

Virtual water and its effect in Huaihe River basin: an analysis using a dynamic multi-region computable general equilibrium model

Jing Zhao, Jinhua Liu, Hongzhen Ni, Yong Zhao, Yuping Han and Zicheng Diao

ABSTRACT

A dynamic multi-region computable general equilibrium (CGE) model is used to analyze virtual water and its effect in the Huaihe River basin, which includes Jiangsu, Anhui, Shandong and Henan provinces. The baseline scenario was first constructed to describe the trade situation and virtual water among different regions and sectors from 2009–2020. Then two hypothetical policy scenarios were set to analyze the economic, water consumption and virtual water trade impacts under different policy shocks. The results show that (1) the Huaihe River basin was a net virtual water outflow region, with $13.977 \times 10^9 \text{ m}^3$ virtual water transferred outside the river basin in 2009, and $26.653 \times 10^9 \text{ m}^3$ VW transferred to outside in 2020. Jiangsu is the largest virtual water outflow province (mainly flows to outside), followed by Anhui. Anhui suffers from severe water shortage, but provides a net virtual water outflow to Henan, Jiangsu and Shandong and outside; (2) reducing Anhui's agricultural output (S1 scenario) and Anhui's agricultural virtual water outflow (S2 scenario) can not only reduce virtual water trade but also save water, but S1 scenario reduced net virtual water outflow by more, and saved more water. S1 had a positive effect on gross domestic product (GDP), but reduced the employment rate.

Key words | dynamic multi-region CGE model, Huaihe River basin, macroeconomic impact, virtual water trade, water consumption

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HIGHLIGHTS

- Role of VWT analyzed using a CGE.
- CGE based on 12 years of data (2009–2020).
- VW study not only focused on agriculture, but also included industry and service sectors.
- Two hypothetical scenarios were set to analyze the economic, water consumption and VWT impact.
- Assessment of VW will change water usage and trade in different upstream and downstream regions of the Huaihe watershed.

INTRODUCTION

Many countries are suffering from water scarcity and it affects a third of the people in the world. Water scarcity is

a serious problem in China and has been getting worse in recent years. China started construction of the South-to-North Water Transfer Project in 2002 to alleviate the uneven spatial and temporal distribution of water, and the 'sending grains from the north to the south' policy was formulated and has been carried out since 1990. So China's

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doi: 10.2166/ws.2020.373

net virtual water trade (VWT) pattern is roughly the opposite of the distribution of its water resources.

VWT has often been recognized for its ability to improve physical and economic access to water in water-scarce regions, allowing regions to save domestic water through the import of water-intensive products (Kumar 2018). The term 'virtual water' (VT) was first proposed in 1994 by Allan (1994). Virtual water is defined as the water embodied in goods during the production process (Hoekstra 2003). VWT has been much studied in recent years. Some studies have focused on the micro-level, such as the virtual water content of products or consumers; for example, Hoekstra & Chapagain (2008) and Chapagain & Hoekstra (2011) have researched the VW content of coffee, tea, rice and meat. Some studies have focused on the national and regional levels, such as those of Hoekstra & Hung (2005), Duarte et al. (2019), Lenzen (2009), Hanasaki et al. (2010). They evaluated the national or regional VW balance in relation to water needs and water availability. Other studies have focused on the macro and global levels; for instance, Hoekstra & Hung (2005) estimated the global VW exports related to international trade in crops from 1995 to 1999. Chen & Chen (2013) studied the VW account of the global economy, with VW profiles of 112 nation-level regions. Their findings highlighted the importance of VWT in water-scarce regions.

Recently, VW calculation methods have also attracted much attention. The methods mainly fall into two categories: one is the production tree method (Hoekstra et al. 2012), and the other is the input-output (IO) method. The IO model is a top-down method, which uses water use data and input-output tables to calculate the direct water coefficient and total water coefficient for each sector or region (Velázquez 2007). The IO model has been utilized as an effective method to assess resource flows and transfers. Some researchers, such as Wang et al. (2013), Arto et al. (2016), Shi & Zhan (2015) and Zhang et al. (2020) have used the IO model to evaluate VW flows. Other researchers such as Jiang et al. (2015) and Deng et al. (2015), have used the multi-regional IO analysis method to analyze VWT among various regions. Their studies have verified that the IO model clearly quantifies inter-regional and inter-sectoral VW flows, and represents both direct and indirect water input during production

processes. Other studies have used a computable general equilibrium (CGE) model to investigate VWT; for example, Roson & Sartori (2010) applied a CGE to the Mediterranean region to assess to what extent VW is a viable adaptive option for water-scarce regions. Their results suggested that VW could help reduce the impacts of water scarcity, but only marginally. Berritella et al. (2007) also used a CGE model to research the role of VW and water scarcity in the context of international trade. They found that VWT could help balance the supply and demand of water resources in regions suffering from water scarcity. The CGE model provides a systemic and disaggregated data representation of multi-regional and national economies. They fully account for circular income flows, inter-sectoral and market linkages. The CGE model has been used as a means to identify the hidden water consumers along the whole supply chain.

Despite the vast body of literature on VWT, however, (1) VWT research have focused more on agriculture, and the VW of industry and services has hardly been studied; (2) structural changes in the economy will lead VWT changes over time. Most work thus far has focused on assessing VWT over a specific year. The effects of long-term changes in VWT have barely been studied; (3) some studies have used the IO model to compute VWT, but the IO model is a static model that considers a specific year.

To the best of our knowledge, no one has studied VW flows using a dynamic (over time) multi-regional CGE model. This study endeavors to bridge these gaps by using a dynamic CGE model, the SinoTERM model (the enormous regional model), which includes 137 sectors in 31 regions on the Chinese mainland, to analyze VWT and its effect on the Huaihe River basin. The concept of VW was incorporated into the CGE model by adding the VW module to the CGE model. The CGE model helps realize a dynamic simulation through annual capital accumulation and regional labor market dynamic adjustment. The baseline scenario simulation is based on 12 years of data (2009–2020). This paper discusses the trade situation and VW features of the Huaihe River basin from 2009–2020. It sets two policy scenarios (the policy simulation result analysis is from 2019 to 2020), to analyze the economic, water consumption and VWT impact under different policies.

DEFINITION

MODELING FRAMEWORK

A dynamically multi-regional CGE model of the Chinese economy (also called SinoTERM) was developed by the Centre of Policy Studies at Victoria University in Australia based on the Australian TERM. The theory of the SinoTERM model is similar to national dynamic CGE models such as MONASH (Dixon & Rimmer 2002) and CHINAGEM (Mai et al. 2010) except that it has multiple regions. Each region in the model is treated as a separate economy, linked to the other regions by trade. The equation system of SinoTERM is similar to other models of the TERM family and is described in Wittwer & Horridge (2008).

The features of the SinoTERM model include full input-output databases, inter-regional trade matrices and behavioral equations for each province. The SinoTERM database contains input-output data for 137 sectors in 31 regions of China's mainland. It includes detailed inter-regional trade, consumption, import, and export data. It includes detailed information under 'margins', covering rail, road, water and air freight, plus pipelines, warehousing, trade (retail plus wholesale) and insurance. The database includes detailed tax matrices, allowing for the possibility (either in the original data or as part of a simulation) that tax rates on a particular good might vary both between regions and users. The equations in the model are linearized for simplicity, which, combined with accuracy via multi-step solution methods, ensures model efficiency through the use of GEMPACK software. This model provides a disaggregated representation of national, regional and multi-regional economies, which fully accounts for circular income flows, inter-sectoral and market linkages. The corresponding resource and environmental impacts resulting from consumption activities in one region can be traced to specific production sectors in other regions through the inter-regional supply chain (Robson et al. 2018).

Dynamic mechanisms

Dynamic mechanisms have been added to SinoTERM (Wittwer & Horridge 2008). The main enhancement of dynamics was to link capital and investment over time.

(1) Physical capital accumulation

Capital in industry j accumulates according to:

$$K_j(t+1) = K_j(t) * (1 - D_j) + I_j(t) \quad (1)$$

$K_j(t)$ is the quantity of capital available for use in industry j during year t ; $I_j(t)$ is the quantity of new capital created for industry j during year t ; D_j is the rate of depreciation, treated as a known parameter.

The mechanism for determining j 's investment can be represented by:

$$E_t[ROR_j(t)] = -1 + \frac{E_t[Q_j(t+1)]}{C_j(t)} * \frac{1}{1+r} + (1 - D_j) * \frac{E_t[C_j(t+1)]}{C_j(t)} * \frac{1}{1+r} \quad (2)$$

$$E_t[ROR_j(t)] = f_{jt} \left(\frac{K_j(t+1)}{K_j(t)} - 1 \right) \quad (3)$$

where E_t denotes an expectation held in year t ; $ROR_j(t)$ is the rate of return on industry j 's investment undertaken in year t ; $Q_j(t+1)$ is the rental on j 's capital in year $t+1$; r is the rate of interest; $C_j(t)$ is the cost of an extra unit of capital installed for industry j in year t ; and f_{jt} is a non-decreasing function.

Equation (2) defines the expected rate of return for industry j in year t as the expected present value of an extra dollar of investment. Equation (3) defines an investment - supply curve: it shows how the rate of return that investors require if they are to advance an extra dollar to industry j depends on the rate of growth of j 's capital stock.

(2) Regional labor market dynamics are also introduced into the SinoTERM model. This allows partial adjustment in regional labor markets to occur over time in response to an economic shock. The regional labor market adjustment mechanism in SinoTERM, in level form, is given by:

$$\left(\frac{W_t^r}{W_{t-1}^r} - 1 \right) = \left(\frac{W_{t-1}^r}{W_{t-2}^r} - 1 \right) + \alpha \left(\frac{EMP_t^r}{EMP_{t-1}^r} - \frac{LS_t^r}{LS_{t-1}^r} \right) \quad (4)$$

If the policy shock weakens the labor market in region r at period t relative to forecast, real wages W_t^r in policy scenario will fall relative to forecast W_{t-1}^r . In addition, there will be an initial enlarged gap between the labor market demand EMP_t^r and supply LS_t^r relative to forecast

levels EMP_t^r and LS_t^r . In successive years, the gap between demand and supply will gradually return to forecast levels through a further decline in real wages. The speed of labor market adjustment is governed by a positive parameter α .

With the dynamic approach, the long-term effect of VWT is represented year-by-year in a simulation.

Virtual water module

The VW module assigned is the water used by final consumption rather than intermediate consumption, which allows the researcher to assess both direct and indirect water requirements of the final consumption pattern of a nation, region, lifestyle group, or household.

The SinoTERM model includes R provinces and N economic sectors, so the total output (X_j^r) of sector j in province r can be expressed as intermediate input ($A_{ij}^r X_j^r$) plus final consumption (Y_j^r):

$$X_j^r = A_{ij}^r X_j^r + Y_j^r \tag{5}$$

Equation (5) be rewritten as:

$$X_j^r = (I - A_{ij}^r)^{-1} + Y_j^r \tag{6}$$

where I is the identity matrix and has the same order as the matrix A_{ij}^r .

The vector of direct water consumption is extended as: $W_j^r = [W_1^r, W_2^r, \dots, W_n^r]$, where W_j^r is the direct water consumption vector of region r .

The water consumption coefficients (water supplied by region r to regions s to generate one monetary unit of final demand) can thus be derived by:

$$D_j^{rs} = (I - A_{ij}^{rs})^{-1} W_j^{rs} \tag{7}$$

where D_j^{rs} denotes the total water supplied by region r to other regions to generate one monetary unit of final demand in sector j of region s .

The virtual water from region s to region r can be calculated as:

$$VW_{ij}^{rs} = D_{ij}^{rs} Y_j^{rs} \tag{8}$$

where VW_{ij}^{rs} is the virtual water volume from i sector in region r to j sector in region s and Y_j^{rs} the output of j sector in region s .

Thus, the total virtual water inflow and outflow of region r can be calculated as:

$$VW_{in}^r = \sum_{i \neq r} VW^{ir} \tag{9}$$

$$VW_{out}^r = \sum_{i \neq r} VW^{ir} \tag{10}$$

where VW_{in}^r is the total virtual water inflow of region r , and VW_{out}^r is the total virtual water outflow of region r .

The SinoTERM model realizes dynamic simulation by capital dynamic accumulation and regional labor market dynamic adjustment. Capital dynamic accumulation has been discussed in detail in Dixon & Rimmer (2002) and Mai et al. (2010). Regional labor market dynamics have been discussed in Wittwer & Horridge (2008).

SCENARIO DEVELOPMENT

A baseline was developed first. It is a business-as-usual scenario without any policies. Then a policy simulation was conducted, and a shock with the VWT policy was added. The effects of VWT are measured by deviations of variables in the policy simulation from their baseline levels.

Research area

The Huaihe River basin is located in the eastern part of China and originates from Tongbai Mountain in Henan Province. The river flows eastward for approximately 1,000 km through Henan, Anhui, Jiangsu and Shandong provinces (Figure 1). The annual precipitation ranges from 600 to 1,500 mm. The uneven spatial and temporal distribution of water resources results in water scarcity. The multi-year average natural runoff of the Huaihe River basin occupies only 2% of China, per-capita annual runoff is only 27% of China, and only 1/20 of the world's average. But the Huaihe River basin accounts for 13% of the population, 7.7% of the gross domestic product (GDP), 12% of the cultivated land area, 19% of food

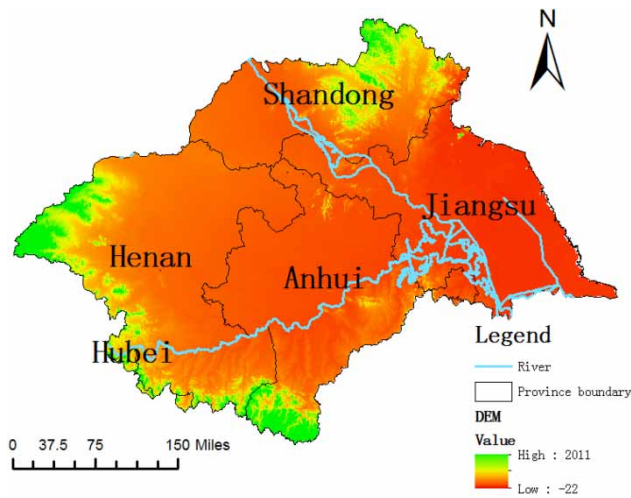


Figure 1 | Map of Huaihe River basin.

production, and 25% of the food that is exported. Rapid economic development and high-density population have exacerbated Huaihe's water scarcity, which restricts the sustainable socio-economic development of the Huaihe River basin.

The four provinces are all water shortage areas, and the amount of water available per capita is far lower than the national average. Jiangsu has the most developed economy in the Huaihe River basin, with a per-capita GDP of 115,168 yuan in 2018, followed by Shandong (per-capita GDP was 76,267 yuan in 2018), Henan (per-capita GDP was 50,152 yuan in 2018), and Anhui (per-capita GDP was 47,712 yuan in 2018). The four provinces in the Huaihe River basin and other regions in the outside of the Huaihe River basin all have VWT, as described in the 'Virtual water trade' section.

Regions and sectors

The database of the SinoTERM model consists of value matrices of commodities, sectors, sources and regions. In order to focus on the VW issue and speed up solution times, we aggregated the sectors and regions to manageable dimensions while retaining detail in the sectors. We also aggregated the SinoTERM database of 137 sectors to 18 sectors. The 18 sectors are listed in Table S1 (Supplementary Information). The Huaihe River basin was divided into four regions: Henan, Anhui, Jiangsu, Shandong.

Baseline scenario

Macro economy

For the baseline scenario, macroeconomic data was divided into two periods, the first (historical) period is from 2009 to 2018 and the second (planned) period is from 2019 to 2020. For the first period, economic variables are assigned values according to the actual economic growth, including main economic indicators such as GDP, consumption, investment, industrial structure, employment and price levels, etc. For the second period, economic data are assigned according to the 13th Five-Year Plan of four provinces. The predictions for economic growth are displayed in Table 1, and the agricultural added value and percentages are displayed in Table 2.

Inter-provincial trade flows

Inter-provincial trade data are obtained from the Inter-regional Input-Output table of 2009. The trade flow of 18

Table 1 | GDP and its speed of growth in the baseline scenario (10⁹ yuan, at 2009 prices)

	GDP							GDP growth speed	
	2009	2015	2016	2017	2018	2019	2020	2019	2020
Henan	104	187	202	218	234	249	264	6.50%	5.85%
Anhui	39	63	68	74	80	85	91	6.70%	6.03%
Jiangsu	97	167	180	193	206	219	232	6.50%	5.85%
Shandong	70	124	133	143	152	162	171	6.30%	5.67%
Total	310	540	584	629	673	717	759	6.55%	5.90%

Table 2 | Agricultural added value and percentages in 2009 (10^9 yuan, at 2009 prices)

	Henan	Anhui	Jiangsu	Shandong	Total
Agricultural added value	1.64	0.88	1.31	0.88	4.71
Agricultural added value as a percentage	34.8	18.7	27.8	18.7	100

sectors of four provinces among the Huaihe basin are shown in Table S2 (Supplementary Information). Henan and Anhui are net trade outflow areas. Jiangsu and Shandong are net trade inflow areas. From the perspective of different sectors, Henan's primary inflows are agriculture, coal, food and textile, and outflows are metallurgy and machinery. Anhui's primary inflows are petroleum, chemistry and construction, and the outflow is agriculture. Jiangsu needs inflows of agriculture and food, and its outflows are machinery. Shandong has an obvious advantage in the petroleum and chemistry sectors, but for agriculture and some service sectors it relies on other regions. Table 3 shows the inter-province trade value flow. The total trade value of the Huaihe River basin was $8,886 \times 10^9$ yuan.

Water data

Water data are collected from various sources. The water use by sector is extracted from the water resource bulletin of Huaihe. Only blue water (i.e., fresh surface and ground-water withdrawals) is included in these statistics. Green water (i.e., precipitation stored in the soil) is not included in this study.

To describe the VW content of the commodities, direct and total water use coefficients were computed according to Hoekstra (2003), Hoekstra & Chapagain (2008), and Chapagain & Hoekstra (2011). The direct water use coefficient

and total water use coefficient of the Huaihe River basin are shown in Table S3 (Supplementary Information). Agricultural output increased per thousand yuan, and it consumes a total of $7,183 \text{ m}^3$ of water, $5,118 \text{ m}^3$ directly and $2,065 \text{ m}^3$ indirectly. The VW content of agriculture is the highest, followed by food and electricity. The total water use coefficient of the same sector between provinces is different.

Virtual water trade

Figure 2 shows VWT of four provinces. The net outflow of VW from the Huaihe River basin was $13,977 \times 10^9 \text{ m}^3$. The net outflow of agricultural VW was $8,753 \text{ m}^3$, accounting for 63% of the total VW (Table S4, Supplementary Information). Agriculture accounts for most VWT, and often decides the direction of VWT among regions. The industrial sector is an important part of VWT and affects the scale of VWT among regions. The service sector water use coefficient is small and does not have a great impact on VWT patterns. Henan and Anhui province were net VW outflow regions. Jiangsu and Shandong provinces were net VW inflow regions in 2009, and the net inflow volumes were, respectively, $300 \times 10^6 \text{ m}^3$ and $145 \times 10^6 \text{ m}^3$ in the Huaihe River basin. VW outflows from Jiangsu and Anhui, respectively, were $6,204 \times 10^6 \text{ m}^3$ and $4,188 \times 10^6 \text{ m}^3$ in 2009. VW outflows from Henan and Shandong, respectively, were $2,387 \times 10^6 \text{ m}^3$ and $1,198 \times 10^6 \text{ m}^3$ in 2009. Henan, Anhui and Jiangsu's VW flows to Shandong were $442 \times 10^6 \text{ m}^3$, $468 \times 10^6 \text{ m}^3$ and $535 \times 10^6 \text{ m}^3$ respectively. Anhui was a net outflow region without VW inflow. Anhui's VW outflows were $76 \times 10^6 \text{ m}^3$, $536 \times 10^6 \text{ m}^3$ and $648 \times 10^6 \text{ m}^3$ to Henan, Jiangsu and Shandong, respectively.

The flow of VW in 2020 is shown in Table 4. The Huaihe River basin will transfer $26,653 \times 10^6 \text{ m}^3$ VW to other regions outside of the basin.

Other parameters

The labor demand elasticity was 0.243, according to the Chinese Academy of Social Sciences (Zheng & Fan 2008). Consumer price elasticity was set at 4, according to the PRGEM model data of the Chinese Academy of Social Sciences (Zheng & Fan 2008). The Frisch parameter and the Armington elasticity were obtained from the CHINAGEM model (Mai et al. 2010). The elasticity of substitution between

Table 3 | Inter-province trade flow (10^9 yuan) in 2009

Outflow Inflow	Henan	Anhui	Jiangsu	Shandong	Total
Henan	2,390	85	136	131	2,742
Anhui	82	798	81	41	1,002
Jiangsu	183	117	2,759	96	3,155
Shandong	142	86	114	1,645	1,987
Total	2,797	1,086	3,090	1,913	8,886

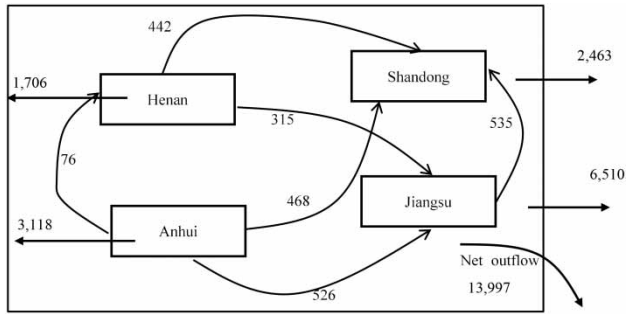


Figure 2 | Pattern of VW flow of the Huaihe River basin in 2009 (10⁶ m³).

primary factors, constant elasticity transformation, the elasticity of household demand expenditure, etc. was obtained from the China version of the ORANI-G model the Centre of Policy Studies at Victoria University (Dixon & Rimmer 2002).

Policy scenario

The net outflow VW region is mainly concentrated in Anhui, which is a water shortage region. In order to alleviate the water stress in the upper reaches of the Huaihe River basin, the outflow of water-intensive commodities should be reduced. Two policy scenarios were set: in S1 Anhui’s agricultural output is reduced by 5%; in S2 Anhui’s agricultural outflow demand is reduced by 5%.

RESULTS

Macroeconomic impact

The macroeconomic impact under the two policy scenarios is shown in Figure 3. In scenario S1, Anhui’s agricultural

output is reduced by 5%, so its GDP will decrease by 0.218%. GDP is defined as a function of underlying capital, labor and technology (generally unchanged), so this decrease reflects the combined effects of capital use (0.132%) and labor adjustments (−0.352%). There is a clear decrease in agricultural production in the Huaihe River basin, and the other three provinces will expand agricultural production and increase the inflow of agricultural commodities from outside at the same time. This boosts an increase in the real GDP of these three provinces, and the GDP of Henan, Jiangsu and Shandong separately increase by 0.109%, 0.147% and 0.112%. The increase of 0.109% in Henan is the combined influence of capital use (0.152%) and labor adjustments (0.042%). The increase of 0.147% in Jiangsu is the combined influence of capital use (0.179%) and labor adjustments (0.08%). The increase of 0.112% in Jiangsu is combined influence of capital use (0.148%) and labor adjustments (0.046%). GDP in 2020 will be 0.037% higher than the baseline scenario in the Huaihe River basin, which reflects the combined effects of capital use (0.403%) and labor adjustments (−0.396%). Agriculture is a labor-intensive sector, employment will be negatively affected in and the whole Huaihe River basin. A decrease in the amount of agricultural commodities will cause an increase in price. The consumer price index (CPI) will be 0.481% higher in 2020 than the baseline. As a result, household real consumption will be 0.174% lower and investment will be 0.296% higher than the baseline in 2020. The price of Anhui agricultural commodities rises relative to outside; the outflow of Anhui decreases by 0.41%, and the inflows increase. Changes in the inflow and outflow of the Huaihe River basin are respectively 0.023% and −0.119%.

Table 4 | Net VW flow matrix of the Huaihe River basin in 2020 (10⁶ m³)

	Henan	Anhui	Jiangsu	Shandong	Net VW outflows	Total VW outflows to other regions outside the basin	Total VW outflow
Henan	–	–148	614	797	1,263	3,071	4,334
Anhui	148	–	1,052	936	2,136	6,236	8,372
Jiangsu	–614	–1,052	–	1,043	–623	12,695	12,072
Shandong	–797	–936	–1,043	–	–2,776	4,652	1,876
Total	–1,263	–2,136	623	2,776	0	26,653	26,653

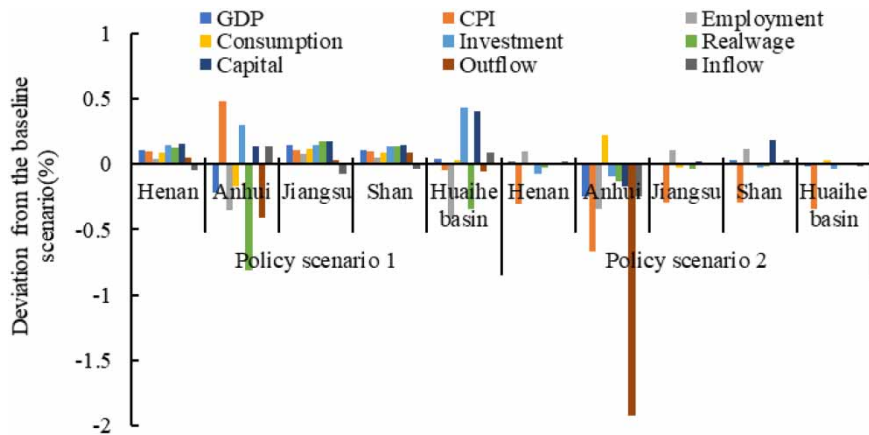


Figure 3 | Macroeconomic impact under two policy scenarios in 2020 (%). Note: % cumulative deviation from the baseline scenario. Source: simulation results.

In scenario S2, Anhui's agricultural outflow demand reduces by 5%, Anhui's GDP is negatively affected, falling by -0.248 in 2020. The decrease of outflow mainly comes from Anhui's agriculture, which is a labor-intensive sector, and employment will be negatively affected (-0.342%) in Anhui.

In S2, more agricultural production is available in Anhui markets, the price of agricultural produce decreases, and CPI shows a downward trend. This effect can affect other regions through inter-regional trade links, Jiangsu and Shandong need to inflow agricultural commodities from outside. As labor and capital move between regions, employment and capital will increase in Henan, Jiangsu and Shandong, leading to an increase in GDP in these three provinces. Employment and capital in Henan will increase 0.094% and 0.013% , lead to a 0.018% increase in GDP. For the Huaihe River basin, the positive influence of the Henan, Jiangsu and Shandong cannot offset the negative influence of Anhui, and the GDP of the Huaihe River basin shows a downward trend. But the impact range of GDP is smaller than that of Anhui.

Water consumption

In S1, the water consumption of Anhui decreases by 2.32% in 2020 (see Table 5), driving agricultural water consumption in the Huaihe River basin to drop by 0.65% . The agricultural output increases in Henan, Jiangsu and Shandong have a large demand for water, so water consumption is 0.08% , 0.10% and 0.69% , respectively, in

2020. Water consumption in most other industries shows a downward trend. Food processing and manufacturing is a downstream industry of agriculture, which results in a decrease in production due to the lack of agricultural products in local markets in Anhui.

In S2, agricultural water consumption reduces by 1.56% , resulting in agricultural water consumption reducing by 0.3% in the Huaihe River basin. Agriculture being the main water consumer, reductions in agricultural water consumption will relieve the water stress of other sectors, and the water consumption of other sectors will increase. Water consumption in food processing and manufacturing will increase by 1.96% due to its upstream industry output increasing. The agricultural output of Jiangsu and Shan will increase, so the water consumption of agriculture increase.

Virtual water flow

In S1, the VW of Anhui decreases by $322 \times 10^6 \text{ m}^3$ in 2020. The VW outflow to outside the basin decreases by $178 \times 10^6 \text{ m}^3$ (see Table 6). Because of Anhui decreasing outflows of agricultural commodities to Henan, Jiangsu and Shandong provinces, these three provinces need to inflow agricultural commodities from elsewhere. The VWT from Henan to Jiangsu and Shandong decreases by $25 \times 10^6 \text{ m}^3$ and $10 \times 10^6 \text{ m}^3$, respectively, and the net VW outflow of Henan decreases by $23 \times 10^6 \text{ m}^3$. The net VW outflow of Jiangsu and Shandong increases by $78 \times 10^6 \text{ m}^3$ and $89 \times 10^6 \text{ m}^3$, respectively, in the Huaihe River basin. But VW

Table 5 | The water consumption impact of different sectors under two policy scenarios in 2020 (%)

Sectors	S1 (%)					S2 (%)				
	Henan	Anhui	Jiangsu	Shandong	Huaihe River basin	Henan	Anhui	Jiangsu	Shandong	Huaihe River basin
Agriculture	0.69	-2.32	0.08	0.10	-0.65	0.00	-1.56	0.01	0.01	-0.30
Coal	-0.15	-0.17	-0.01	-0.01	-0.20	0.05	0.28	0.03	0.03	0.00
Petroleum	-0.21	-0.26	-0.01	-0.01	0.00	0.07	0.29	0.04	0.06	0.00
Other mining	-0.11	-0.25	-0.01	-0.01	0.00	0.09	0.32	0.10	0.09	0.00
Food	0.19	-0.33	0.03	0.03	-0.08	-0.22	1.96	-0.48	-0.23	0.70
Textile	-0.17	-0.40	-0.01	-0.01	0.00	-0.05	1.37	-0.09	-0.04	0.34
Papermaking	-0.3	-0.20	-0.01	-0.02	-0.26	0.04	0.69	-0.02	0.02	0.00
Chemistry	-0.31	-0.37	0.00	-0.01	0.00	0.01	0.48	0.01	0.02	0.12
Building materials	-0.11	-0.40	-0.01	-0.01	0.30	0.03	0.40	0.02	0.01	0.30
Metallurgy industry	-0.2	-0.29	0.00	0.00	0.00	0.05	0.36	0.08	0.10	0.13
Machine	-0.21	-0.23	0.00	0.00	0.00	0.09	0.35	0.04	0.09	0.00
Electronic industry	-0.38	-0.29	0.00	0.00	0.00	0.17	0.35	-0.01	0.03	0.00
Electricity	-0.22	-0.57	0.01	0.00	0.21	0.05	0.41	0.04	0.04	0.19
Other industry	-0.33	-0.09	-0.01	-0.01	0.00	0.05	0.62	-0.04	0.04	0.00
Construction	-0.13	-0.09	0.00	-0.01	0.00	0.00	0.12	-0.02	0.00	0.00
Transportation	-0.02	-0.02	0.00	-0.02	0.00	-0.01	-0.10	0.00	0.01	0.00
Wholesale-retail	-0.03	-0.02	0.00	-0.02	0.00	-0.01	-0.18	-0.01	0.00	0.00
Other services	-0.03	-0.04	0.00	0.00	0.00	0.01	0.05	0.00	0.01	0.00
Total	-0.35	-1.78	-0.07	-0.09	-0.14	0.00	-1.00	0.01	0.00	-0.21

Note: % cumulative deviation from baseline scenario. Source: simulation results.

Table 6 | The VW transfer of S1 in 2020 (10^6 m^3)

Outflows Inflows	Henan	Anhui	Jiangsu	Shandong	Net VW outflows	Total VW outflows to other regions outside of the basin	Total VW outflow
Henan	-	12	-25	-10	-23	-88	-111
Anhui	-12	-	-85	-47	-144	-178	-322
Jiangsu	25	85	-	-32	78	-106	-28
Shandong	10	47	32	-	89	-22	67
Huaihe River basin	88	178	-78	-89	0	-394	-394

Note: 10^6 m^3 cumulative deviations from the baseline scenario. Source: simulation results.

outflows to other regions outside of the basin decrease by $106 \times 10^6 \text{ m}^3$ in Jiangsu and $22 \times 10^6 \text{ m}^3$ in Shandong. The total VW outflow of the Huaihe River basin decreases by $394 \times 10^6 \text{ m}^3$.

In S2, net VW outflows decrease by $89 \times 10^6 \text{ m}^3$ in the basin, and the VW outflows to other regions outside of the basin decrease by $116 \times 10^6 \text{ m}^3$ (see Table 7). Jiangsu and

Shandong increase the inflows of agricultural commodities from Henan, and Anhui decreases agricultural commodities inflows from Henan. The VW transfer from Henan to Jiangsu and Shandong increases by $24 \times 10^6 \text{ m}^3$ and $15 \times 10^6 \text{ m}^3$, respectively. The VW transfer from Henan to Anhui decreases by $7 \times 10^6 \text{ m}^3$. The net VW outflow of Henan decreases by $80 \times 10^6 \text{ m}^3$. The net

Table 7 | The VW transfer of S2 in 2020 (10^6 m^3)

Outflows Inflows	Henan	Anhui	Jiangsu	Shandong	Net VW outflows	Total VW outflows to other regions outside of the basin	Total VW outflow
Henan	–	7	24	15	46	–80	–34
Anhui	–7	–	–46	–36	–89	–116	–205
Jiangsu	–24	46	–	0	32	–43	–11
Shandong	–15	36	0	–	21	–2	19
Huaihe River basin	–46	89	–32	–21	0	–241	–241

Note: 10^6 m^3 cumulative deviations from the baseline scenario. Source: simulation results.

VW outflow of Jiangsu and Shandong decreases by $43 \times 10^6 \text{ m}^3$ and $2 \times 10^6 \text{ m}^3$. The total VW outflow of the Huaihe River basin decreases by $241 \times 10^6 \text{ m}^3$.

DISCUSSION

Water management and policy considerations

Unlike previous studies, this study uses a dynamic multi-region CGE model to provide an explanation of the macroeconomic, water consumption and VWT impacts on different regions and sectors. Two policy scenarios were set up, and S1 (Anhui's agricultural output reduced by 5%) can effectively reduce VW outflow and save more water resources. S1 causes an increase of 0.112% in GDP in the Huaihe River basin in 2020, but GDP in S2 decreases by 0.013%. However, employment declines in S1 and remains unchanged in S2. This finding calls for attention to the comprehensive impact (such as GDP, employment, consumption, food security) of inter-regional VW policies.

There is an interesting phenomenon: commodity trade and VWT flow from underdeveloped areas (Henan and Anhui) to relatively developed areas (Jiangsu and Shandong) and flow from areas with severe water scarcity to relatively water-rich areas. This phenomenon is a deviation from the concept of water-related sustainable development. The main causes are that many factors (such as coal and land) determine the distribution of economic production and productivity. The upstream areas of the Huaihe River basin have a large coal base and a major arable area, and these resources provide comparative advantages. In addition, the upstream areas occupy an absolute advantage in other

mining, food, papermaking, building materials and metallurgy industry (these are water-intensive and pollution-intensive industries). Water trade is not only used as a water management strategy, but also uses a land or resource management strategy. VWT improves global land-use efficiency (Seekell 2011). This finding should call attention to the impact of inter-regional VW transfer on local water stress and ecological environment.

Impact of the South-North Water Transfer Project on VWT

The South-North Water Transfer Project (SNWTP) represents the largest-scale attempt to solve the uneven spatial-temporal distribution of water resources and relieve the North China Plain's water problems (Barnett et al. 2015). By March 20, 2019, the middle line of SNWTP had transferred a total of $20.5 \times 10^9 \text{ m}^3$ water. Henan province received the largest amount of water: $6.942 \times 10^9 \text{ m}^3$. Annual water transfer is increasing year by year. SNWTP alleviated the water shortage in Henan, but total VW outflows will reach $4.3 \times 10^9 \text{ m}^3$ in 2020, which will further exacerbate water stress in Henan. The east line of SNWTP had continuously transferred a total of $3 \times 10^9 \text{ m}^3$ water to Shandong, but total virtual water outflows will reach $1.8 \times 10^9 \text{ m}^3$ in 2020, which will further exacerbate water stress in Shandong. SNWTP has a limited impact on alleviating water shortage, but it may exacerbate the VW outflow in water-scarce regions.

Limitations

There are several limitations that require future research. Firstly, only blue water was taken into consideration, and

green and grey water (or water pollution) has been ignored. Secondly, 18 sectors were considered, but agriculture was not further split into crops, livestock and other agricultural products, forestry, and fishing, which could be corrected in the future by analyzing different agricultural sub-sectors. Thirdly, surface water and groundwater were not distinguished. It is important that the sectoral dependence on surface water and groundwater are distinguished in the future.

CONCLUSIONS

This study has progressed the following aspects. Firstly, the study is a meaningful attempt to analyze the role of VWT by using a dynamic multi-regional CGE. 18 sectors and four regions (Henan, Anhui, Jiangsu and Shandong) in the Huaihe River basin are included in the model. This allows the reader an in-depth appreciation of the impact of different VWT on the sectors and regions. The CGE is based on 12 years of data (2009–2020), which means long-term changes in spatial patterns of production, consumption, trade and VW flows can be studied. Secondly, the VW study is not only focused on agriculture, but also includes industry and service sectors. Thirdly, two hypothetical scenarios were set to analyze the economic, water consumption and VWT impact.

Our results show that the Huaihe River basin is a net VW outflow region, with a transfer of $26.653 \times 10^9 \text{ m}^3$ VW in 2020; agriculture VWT accounts for 63% of the total VWT and therefore often decides the direction of VWT among regions. The industry sector is an important part of VWT, and affects the scale of VWT among the regions. The service sector's water use coefficient is small and does not have a great impact on VWT patterns. Jiangsu is the largest VW outflow province (main outflow is to outside), followed by Anhui. The VW outflows of these two provinces respectively are $12.072 \times 10^9 \text{ m}^3$ and $8.372 \times 10^9 \text{ m}^3$ in 2020. Anhui is a region with severe water stress, but is a net VW outflow province to Henan, Jiangsu and Shandong and outside of the Huaihe River basin. Henan and Anhui are net virtual water outflow areas, while Jiangsu and Shandong are net virtual water inflow areas in the Huaihe River basin. This reality contradicts the concept of sustainable

water development. S1 (Anhui's agricultural output reduced by 5%) can effectively reduce VW outflow and save more water resources. S1 also causes an increase of 0.112% in the GDP of the Huaihe River basin in 2020, but S2 causes GDP to decrease by 0.013%. Employment declines in S1 but is unchanged in S2.

ACKNOWLEDGEMENTS

This work was funded by National Natural Science Foundation of China (52009042, 52025093), National Key R&D Program of China (2017YFC1502405, 2017YFC0405805-03) and State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin (China Institute of Water Resources and Hydropower Research) open research funds (IWHR-SKL-KF201918).

DATA AVAILABILITY STATEMENT

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

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First received 30 July 2020; accepted in revised form 9 December 2020. Available online 28 December 2020