


## Quantitative analyzes of virtual water net exports under the impacts of natural changes and human activities in the last 20 years in Shandong Province, China

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### ABSTRACT

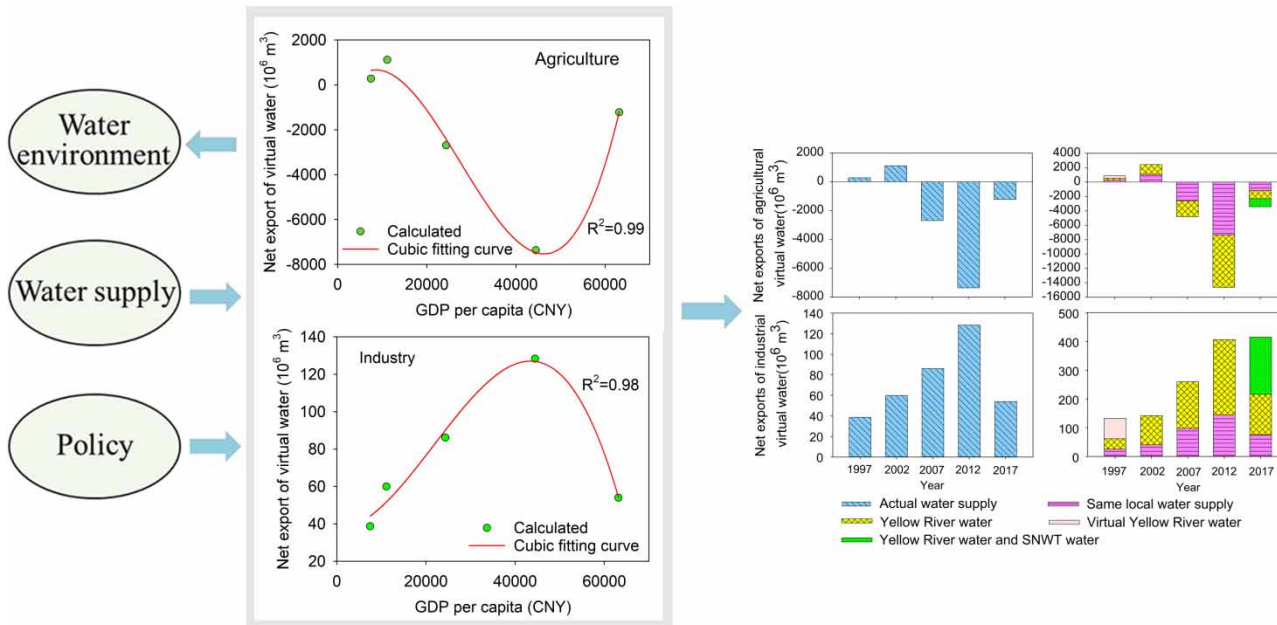
Virtual water trade in a region is affected by both nature and by humans. To study the contribution of human activities on virtual water trade quantitatively, an innovative method of quantitative comparison and analysis is put forward. At first, climates are adjusted into a unified standard. Then the impacts of increment and reduction of foreign water are studied. Additionally, the impacts of water management policy are studied according to the comparable water quotas. Results show that with the development of the economy, an N-shaped trend and inverted U-shaped trend exist with regard to the net exports of agricultural and industrial virtual water, respectively. The net imports of virtual water have beneficial effects to water environments in water deficient areas, while net exports have negative effects. In 1997, the net exports of agricultural and industrial virtual water reduced by 20.13% and 49.67% respectively due to the cut-off of the Yellow River channel compared with that under average Yellow River water diversion. In 2017, they increased by 1.32% and 41.99% respectively because of the South-to-North Water Transfer (SNWT) project and reduced by 10.01% and 20.39% respectively under the effects of the most stringent water management policy.

**Key words:** agricultural virtual water, foreign water quantity, industrial virtual water, Shandong Province, water management policy

### HIGHLIGHTS

- Impact of human activities on virtual water trades are analyzed quantitatively.
- Net exports of virtual water are harmful to the ecological environment.
- Increment of foreign water accelerates the net export of virtual water.

## GRAPHICAL ABSTRACT



## 1. INTRODUCTION

The concept of ‘virtual water’ was introduced by Tony Allan in the early nineties (Allan 1993, 1994). Under a virtual water strategy, water deficient countries and areas purchase water intensive agricultural products from water rich countries to obtain water and food security, and it has become a way to solve water shortage (Zhao *et al.* 2020). Delpasand *et al.* (2020) suggested that Iran should import wheat and export potatoes, tomatoes as well as iron ore. Israel, Iran and other countries facing water shortage should increase the exports of products with low water consumption and high economic value, and increase the imports of products with high water consumption and low economic value (Shtull-Trauring & Bernstein 2018; Bazrafshan *et al.* 2020). However, the implementation of virtual water strategy is not simply to restrict high water-consuming industries, nor to directly import water-intensive products, but to optimize industry structures and trade volumes, and to consider the suitability of regional socio-economic and environmental conditions (Wang *et al.* 2014).

Quantitative analyzes can not only study the virtual water trade in a region, but also study the flow networks between different regions (Chowdhury *et al.* 2017). Recently, the impact of geographic distances on the global virtual water trade has gradually weakened. From 1986 to 2013, the global virtual water trade networks have become increasingly interconnected. The largest virtual water net exporters in the world are mainly distributed in North America and South America, while the largest net importers are scattered around the world, such as China, Japan, Germany and Egypt (Fan *et al.* 2019). In China, the virtual water trade flows from North to South (Qian *et al.* 2020). The grain export areas are mainly in the Northeast, Northwest and North China Plain, and the import areas are mainly in the Eastern coastal and Southern developed provinces (An *et al.* 2020). In 2012, China’s virtual water flow reached 1,179.24 ( $1,179.24 \times 10^9$ )  $m^3$  and generated economic benefits of 7410 billion Chinese Yuan (CNY) (Wang *et al.* 2019).

Although virtual water trade can save water resources at the global or national level (Schwarz *et al.* 2019; Delbourg & Dinar 2020), it has negative impacts for the virtual water net exporters. For example, Arizona exports 67% of its available water to other parts of the country and abroad through trade, bringing huge challenges to availability of local water resources, which can be improved by raising the irrigation efficiency and reducing crop exports (Bae & Dall’Erba 2018). In Shouguang City, Shandong Province, for every 10 million  $m^3$  of vegetable virtual water exported in 1980–1990, the saltwater intrusion area increased by 13.8  $km^2$  in this area, which can be improved by changing the planting structure of vegetables (Li *et al.* 2020). In addition, the use of reclaimed water is beneficial to balancing virtual water trade. Through reclaimed water reuse, the change rate of virtual fresh water consumption in China’s developed provinces has decreased by more than 10% (Qi *et al.* 2021). Desalination is also a measure to cover the water resources shortage in the Maghreb (Sebri 2017).

Research on virtual water trade can promote the improvement and development of water policies (Sun *et al.* 2021). For water policy making, factors such as physical water, virtual water, science, and climate should be considered simultaneously, and adjustments of space and time are also needed (Katyaini *et al.* 2020; Xu *et al.* 2020).

Shandong Province is one of the water scarce provinces in Northern China. The annual average local water resources only account for 1.1% of the total water resources of the country. Per capita water resources are less than 1/6 of the national average, only 1/24 of the world's average, and the Province belongs to the severely water deficient areas identified by the United Nations. What's more, the spatial and temporal distribution of water resources is uneven in Shandong Province. The annual rainfall varied from 1997 to 2017, with maximum rainfall of 936 mm in 2003 and minimum rainfall of 420 mm in 2002. Average rainfall over 20 years was 680 mm, and the standard deviation was 114 mm.

Problems of water shortage in Shandong Province can be solved by increasing water supply, controlling water usage, and improving water use efficiency (Deng *et al.* 2018; Fu *et al.* 2021). Besides the local water resources, 7 billion m<sup>3</sup> of Yellow River water is allocated to Shandong Province as foreign water by the central government, which is an important source of water supply in Shandong Province. However, affected by the cut-off of the Yellow River in 1997–1999, the average diversion amount of Yellow River water in Shandong Province was only 1.99 billion m<sup>3</sup> in the three years. The diversion amount of Yellow River water did not return to the normal level until the year 2000 when it was 5.36 billion m<sup>3</sup> and since then there has been no cut-off of the Yellow River channel because of the unified management of whole basin by central government. Additionally, with the implementation of the South-to-North Water Transfer (SNWT) project, SNWT water has been transferred to Shandong Province since 2014, with a total of 2.19 billion m<sup>3</sup> until 2019. Furthermore, in order to control the use of water, the Shandong Provincial Government has issued a series of documents to implement the most stringent water management policy since 2015, including three red lines of total water consumption, water use efficiency and of limited pollutant carrying capacity of the water function area, which has achieved good results. Of course, the problem of water shortage can also be solved through virtual water trade (Deng *et al.* 2015).

Nevertheless, the above research suffers from two shortcomings. Firstly, virtual water trade is not only related to local natural conditions, but also affected by human activities. The above investigations fail to distinguish the two factors, so that they can't quantitatively analyze the impacts of natural and human activities on virtual water trade. Secondly, the time series of virtual water trade research in Shandong Province is short, and the longest time series so far is 15 years (Li *et al.* 2019). Therefore, this study aims to analyze the dynamic changes of virtual water trades in Shandong Province over the past 20 years and propose a new comparative analysis method. Impacts of the increment and reduction of foreign water on virtual water net exports are analyzed within a year. Impacts of the most stringent water management policy on virtual water net exports are analyzed at an annual level. This method can quantitatively analyze the impacts of different foreign water supply sources and water management policies on virtual water trade, so as to provide bases for managers to formulate comprehensive water management policies for physical water and virtual water, and promote the sustainable utilization and development of regional water resources.

## 2. METHOD

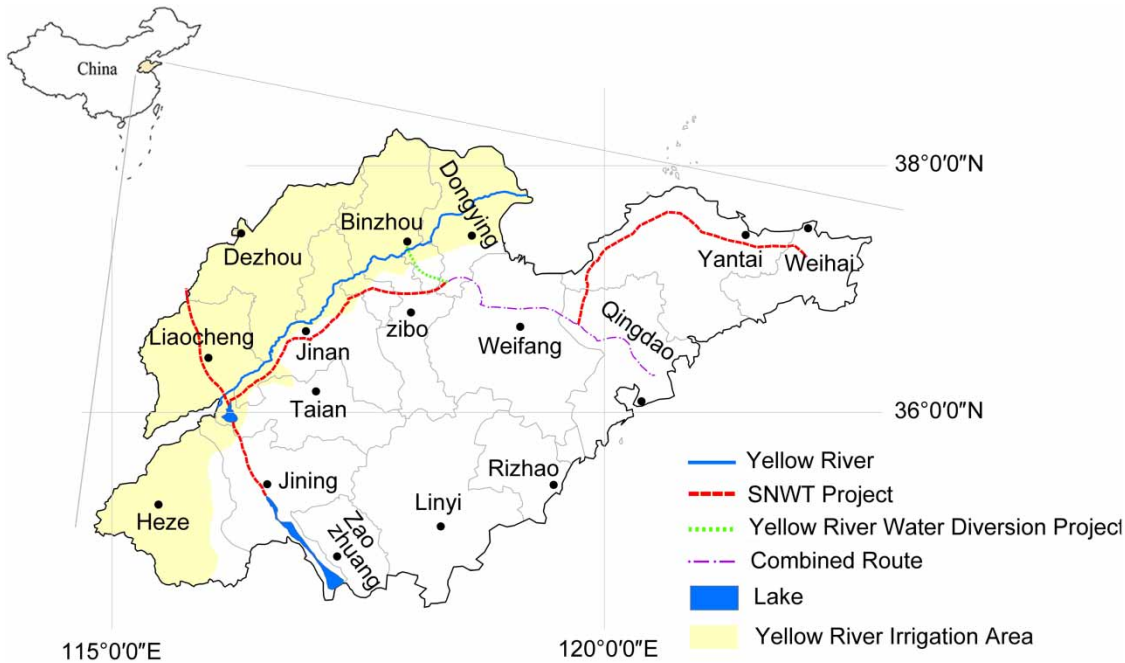
### 2.1. Study area

Shandong province is located on the eastern coast of China, where the latitude is 34°–39°N and longitude is 114°–123°E, with a temperate monsoon climate. The Yellow River is an important water source in Shandong Province. In order to alleviate the water shortage in Qingdao, Yellow River water has been diverted from Binzhou to Qingdao. In addition, the East Route of the SNWT project passes through Shandong Province. After being regulated and stored by Dongping Lake in Taian, the Yangtze River water is supplied to the north area of the Yellow River and to eastern Shandong Province. In eastern Shandong Province, Yangtze River water is transferred by part of the route of the Yellow River water diversion project. A schematic diagram of water transfer projects in Shandong Province is shown in Figure 1.

### 2.2. Calculation of virtual water net export

Virtual water net export can be calculated as follows in Equation (1):

$$\Delta W_j^i = \frac{W_{jC}^i}{Y_{jT}^i} (Y_{jE}^i - Y_{jI}^i) \quad (1)$$



**Figure 1** | Schematic diagram of water transfer projects in Shandong Province.

where  $\Delta W_j^i$  and  $W_{jC}^i$  are the virtual water net export and total water consumption of sector  $j$  in year  $i$ , respectively, in  $m^3$ .  $Y_{jT}^i$ ,  $Y_{jE}^i$  and  $Y_{jI}^i$  are the total output value, export value and import value of sector  $j$  in year  $i$ , respectively, in CNY.  $W_{jC}^i/Y_{jT}^i$  is the water consumption per unit output value, in  $m^3/CNY$ .

**2.3. Quantitative comparison and analysis of virtual water net export changes**

In this paper, a new method is proposed to analyze quantitatively the impacts of human activities on virtual water net exports. The impacts of foreign water are studied in two scenarios: the Yellow River water reduction and the SNWT water increment. Firstly, the common comparative basis is that the rainfalls of the five statistical years are assumed to be the same, with the local water supply and consumption being consistent, correspondingly. Consequently, the differences of virtual water trade caused by different foreign water supplies in different hydrological years can be eliminated. Secondly, it is considered that water saving and using levels are changeless, that is, the water consumption per unit output value is changeless, then the relationships between output value and water consumption are established. Finally, if the adjusted water supply amount is larger than the actual water consumption in the statistical year, the export value will increase, causing the increment of the virtual water exports. By contrast, virtual water imports will increase. Accordingly, the quantitative impacts of foreign water on virtual water net exports are discussed. For water saving measures, it is the impacts of the most stringent water management policy on virtual water net exports since 2015 according to the comparable water quotas that are paid attention to.

**2.3.1. Adjustment principle of balance between water demand and supply for virtual water trade**

If the adjusted water supply of sector  $j$  increases compared with the actual water supply in year  $i$  in a region, the outputs will also increase, so the exports of products will increase under the premise of the unchanged local demand. Conversely, if the adjusted water supply of sector  $j$  reduces compared with the actual water supply, the outputs will reduce too, so the imports of products will increase. From the perspective of output value, export value and import value increase respectively. Thus, the virtual water net exports can be calculated as follows in Equations (2) and (3).

$$\alpha_j^i = \frac{W_{jC}^{i\varphi}}{W_{jC}^i} \tag{2}$$

$$\Delta W_j^{i\varphi} = \begin{cases} \frac{W_{jC}^i}{Y_{jT}^i} (\alpha_j^i Y_{jE}^i - Y_{jI}^i), & \alpha_j^i > 1 \\ \frac{W_{jC}^i}{Y_{jT}^i} [Y_{jE}^i - (2 - \alpha_j^i) Y_{jI}^i], & \alpha_j^i < 1 \end{cases} \quad (3)$$

where  $W_{jC}^{i\varphi}$ ,  $W_{jC}^i$  and  $\Delta W_j^{i\varphi}$  are adjusted water supply, actual total water consumption and adjusted virtual water net export of sector  $j$  in year  $i$  respectively, in  $m^3$ .  $\alpha_j^i$  is the change rate of water supply of sector  $j$  in year  $i$ .

### 2.3.2. Quantification under the same annual rainfall

The annual rainfalls at 20, 50, 75, and 95% frequencies were 796, 670, 579, 463 mm, respectively in Shandong Province from 1956 to 2000. The rainfalls were 553, 420, 773, 651, 636 mm in 1997 (dry year), 2002 (extraordinary dry year), 2007 (slight wet year), 2012 (normal year), and 2017 (slight dry year), respectively. Although the hydrological characteristics of these 5 years were mostly dry years, 2007 was a slight wet year and 2012 was a normal year, which makes these five years have a certain representativeness of wet, normal and dry years. Therefore, rainfall is assumed to be 606 mm, being the annual average of five statistical years. The corresponding total water supply is calculated as Equation (4).

$$W_{S0}^{i'} = \frac{1}{5} \sum_{i=1}^5 W_S^i, \quad i = 1, 2, 3, 4, 5 \quad (4)$$

where  $i = 1, 2, 3, 4, 5$  represent the years 1997, 2002, 2007, 2012 and 2017, respectively.  $W_{S0}^{i'}$  is the adjusted total water supply under the same annual rainfall in year  $i$ , in  $m^3$ .  $W_S^i$  is the actual water supply in year  $i$ , in  $m^3$ .

Water consumption of sector  $j$  is expressed as Equation (5).

$$W_{jC}^{i'} = \frac{W_{jC}^i}{W_S^i} \times W_{S0}^{i'} \quad (5)$$

where  $W_{jC}^{i'}$  is adjusted water consumption of sector  $j$  under the same annual rainfall in year  $i$ , in  $m^3$ .

Then virtual water net exports can be calculated according to Equations (2) and (3).

### 2.3.3. Impacts of the reduction of Yellow River water

The adjusted total water supply considering Yellow River water can be calculated as Equation (6).

$$W_{S1}^{i''} = W_{S0}^{i'} + W_{Ye}^i \quad (6)$$

where  $W_{S1}^{i''}$  is the adjusted total water supply considering Yellow River water in year  $i$ , in  $m^3$ .  $W_{Ye}^i$  is the quantity of Yellow River water in year  $i$ , in  $m^3$ .

In order to study the impact of the cut-off of the Yellow River channel on virtual water exports in 1997, a virtual quantity of Yellow River water is defined. The adjusted total water supply considering the virtual Yellow River water can be calculated as Equation (7).

$$W_{S2}^{i''} = W_{S0}^{i'} + \frac{1}{4} \sum_{i=1}^4 W_{Ye}^i \quad i = 1, 2, 3, 4 \quad (7)$$

where  $i = 1, 2, 3, 4$  represent the years 2002, 2007, 2012, 2017.  $W_{S2}^{i''}$  is the adjusted total water supply considering the virtual Yellow River water in year  $i$ ,  $m^3$ .

The adjusted water consumption of sector  $j$  can be calculated as follows in Equations (8) and (9).

$$W_{jC1}^{i''} = \frac{W_{jC}^i}{W_S^i} \times W_{S1}^{i''} \quad (8)$$

$$W_{jC2}^{i''} = \frac{W_{jC}^i}{W_S^i} \times W_{S2}^{i''} \quad (9)$$

where  $W_{jC1}^{i''}$  and  $W_{jC2}^{i''}$  are adjusted water consumptions of sector  $j$  when considering the actual and virtual Yellow River in year  $i$ , respectively, in  $m^3$ .

Similarly, virtual water net exports can be calculated according to Equations (2) and (3).

#### 2.3.4. Impacts of the increment of SNWT water

When considering the SNWT project, the SNWT water is assumed to be consumed by industry entirely because most of it is distributed to industry. If the industrial water supply is sufficient, the water previously occupied by industry will be returned to agriculture. Subsequently, the agricultural water supply will increase. The impacts of SNWT water on agricultural virtual water net exports are discussed in this case. What's more, agriculture refers to generalized agriculture in this paper, including the four industries of planting, forestry, animal husbandry, and fishery.

Consequently, the adjusted water consumptions of agriculture and industry can be calculated as follows in Equation (10) under the effects of the Yellow River water and SNWT water.

$$W_{jC}^{i'''} = \frac{W_{jC}^i}{W_S^i} \times W_{S1}^{i''} + W_{SNWT}^i \quad (10)$$

where  $W_{jC}^{i'''}$  is the water consumption of sector  $j$  under the effects of the Yellow River water and SNWT water in year  $i$ , in  $m^3$ .  $W_{SNWT}^i$  is the quantity of SNWT water in year  $i$ , in  $m^3$ .

Similarly, virtual water net exports can be calculated according to Equations (2) and (3).

#### 2.3.5. Impacts of the water management policy

The impacts of the most stringent water management policy on virtual water net exports are studied by comparable water quotas. In the calculation of comparable water quota, the effects of SNWT water should be removed. The calculation of comparable water quota is shown in Equation (11).

$$\theta_j^i = \frac{W_{jC}^i - W_{SNWT}^i}{Y_{jT}^i} \quad (11)$$

where  $\theta_j^i$  is comparable water quota of sector  $j$  in year  $i$ , in  $m^3/CNY$ .  $Y_{jT}^i$  is the total comparable output values of sector  $j$  and the base year is 2007.

### 2.4. Data

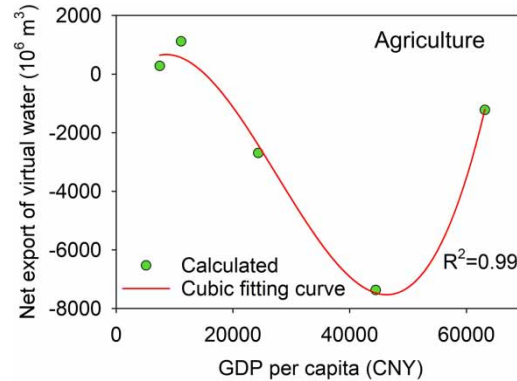
The input and output values of agriculture and industry are from Input-Output Tables of Shandong Province in 1997, 2002, 2007, 2012 and 2017. The rainfall, groundwater funnel areas, quantities of Yellow River water and SNWT water are from Water Resources Bulletins of Shandong Province in 1997–2017. The gross domestic product (GDP) and discharge amounts of industrial wastewater are from the Shandong Statistical Yearbooks in 1998–2018.

## 3. RESULTS AND DISCUSSIONS

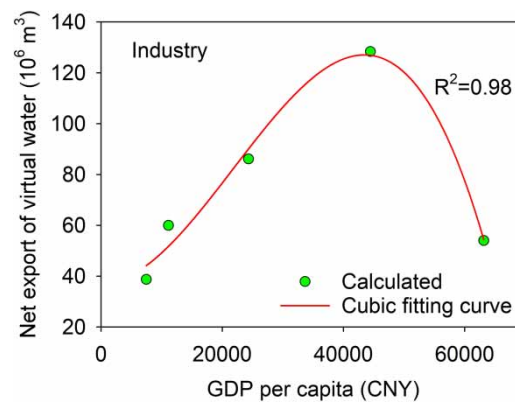
### 3.1. Virtual water net exports of agriculture and industry

The actual agricultural and industrial virtual water net exports are calculated by Equation (1). Virtual water net exports and *per capita* GDP changes are shown in Figures 2 and 3.

From Figure 2, with the development of economy, an N-shaped trend exists with regard to the net exports of agricultural virtual water. In the first stage, net exports increased slowly in the period from 1997 to 2002. In the second stage, net



**Figure 2** | Agricultural virtual water net exports.



**Figure 3** | Industrial virtual water net exports.

exports decreased. The net exports of agriculture did not become imports until the GDP *per capita* was 14,540 CNY in 2004. Then the net imports were increasing. The net imports reached the maximum of 7,524.54 million  $\text{m}^3$  when the GDP became 48,763 CNY in 2013. In the third stage, the net imports decreased, but it was still net imports of 1,220.61 million  $\text{m}^3$  in 2017.

From Figure 3, with the development of the economy, an inverted U-shaped trend exists with regard to the net export of industrial virtual water. With the increase of GDP *per capita*, industrial virtual water remains a net export. In the first stage, the net exports increased. The net exports reached the maximum when the GDP became 44464 CNY in 2012 and the amount was 128.38 million  $\text{m}^3$ . In the third stage, the net exports decreased to 53.98 million  $\text{m}^3$  when GDP was 63162 CNY in 2017.

Comparing virtual water net exports of agriculture with industry, it is found that agriculture is a big water user.

### 3.2. Relationships between virtual water net exports and water environments

The annual average total water supply for Shandong Province in 2010–2015 was 24.7 billion  $\text{m}^3$ , of which groundwater supply accounts for 53%, surface water supply accounts for 25% and foreign water accounts for 22%. Furthermore the development and utilization rate of local surface water is 32%, and the exploitation rate of shallow groundwater is 64%. Overexploitation of water resources first has negative impacts on groundwater.

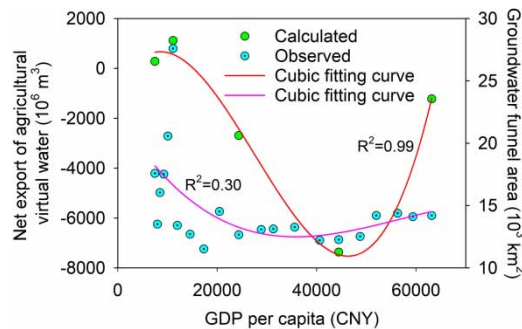
Additionally, the uneven distributions of rainfall at inter-annual and inter-decadal levels and the constructions of reservoirs make the ecological water amount of the river seriously insufficient. Although the ecological water quantity of the river is only required to be 10% of the average annual runoff quantity, it is difficult to achieve for most large and medium-sized reservoirs. In non-flood season, river channels are mainly recharged by reclaimed water. Hence the quality of the treated industrial wastewater has important influence on the quality of the ecological water of the river.

Therefore, in order to study the impacts of virtual water net exports on water environments, groundwater funnel areas and treated industrial wastewater amounts are taken as examples.

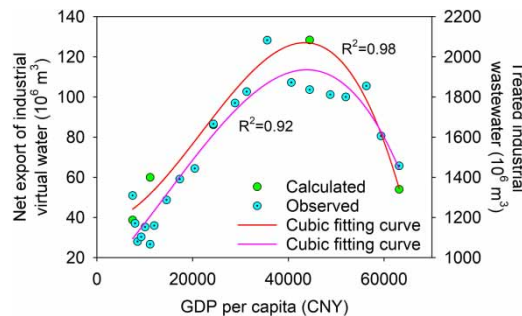
As is shown in Figure 4, with the economic growth, the groundwater funnel area first reduced and then increased in 1997–2017. In 2002–2017, it had the same trend with agricultural virtual water net exports roughly. Broadly speaking, in 2002–2012, for every 1000 CNY of GDP *per capita* increase, the groundwater funnel area reduced by 106.44 km<sup>2</sup>; in 2012–2017, the groundwater funnel area increased by 92.43 km<sup>2</sup>. Similarly, for every 1000 CNY of GDP *per capita* increase, the agricultural virtual water net export reduced by 275.70 million m<sup>3</sup> in 2002–2012 and increased by 237.30 million m<sup>3</sup> in 2012–2017. Thus, in 2002–2012, for every 1 million m<sup>3</sup> of agricultural virtual water net export reduction, the groundwater funnel area reduced by 0.38 km<sup>2</sup>. In 2012–2017, for every 1 million m<sup>3</sup> of agricultural virtual water net export increase, the groundwater funnel area increased by 0.39 km<sup>2</sup>.

As is shown in Figure 5, with the economic growth, the treated industrial wastewater first increased and then reduced in 1997–2017, being consistent with the changes of industrial virtual water net exports. For every 1000 CNY of GDP *per capita* increase, in 1997–2012, the discharge amount of treated industrial wastewater increased by 24.49 million m<sup>3</sup>; in 2012–2017, it reduced by 19.12 million m<sup>3</sup> correspondingly. Similarly, for every 1000 CNY of GDP *per capita* increase, the industrial virtual water net exports increased by 2.60 million m<sup>3</sup> in 1997–2012 and reduced by 2.80 million m<sup>3</sup> in 2012–2017. Thus, in 1997–2012, for every 1 m<sup>3</sup> of industrial virtual water export increase, the discharge amount of wastewater increased by 9.41 m<sup>3</sup>. In 2012–2017, for every 1 m<sup>3</sup> of industrial virtual water export reduction, the discharge amount of wastewater reduced by 6.82 m<sup>3</sup>.

From the above correlation analysis, it can be concluded that the change trends of the groundwater funnel area and treated industrial wastewater are related to the virtual water net exports of agriculture and industry respectively to a certain extent. As the agricultural virtual water net exports increase, groundwater funnel areas increase, which will lead to insufficient groundwater supply and land subsidence, worsening the ecological environment. Similarly, as the industrial virtual water net exports increase, the discharges of industrial wastewater increase, which will put pressure on wastewater treatment in factories. At the same time, the treated wastewater discharged into the river will also change the original ecological environment and have a certain impact on the water environment of the river. Fortunately, with the development of the economy, the net imports of agricultural virtual water are maintained and the net exports of industrial virtual water are reduced, which is beneficial to the ecological environment of Shandong Province. It can be said that the increment of net imports or the reduction of net exports of industrial virtual water not only reduces the intake of physical water, but also reduces the discharges of industrial



**Figure 4** | Agricultural virtual water net exports and groundwater funnel areas.



**Figure 5** | Virtual water net exports and wastewater discharge amounts of industry.



wastewater and water pollution. There is no doubt that it is one of the effective measures for industrial water saving, and can achieve many benefits at one stroke. What's more, the increment of net imports or reduction of net exports of agricultural virtual water can reduce groundwater overdraft areas and increase the ecological water consumptions of the river, bringing eco-environmental benefits.

### 3.3. Comparison of virtual water net exports under human activities

#### 3.3.1. Impacts of foreign water

The virtual water net exports of agriculture and industry under different foreign water supplies are calculated by Equations (2)–(10). The results are presented in Figure 6.

As is depicted in Figure 6, when the Yellow River water and the SNWT water are considered, there are increments on the virtual water net exports of agriculture and industry compared with that under the adjusted same local water supply. When considering the Yellow River water, the agricultural virtual water net exports of the five statistical years increased by 4.31%, 22.65%, 16.71%, 1.29% and 6.32%, respectively compared with that under the adjusted same local water supply. Correspondingly, the industrial virtual water net exports increased by 52.02%, 150.19%, 67.08%, 82.07% and 85.43%, respectively. The results show that the Yellow River water impacts industrial virtual water net exports more than the agricultural virtual water net exports do. Subsequently, the impacts of Yellow River water reduction and SNWT water increment on virtual water net exports are studied taking 1997 and 2017 as examples, respectively. The results are shown in Tables 1 and 2.

From Table 1, the net export of agricultural virtual water was 265.69 million m<sup>3</sup> under the adjusted same local water supply ( $W'_{S0}$ ) in 1997. After considering the Yellow River water ( $W''_{S1}$ ), the net export of agricultural virtual water increased by 11.46 million m<sup>3</sup> and 4.31% compared with that under  $W'_{S0}$ . After considering the virtual Yellow River water ( $W''_{S2}$ ), the net export of agricultural virtual water increased by 81.32 million m<sup>3</sup> and 30.61% compared with that under  $W'_{S0}$ . The net export of agricultural virtual water reduced by 69.86 million m<sup>3</sup> and 20.13% in  $W''_{S1}$  compared with that under  $W''_{S2}$ .

For industrial virtual water, the net export was 23.57 million m<sup>3</sup> under the adjusted same local water supply ( $W'_{S0}$ ) in 1997. After considering the Yellow River water ( $W''_{S1}$ ) and virtual Yellow River water ( $W''_{S2}$ ), the net exports of industrial virtual water increased by 12.26 million m<sup>3</sup> and 47.62 million m<sup>3</sup> respectively compared with that in  $W'_{S0}$ , increasing 52.02% and 202.04% respectively. The net exports of industrial virtual water reduced by 35.36 million m<sup>3</sup> and 49.67% under  $W''_{S1}$  compared with that under  $W''_{S2}$ .

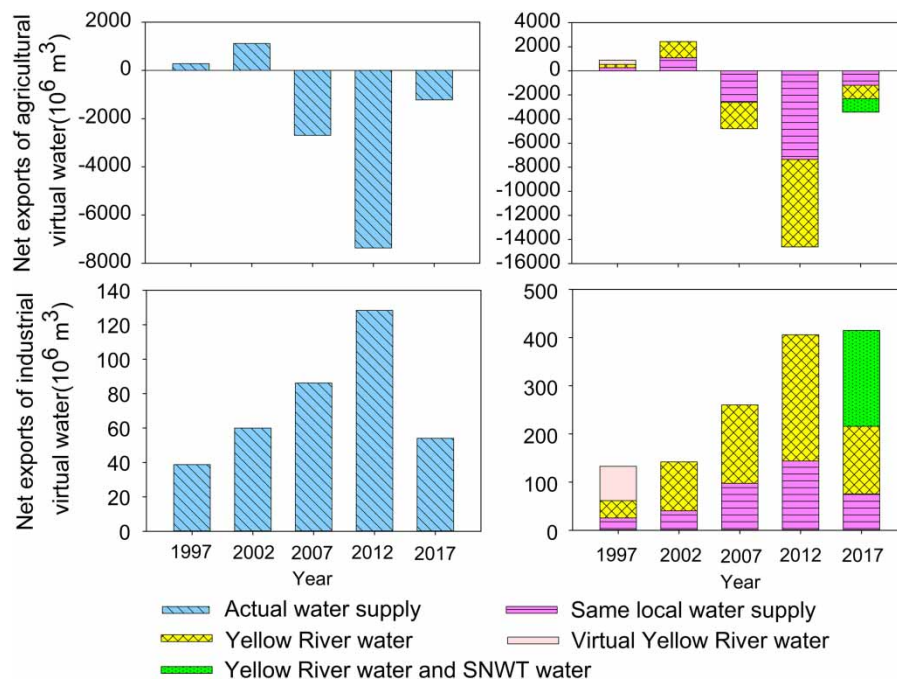


Figure 6 | Virtual water net exports under different foreign water supplies.

**Table 1** | Virtual water net exports in 1997 (Unit:  $10^6 \text{ m}^3$ )

Water supply	Agriculture	Industry
$W'_{S0}$	265.69	23.57
$W''_{S1}$	277.15	35.83
$W''_{S2}$	347.01	71.19

**Table 2** | Virtual water net exports in 2017 (Unit:  $10^6 \text{ m}^3$ )

Water supply	Agriculture	Industry
$W'_{S0}$	-1,195.22	75.63
$W''_{S1}$	-1,119.66	140.24
$W''_{S1} + W_{SNWT}$	-1,104.84	199.12

Therefore, it can be seen that the virtual water net exports of agriculture and industry reduced by 20.13% and 49.67% respectively due to the cut-off of the Yellow River channel compared with that without a cut-off.

From Table 2, the net export of agricultural virtual water was  $-1,195.22$  million  $\text{m}^3$  under the adjusted same local water supply ( $W'_{S0}$ ) in 2017. After considering the Yellow River water ( $W''_{S1}$ ), the net export of agricultural virtual water increased by 75.56 million  $\text{m}^3$  and 6.32% compared with that under  $W'_{S0}$ . When considering the quantity of water returned by industry, the net export of agricultural virtual water increased by 90.38 million  $\text{m}^3$  and 7.56% under the combined effects of foreign water ( $W''_{S1} + W_{SNWT}$ ) compared with that under  $W'_{S0}$ . The net exports of agricultural virtual water increased by 14.82 million  $\text{m}^3$  and 1.32% under  $W''_{S1} + W_{SNWT}$  compared with that under  $W''_{S1}$ .

For industrial virtual water, the net export was 75.63 million  $\text{m}^3$  under the same local water supply ( $W'_{S0}$ ) in 1997. The net export increased by 64.61 million  $\text{m}^3$  and 123.49 million  $\text{m}^3$  respectively under the  $W''_{S1}$  and  $W''_{S1} + W_{SNWT}$  compared with that under  $W'_{S0}$ , increasing 85.43% and 163.28% respectively. The net exports of industrial virtual water increased by 58.88 million  $\text{m}^3$  and 41.99% in  $W''_{S1} + W_{SNWT}$  compared with that under  $W''_{S1}$ .

Therefore, it can be seen that if the SNWT water is consumed by industry, the net export of industrial virtual water will increase by 41.99% compared with that without SNWT water. If industry returns the corresponding amount of water to agriculture, the net export of agricultural virtual water will increase by 1.32% compared with that without SNWT water.

### 3.3.2. Impacts of water management policy

Comparable water quotas of agriculture and industry are calculated by Equation (11). The results are shown in Table 3.

It can be seen from Table 3 that the comparable water quotas of agriculture and industry are reducing year by year. For the agricultural water quota, it reduced by 24.26% in 2012 compared with that in 2007, and reduced by 31.84% in 2017 compared with that in 2012. For the industrial water quota, it reduced by 35.29% and 48.49% respectively. The effects of SNWT water on the comparable water quotas have been removed. Moreover, it is assumed that the water saving level in the two five years is the same. Therefore, if the most stringent water management policy had not been implemented in 2015, the water quotas of agriculture and industry in 2017 should be 20,415.68  $\text{m}^3/\text{million CNY}$  and 176.54  $\text{m}^3/\text{million CNY}$ , respectively. It can be concluded that because of the implementation of the policy, the water quotas of agriculture and industry reduced by 10.01% and 20.39%, respectively compared with that without the policy in 2017. That is, the reductions of virtual water net exports were consistent with that of the water quotas in 2017.

**Table 3** | Comparable water quotas of agriculture and industry (Unit:  $\text{m}^3/10^6 \text{ CNY}$ )

Year	Agriculture	Industry
2007	35,587.02	421.59
2012	26,954.95	272.82
2017	18,371.30	140.54

In summary, the increments of agricultural and industrial virtual water net exports from 1997 to 2002 are mainly due to the increments of Yellow River water. The increment of agricultural virtual water net exports from 2012 to 2017 is mainly due to the SNWT water, while the reduction of industrial virtual water net export was mainly due to the water management policy.

#### 4. CONCLUSIONS

In this paper, the virtual water net exports of agriculture and industry have been studied under the effects of both nature and human activities over the past 20 years in water-short Shandong Province. The main conclusions of this research are as follows.

From 1997 to 2017, with the development of the economy, an N-shaped trend and inverted U-shaped trend exist with regard to the net exports of agricultural and industrial virtual water, respectively. Agricultural virtual water changed from net export to net import in 2004, and has been a net import ever since. Industrial virtual water has constantly been a net export.

Virtual water net imports are beneficial to water environments of water deficient areas, while net exports are harmful. Correlation analysis showed that in 2002–2012, for every 1 million m<sup>3</sup> of agricultural virtual water net export that was reduced, the groundwater funnel area reduced by 0.38 km<sup>2</sup>. In 2012–2017, for every 1 million m<sup>3</sup> of agricultural virtual water net export was increased, the groundwater funnel area increased by 0.39 km<sup>2</sup>. In 1997–2012, for every 1 m<sup>3</sup> of industrial virtual water export increased, the wastewater increased by 9.41 m<sup>3</sup>. In 2012–2017, for every 1 m<sup>3</sup> of industrial virtual water export reduced, the wastewater reduced by 6.82 m<sup>3</sup>. The increment of net imports or the reduction of net exports of industrial virtual water not only reduce the physical water intakes, but also reduce the discharge of industrial wastewater and water pollution. This is one of the effective measures of industrial water saving, and can achieve many benefits at one stroke. What is more, the increments of net imports or reduction of net exports of agricultural virtual water can reduce the groundwater overdraft area and increase the ecological water consumption of the river, bringing eco-environmental benefits.

From 1997 to 2002, the increments of agricultural and industrial virtual water net exports were affected by the Yellow River water. In 1997, the net exports of agricultural and industrial virtual water reduced by 20.13% and 49.67% respectively because of the cut-off of the Yellow River channel. In 2017, if the SNWT water is consumed by industry, the net export of industrial virtual water increases by 41.99% compared with that without SNWT water. If the industry returns the corresponding amount of water to agriculture, the net export of agricultural virtual water increases by 1.32% compared with that without SNWT water. Because of the implementation of the policy, the reductions of agricultural and industrial virtual water net exports were reduced by 10.01% and 20.39% respectively compared with that without the policy in 2017. Therefore, from 2012 to 2017, the increment of agricultural virtual water net exports was affected by SNWT water, while the reduction of industrial virtual water net exports was affected by water management policy.

In this paper, a new comparative analysis method has been proposed. Climates are adjusted into a unified standard, and the impacts of human activities on the virtual water net exports are studied quantitatively under the premise of considering economic developments and water-saving levels. However, the statistics of Input-Output Tables are only performed on the year with last digits of 2 and 7. Data are relatively less because of the long time interval of five years, but certain trends can be reflected. This paper provides direction for the quantitative analysis of virtual water trade under the effects of human activities – i.e. of foreign water and water policy. The reasons of the changes of virtual water trade are explained. It can be concluded that the application of the virtual water tools have led to a higher precision in the quantification and in the coherence and quality of water management decisions than by using classical hydrological evaluation and quantification procedures. From a new perspective, it provides a scientific basis for the decision-making of integrated water management of physical water and virtual water in Shandong Province, as well as in other water shortage areas.

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#### DATA AVAILABILITY STATEMENT

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

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