has a partial rebound. The relationship between agricultural water and the agricultural output value is in the strong and weak decoupling states, and there is a weak negative decoupling state somewhere. Based on this, optimize the agricultural input structure; carry out comprehensive water-saving measures; pay attention to water-saving and stable production.

Keywords. agricultural water; rebound effect; North China Plain; DEA model; Tapio decoupling model

1 Introduction

Water shortage in China is a serious threat to agricultural production, so it is necessary to promote water-saving technology to improve irrigation efficiency. Water-saving technology progress refers to the use of advanced agricultural technologies to promote agricultural productivity[1]. China has promoted water-saving irrigation as a revolutionary measure[2]. Although China's water-saving irrigation area increased from 15,050 thousand hectares in 1999[3] to 37,796 thousand hectares in 2020, agricultural water only decreased from 386.9 billion m^3 in 1999 to 361.2 billion m^3 in 2020. The fact that the water-saving effect is not significant indicates that agricultural water may have a rebound effect. The "rebound effect" originates from energy research. Technological progress improves machine efficiency and reduces energy usage, but it also reduces energy prices, which leads to the substitution effect and income effect and increases energy demand[4]. At present, there are two definitions of the "rebound effect of agricultural water" in academic circles: the first view emphasizes that the water-saving effect is partially offset by the new water use[4][5][6][7]; the second view emphasizes that water-saving

MSIEID 2022, December 09-11, Chongqing, People's Republic of China

DOI 10.4108/eai.9-12-2022.2327596

technologies have increased total agricultural water[8][9]. These differences come from definitions of water-saving technology. The second view can be regarded as a special case of the first one. Previous studies have shown that the effect of agricultural water in China shows a worsening trend[10], and there is a rebound effect of water resource utilization with 61.49%, and significant differences among provinces[11]. The rebound effect of agricultural water in northern and western China is larger than that in southern and eastern China[12]. The rebound effect of agricultural water also generally exists in the over-exploitation area of groundwater in Hebei Province[1]. Nonetheless, the studies have not clarified the relationship between the agricultural water demand caused by technological progress and the theoretical amount of water saving brought by water-saving technology, nor have they classified the rebound effect of agricultural water caused by technological progress. In this paper, a measurement framework for the rebound effect of water use is constructed, and the rebound effect of agricultural water is further subdivided according to the theory of water demand and supply, in order to clarify the degree of the rebound effect of water use and the theoretical mechanism of rebound effect caused by technological progress. The DEA model was used to estimate the rebound effect of agricultural water. The Tapio decoupling model was used to measure the decoupling degree of water consumption and agricultural output value, which is of great significance for reflecting the water-saving effect of water-saving technologies, supporting precise management of groundwater over-exploitation, and promoting sustainable agricultural development. Furthermore, the empirical findings of this research work could have important implications for farmers in terms of fully understanding groundwater over-exploitation consequences and the importance of water for their performance.

2 Methodology

2.1 Study Site

The North China Plain is located to the east of the Taihang foothills and north of the Yellow River, covering all the plains of Beijing, Tianjin and Hebei Province, and the plains north of the Yellow River in Henan and Shandong provinces[13]. The North China Plain is the main grain-producing area in China, and irrigation mainly depends on groundwater. The problem of groundwater over-exploitation is increasingly prominent, with an area of 180,000 km^2 of groundwater over-exploitation and a cumulative groundwater deficit of 1800 m^3[14]. Over-exploitation of groundwater seriously threatens water security and food security. In the long run, it is not sustainable to rely on groundwater to guarantee food production[15][16]. At present, the local government is promoting some measures by developing water-saving technology, replacing groundwater resources, and changing planting structures [14].

2.2 Data

The data on technical efficiency, rebound effect, and the decoupling effect was obtained from the China Statistical Yearbook and the statistical yearbooks of the above five regions. The rest of the data were obtained from China Water Yearbook.

2.3 Methods

2.3.1 Measurement of Technical Efficiency

(1) Model Description

The DEA-BCC model was used to estimate the technical efficiency. The equation is as follows[17][18]:

$$\min\left[\theta-\varepsilon\left(\sum_{r=1}^{t}s_r^{+}\right)+\left(\sum_{i=1}^{m}s_i^{-}\right)\right] \tag{1}$$

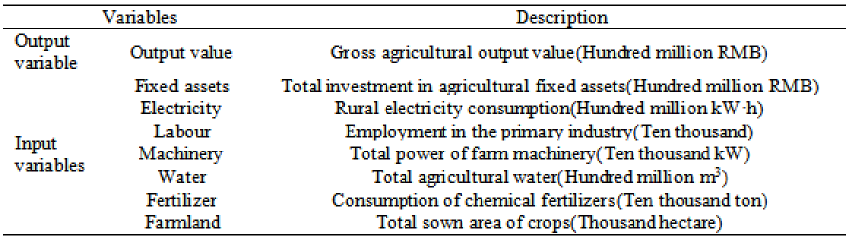
$$\sum_{j=1}^{n}\lambda_j x_{ij}+s_i^{-}=\theta x_{ij0} \tag{2}$$

$$\sum_{j=1}^{n}\lambda_j x_{ij}-s_r^{+}=y_{ij0} \tag{3}$$

$$\left(\lambda_j\geq 0; s_i^{-}\geq 0; s_r^{+}\geq 0;\ \ j=1,2,3\ldots n\right)$$

Where, θ is efficiency; s_i^{-} is redundancy; s_j^{+} is output deficiency; ε is a higher order infinitesimal quantity; λ_j is the combined proportion of the j DMU in the effective DMU constructed concerning the DMU; n is the number of decision-making units; m and t are the numbers of input and output indicators; i and r are the input index and output index; x_{ij} is the input amount of the I DMU to the J input factor; y_{rj} is the value of the r output index in the j decision-making unit. Deep 2.1 is used to calculate the technical efficiency[1]. When the technical efficiency is 1, the investment at the current technical level is completely effective. The closer it is to 1, the higher the efficiency of resource input.

(2) Variables



Variables		Description
Output variable	Output value	Gross agricultural output value(Hundred million RMB)
Input variables	Fixed assets	Total investment in agricultural fixed assets(Hundred million RMB)
	Electricity	Rural electricity consumption(Hundred million kW·h)
	Labour	Employment in the primary industry(Ten thousand)
	Machinery	Total power of farm machinery(Ten thousand kW)
	Water	Total agricultural water(Hundred million m^3)
	Fertilizer	Consumption of chemical fertilizers(Ten thousand ton)
	Farmland	Total sown area of crops(Thousand hectare)

Fig. 1. Description of Variables

2.3.2 Calculation of Rebound Effect

The definition of the agricultural water rebound effect is as follows[2]:

$$WRE=\frac{RWU}{EWS}=\frac{EWS-AWS}{EWS}\times 100\% \tag{4}$$

WRE is the rebound effect of agricultural water, EWS is the expected amount of water saving after the improvement of water-saving technology, RWU is the absolute value of the rebound amount of agricultural water, and AWS is the actual amount of water saving after the improvement of water-saving technology.

The agricultural water intensity WE can be expressed as the ratio of the total agricultural water W to the total agricultural output value Y:

$$WE = \frac{W}{Y} \tag{5}$$

The theoretical amount of water saving:

$$M_t = \left(WE_{t-1} - WE_t\right) \times Y_t \tag{6}$$

M is the theoretical amount of water saving, and t is the time. $M_t>0$ means the theoretical amount of water saving brought by the improvement of water-saving technical efficiency. $M_t<0$ means the increase in water intensity.

The actual demand for water resources brought by technical efficiency:

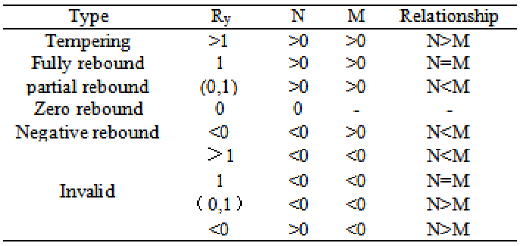
$$\mathrm{N}_t = T_y \times \left(Y_t - Y_{t-1}\right) \times WE_t \tag{7}$$

T is the technical efficiency of water saving. $N_t>0$ means the actual demand for water resources brought by the improvement of technical efficiency; $N_t<0$ indicates that the total agricultural output value decreases, and technological progress will not lead to water demand increasing by promoting economic growth.

The rebound effect of agricultural water caused by the improvement of water-saving technical efficiency:

$$R_y = \frac{N_t}{M_t} = \frac{T_y \times \left(Y_t - Y_{t-1}\right) \times WE_t}{\left(WE_{t-1} - WE_t\right) \times Y_t} \times 100\% \tag{8}$$

The categories of the water rebound effect are shown in Fig. 2.



Type	Ry	N	M	Relationship
Tempering	>1	>0	>0	N>M
Fully rebound	1	>0	>0	N=M
partial rebound	(0,1)	>0	>0	N<M
Zero rebound	0	0	-	-
Negative rebound	<0	<0	>0	N<M
Invalid	＞1	<0	<0	N<M
	1	<0	<0	N=M
	（0,1）	<0	<0	N>M
	<0	>0	<0	N>M

Fig. 2. Categories of water use rebound effect

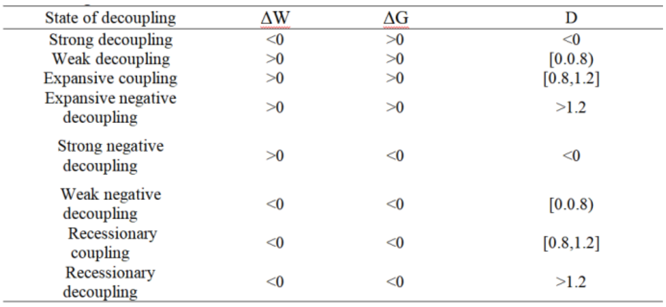
2.3.3 Measurement of the Decoupling stat

The Tapio decoupling model is used to measure the decoupling effect between resource consumption and economic development. The formula is as follows.

$$D_t = \frac{\Delta W}{\Delta G} = \frac{(W_a - W_b)/W_b}{(G_a - G_b)/G_b} \tag{9}$$

Where D is the decoupling effect, ΔW and ΔD are the rates of agricultural water consumption and agricultural output value, and t, a and b represent different periods.

The decoupling degree classification is in Fig. 3.



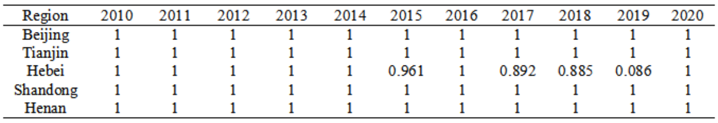
State of decoupling	ΔW	ΔG	D
Strong decoupling	<0	>0	<0
Weak decoupling	>0	>0	[0.0.8)
Expansive coupling	>0	>0	[0.8,1.2]
Expansive negative decoupling	>0	>0	>1.2
Strong negative decoupling	>0	<0	<0
Weak negative decoupling	<0	<0	[0.0.8)
Recessionary coupling	<0	<0	[0.8,1.2]
Recessionary decoupling	<0	<0	>1.2

Fig. 3. Relationship between agricultural water and agricultural output value

3 Results

3.1 Effects of Water Use Rebound

The technical efficiency is shown in Fig. 4.

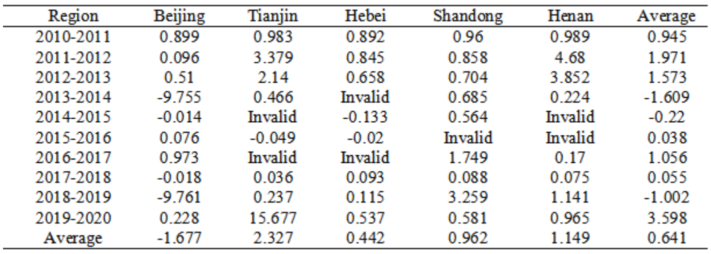


Region	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Beijing	1	1	1	1	1	1	1	1	1	1	1
Tianjin	1	1	1	1	1	1	1	1	1	1	1
Hebei	1	1	1	1	1	0.961	1	0.892	0.885	0.086	1
Shandong	1	1	1	1	1	1	1	1	1	1	1
Henan	1	1	1	1	1	1	1	1	1	1	1

Fig. 4. Technical efficiency by region.

From 2010 to 2020, the annual technical efficiency of Beijing, Tianjin, Shandong and Henan is all 1, indicating that the input has reached the optimal level. However, the technical efficiency of Hebei has a slight fluctuation. The technical efficiency of 2015, 2017, 2018 and 2019 did not reach 1, and showed a downward trend, indicating that the input structure of agricultural production factors was ineffective and input kept increasing, which led to the failure of technological progress to fully play the role of water saving.

The rebound effect is presented in Fig. 5.



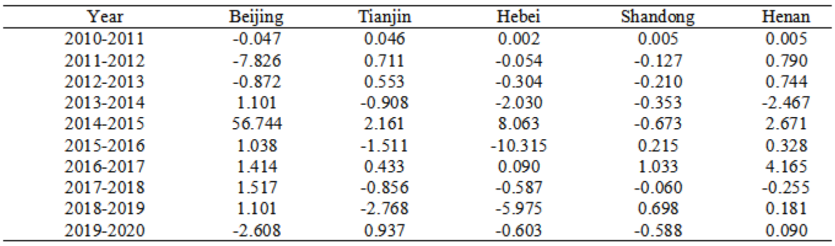
Region	Beijing	Tianjin	Hebei	Shandong	Henan	Average
2010-2011	0.899	0.983	0.892	0.96	0.989	0.945
2011-2012	0.096	3.379	0.845	0.858	4.68	1.971
2012-2013	0.51	2.14	0.658	0.704	3.852	1.573
2013-2014	-9.755	0.466	Invalid	0.685	0.224	-1.609
2014-2015	-0.014	Invalid	-0.133	0.564	Invalid	-0.22
2015-2016	0.076	-0.049	-0.02	Invalid	Invalid	0.038
2016-2017	0.973	Invalid	Invalid	1.749	0.17	1.056
2017-2018	-0.018	0.036	0.093	0.088	0.075	0.055
2018-2019	-9.761	0.237	0.115	3.259	1.141	-1.002
2019-2020	0.228	15.677	0.537	0.581	0.965	3.598
Average	-1.677	2.327	0.442	0.962	1.149	0.641

Fig. 5. Rebound effect of agricultural water

In general, there is a rebound effect of agricultural water in the groundwater over-exploitation area of the North China Plain. The average rebound effect of water use from 2010 to 2020 is 64.1%, indicating that the expected amount of water saving only reaches 35.9%, which is similar to the conclusion of the previous studies[1]. The water-saving effect of Beijing was obvious, with a negative rebound effect during 2013-2015 and 2017-2019, with an average rebound effect of -1.667. In general, technological progress did not lead to an increase in agricultural water. Shandong and Henan had the most serious rebound problem, with the rebound effect of agricultural water occurring every year. The average amount of water saving in Shandong was 3.8%, while the "tempering effect" occurred in Henan. The main reason is the improvement of irrigation efficiency caused by technological progress, which leads to the reduction of the marginal cost of agricultural water. Farmers who have reduced unit cost have surplus capital, and they improve agricultural production structure intending to maximize benefits and minimize cost, such as expanding planting area and changing seeds with high yield. Shandong and Henan have a high endowment of agricultural resources and developed agricultural industries. The change in irrigation behaviour of lots of farmers induced the rebound effect of agricultural water. In addition, the overall temperature in Henan showed an upward trend from 1961 to 2018, and the high temperature promoted farmers to increase irrigation water[19]. In Hebei, the rebound effect of water use was 44.2%, and the expected amount of water saving was 55.8%. Hebei Province is the most affected area by groundwater over-exploitation. To control the over-exploitation of groundwater, Hebei increased the establishment of water conservancy facilities in 2015, and the fixed assets investment increased. Although the high-tech irrigation facilities reduce the irrigation water per unit area, they promote the expansion of the planting area of crops with high water consumption. The theoretically expected water-saving amount is lower than the new water consumption, and the total agricultural water rises accordingly, resulting in the rebound effect of agricultural water. The rebound effect value of average agricultural water in Tianjin was the highest, and the actual agricultural water was 132.7% higher than the expected amount of water saving. Tianjin has a large annual variation of precipitation and frequent middle drought[20]. When drought occurred, the temperature increased and precipitation decreased. For example, the precipitation in 2011, 2013 and 2019 were 485.8mm, 411.5mm and 490mm. Under drought stress, farmers would increase irrigation times and water quotas to ensure yield and income, resulting in the rebound effect.

3.2 Effects of Decoupling

Fig. 6 shows the decoupling state in various regions.



Year	Beijing	Tianjin	Hebei	Shandong	Henan
2010-2011	-0.047	0.046	0.002	0.005	0.005
2011-2012	-7.826	0.711	-0.054	-0.127	0.790
2012-2013	-0.872	0.553	-0.304	-0.210	0.744
2013-2014	1.101	-0.908	-2.030	-0.353	-2.467
2014-2015	56.744	2.161	8.063	-0.673	2.671
2015-2016	1.038	-1.511	-10.315	0.215	0.328
2016-2017	1.414	0.433	0.090	1.033	4.165
2017-2018	1.517	-0.856	-0.587	-0.060	-0.255
2018-2019	1.101	-2.768	-5.975	0.698	0.181
2019-2020	-2.608	0.937	-0.603	-0.588	0.090

Fig. 6. the Decoupling state of agricultural water and agricultural output value.

In general, the total agricultural water and gross agricultural output value showed the optimal state, and the proportion of strong decoupling and weak decoupling was 66%. This indicates that the dependence of agricultural output value on total agricultural water is weakening and technological progress has become the driving force of agricultural economic development.

In Beijing, unsatisfactory recessionary coupling and recessionary decoupling occurred in 60%, which is similar to the conclusions of previous studies[14]. The main reason is that the rapid development of urbanization has significantly reduced the sown area and yield of grain in Beijing.

Tianjin shows weak decoupling. It appeared serious drought in 2017, and the spring temperatures rise, leading to a shortage of water resources. So agricultural water and the agricultural output value are greatly reduced, and the rate of economic decline is greater than the rate of resource consumption, Increased rainfall in Tianjin in 2014-2015 and 2019-2020 replenished river courses, reservoirs and groundwater for agricultural production.

Hebei has evolved from a relatively ideal weak decoupling state to an ideal strong decoupling state. The strong negative decoupling occurred in 2013-2014 due to the negative impact of groundwater over-exploitation, the destruction of the farming environment, and the significant increase of agricultural water. After comprehensive groundwater remediation in 2015, the groundwater over-exploitation was alleviated, and the technological progress from 2014 to 2016 brought a negative rebound effect. Subsequently, agricultural water and agricultural output also gradually stabilized.

The weak decoupling state and strong decoupling state appeared alternately in Shandong, indicating that the agricultural water did not decline steadily. In 2016-2017, there was a Recessionary coupling, which indicated that both agricultural output value and total water use were declining.

However, the "tempering effect" of agricultural water in 2016-2017 showed that the reduction of agricultural water brought by water-saving technology was completely offset by the increase of agricultural water brought by technological progress, which indicated that other water-saving measures, like the comprehensive reform of the price of agricultural water and the adjustment of the planting structure, have greatly reduced agricultural water. The agricultural water and agricultural output value in Henan are mainly Weak decoupling. The rebound effect of water consumption in Henan is 1.149, so the agricultural water in Henan is constantly increasing, and technological progress has not brought into full play the water-saving effect. The expansionary negative decoupling showed that both agricultural output value and agricultural water were increasing from 2014 to 2015, but the rate of agricultural water was greater than the growth rate of agricultural output value, and the increase of agricultural output value was over-dependent on agricultural water. Weak negative decoupling and recessionary decoupling occurred in 2015-2016 and 2016-2017, respectively. Although the total agricultural water in Henan was controlled, the agricultural output value declined year by year.

4 Conclusion

From 2010 to 2020, the total agricultural water in the groundwater over-exploitation areas of the North China Plain showed a downward trend. There is a general rebound effect of agricultural water of groundwater over-exploitation, and the average rebound effect is 64.1%. Beijing has the most obvious water-saving effect, Tianjin, Shandong and Henan have a "tempering effect", and Hebei has a partial rebound. The relationship between agricultural water and agricultural output value in this region is generally strong decoupling and relatively weak decoupling state, which indicates that the dependence of agricultural output value on agricultural water is weakening, and technological progress has become the driving force of agricultural economic development. It is suggested to optimize the agricultural input structure, rationally allocate the endowment of agricultural resources; carry out comprehensive water-saving measures; conserve water under the premise of stable grain production.

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