

The relationships and trends of interregional virtual water trade based on an MRIO model

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ABSTRACT

To consider the problem of uneven distribution of water resources, a study on the relationship and trend of virtual water trade between regions based on an Multi-Regional Input-Output (MRIO) model was proposed. Using an MRIO model, the spatial distribution and changing trends of China's inter-regional virtual water trade from 2014 to 2019 were evaluated. The empirical results show that, due to the difference in water use efficiency and production processes in different sectors, the direct and indirect water use coefficients and demand coefficients are different in different regions. In some water-poor areas (regions with low water availability), more products with high water use coefficients are exported, while more water-rich areas (regions with high water availability) export products with lower water use coefficients. The inter-regional virtual water trade only alleviates the shortage of water resources in some poor water areas in China. Some poor water areas export a large amount of virtual water, and the rich water areas import a large amount of virtual water or only maintain a partial virtual water balance. However, the demand coefficient tends to increase, and the trade adjustment trends in different regions and changes in regional virtual water trade relations are not conducive to alleviating the shortage of water resources caused by uneven distribution. The tension coefficients between the food manufacturing and tobacco processing industry, the textile and clothing industry, and the wood processing and furniture manufacturing industries in the Northeast region are relatively large, with the demand coefficients are 92.9, 65.5 and 156.7 respectively. Relatively speaking, the tensile coefficients of areas rich in natural water resources such as the eastern coastal, southern coastal, southwest, and central areas are generally low. According to the production situation, the regional virtual water trade relationship should be adjusted from the level of the national master plan.

Key words: direct water consumption, distribution of water resources, indirect water consumption, virtual water transfer

HIGHLIGHTS

- Innovations in the water utilization efficiency of agricultural entities and establish a virtual water compensation mechanism and cooperation mechanism are proposed.
- Suggestions for optimizing the regional industrial structure are put forward, providing a scientific basis for the sustainable use of water resources.
- An MRIO model was used to analyze the relationship and trend of the virtual water trade between regions.

1. INTRODUCTION

Water is the source of life and an indispensable resource for economic and social development (Bi *et al.* 2021; Sun & Khayatnezhad 2021; Tao *et al.* 2021; Xu *et al.* 2021; Yin *et al.* 2021; Zhu *et al.* 2021). In 2011, China's total water resources reached 2325.8 billion cubic meters (BCM), ($2325.8 \times 10^8 \text{ m}^3$) ranking first in the world, but the per capita water resource was only $1,726 \text{ m}^3$, which was very close to the international water shortage warning line (Duarte *et al.* 2019). Several studies have shown that the intensity of water demand is increasing with rapid economic growth (Jia *et al.* 2020; Karasakal *et al.* 2020; Si *et al.* 2020; Huang *et al.* 2021; Li *et al.* 2021; Ma *et al.* 2021; Ren & Khayatnezhad 2021; Sun *et al.* 2021). What's more, the spatial distribution of China's water resources is quite different. The northern area, whose population accounts for 46% of the country, only accounts for 25% of the country's water resources (Chouchane *et al.* 2017).

Uneven distribution of water resources aggravates the possibility of water crisis. There are different ways to alleviate the lack of water resources, especially the uneven spatial distribution, such as by the direct allocation of water resource, e.g., the South to North Water Diversion Project, the establishment of industrial structures in line with local water resource

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conditions and the construction of a water-saving society, as well as a virtual water strategy and its implementation, to be discussed in this paper. The goal of so-called virtual water strategy is to make water deficient areas obtain products with high water consumption intensity by regulating interregional product trade (Serrano & Valbuena 2020), so as to meet the demand of products and indirectly reallocate water resources, so as to make full use of the national water resources and alleviate the water shortage situation in water deficient areas (Antonelli *et al.* 2017).

Virtual water trade is the core of virtual water strategy, that is, the water trade behind interregional product trade. The related technical problem is how to reveal virtual water trade through product trade, so as to provide a quantitative basis for further analysis or future planning (Duarte *et al.* 2019). Existing studies include Quanliang *et al.* (2018) who established a multi-objective optimization model considering the trade-off between the economic benefits of water use and environmental impact, and optimized the allocation of physical water resources and virtual water resources of different water users in Beijing. Surface water, groundwater, transfer water and reclaimed water constitute the physical resources of the water supplier, while the virtual water flow is related to the trade of five main crops and three livestock products in the agricultural sector. In terms of water demand, cities, industry, environment and agriculture are considered. For the traditional allocation of physical water resources, the results showed that agriculture and city were the two main water users, while groundwater and surface water met about 70% of the water demand of different water users. When the virtual water trade of eight kinds of agricultural products was considered in the process of water allocation, the proportion of agricultural consumption in the total water demand dropped to 45%, and the proportion of groundwater consumption in the total water supply dropped to 24%. Virtual water trade overturned the traditional composition of agricultural water supply from different sources and become the largest water source in Beijing. In addition, it was found that environmental demand accounted for a similar percentage of water consumption in each water source, and reclaimed water was the main water source for industrial and environmental users. The results showed that material water resources mainly met the consumption of cities and environment, and the imbalance between supply and demand of water resources in water shortage areas could be compensated by virtual water import.

Yicheng *et al.* (2018) described the process of crop virtual water content and flow. In order to establish an evaluation system of virtual water trade of agricultural products and quantitatively determine the virtual water flow in the region, using the meteorological and agricultural data from 2014 to 2019, the virtual water trade of agricultural products in China and elsewhere was comprehensively analyzed, and the virtual water and virtual water trade of three main crops were discussed. The virtual water content of grain crops in North and South China was 1293 and 942 M/T, respectively, and the national average value was 1117 M/T. There was a significant regional difference in the virtual water content of each crop. The virtual water trade of agricultural products among regions in China was not in line with the expectation of water resource endowment. The transfer of crops from North to South China would have a significant impact on the sustainable use of water resources, and would increase the shortage of water resources in northern China. China has a trade surplus in the global virtual water trade of agricultural products. The export volume of virtual water of agricultural products was 31.5 BCM/year, whilst the import volume was 145 BCM/year. The net import volume of virtual water of agricultural products increased from 44 BCM/year to 25 BCM/year in 2019, and reached 178 BCM/year in 2014. In 2019, the further conclusion was that the trend of total virtual water, green water and blue water of agricultural products increased year by year, and the sharp increase of agricultural imports led to the decline of the domestic agricultural production self-sufficiency rate, which provided a basis for the comprehensive evaluation of crop planting structure adjustment, grain import and export and regional water resources development and utilization potential. Based on the interregional input-output model, Xueni (2014) studied the spatial distribution and change trend of China's Interregional virtual water trade from 2014 to 2019, in order to demonstrate whether China's existing interregional trade has really played a role in alleviating the pressure of water shortage. The empirical results showed that, due to different water use efficiency and different production processes, the direct water use coefficient, indirect water use coefficient and demand coefficient were different in different regions and sectors. Some water deficient regions exported more products with high water use coefficient, while water rich regions exported more products with low water use coefficient. Cross regional virtual water trade only alleviated the water shortage problem in some water deficient regions of China. Some water deficient regions exported a large amount of virtual water, while the net inflow of virtual water in water rich regions was large or only maintained the balance of local virtual water inflow and outflow. With the gradual increase of water consumption, the direct water consumption coefficient and total water consumption coefficient of different sectors in different regions generally decreased, but the demand coefficient had an increasing trend. The trade adjustment trend of different departments in different regions and the change of regional virtual water trade relationship were not conducive to alleviate the water shortage caused by uneven distribution. Xinxueqi *et al.* (2020) conducted a quantitative analysis on the production water footprint of main crops in Northwest China

from 2014 to 2019 and on the virtual water flow relationship with agricultural products trade. On this basis, the water resource pressure caused by agricultural products trade export in Northwest China was evaluated. The results showed that the production water footprint of main crops in Northwest China showed an upward trend from 2014 to 2019. At the same time, the virtual water momentum associated with agricultural products trade increased significantly, from 22 BCM in 2014 to 27.299 BCM in 2019, which seriously increased the pressure on local water resources.

For this reason, from the perspective of technological development and macro-strategy, it is proposed to innovate the water utilization efficiency of agricultural entities and establish a virtual water compensation mechanism and cooperation mechanism. Countermeasures and suggestions for optimizing and adjusting the regional industrial structure are put forward, providing a scientific basis for the sustainable use of water resources in Northwest China. Based on the above research background, this paper uses the Multi-Regional Input-Output (MRIO) model to analyze the relationship and trend of the virtual water trade between regions. The MRIO model can cover the production conditions of the country and all trading partners, overcome the estimation bias of water resources utilization, and objectively define the national water trade, to better illustrate the relationship and trend of virtual water trade between regions to alleviate the current situation of water shortage.

2. MATERIALS AND METHODS

2.1. Research methods

Application of artificial intelligence is one of the main techniques for planning and management of research concepts (Zhou *et al.* 2016, 2021a, 2021b, 2021c; Li *et al.* 2017; Deng *et al.* 2019, 2021; Guo *et al.* 2021; Hou *et al.* 2021). The MRIO model was first proposed by economist Leontief in the 1930s, mainly to reflect the relationship between various sectors (industries) of the economic system (Nulkar 2020). The interregional input-output table is based on the regional input-output table, using interregional trade data to internalize the inflow and outflow of interregional goods and services, and connecting and adjusting them according to the same industry classification. Therefore, it can more comprehensively and systematically reflect the economic relations between areas than a single regional input-output table (Masud *et al.* 2019). In this paper, the method is used to reflect the material and technical connection of water use between different departments in different areas, and to show the direct and indirect water demand from different departments in different areas. An interregional input-output table including water consumption was constructed, and the specific method is shown in Table 1.

Using the interregional input-output table to reflect the use of water resources in various areas and departments is mainly done through the direct water consumption coefficient, which represents the water consumption of goods or services per unit of production. The direct use of water system number w'_i is more intuitive and has a clear physical meaning, with the following formula:

$$w'_i = \frac{w'_i}{X'_i} (r = 1, 2 \dots, 8; i = 1, 2 \dots, 14) \quad (1)$$

where w'_i is the direct water use coefficient, and X'_i is the total output (total input) of region r in sector i .

Indirect water consumption in the process of economic production refers to the water resources used by other departments in the area or other regional departments to provide necessary production conditions to meet production needs. Although this part of water consumption does not occur in the department, it is regarded as indirect water consumption in the production of the department, and the direct water consumption and indirect water consumption are added together, that is, the total water consumption is the added value of the water consumption of the whole economic system as a result of increasing the output of a product unit in the department. Since imported products are produced abroad, the output directly and indirectly generated in the production process needs to be eliminated from the total output of all sectors in China. It is assumed that the proportion of imported and domestic products in final use and intermediate use of all sectors is the same, and the proportion of imported products in intermediate use of all sectors is the same. The calculation formula of the complete water consumption coefficient is as follows:

$$\overline{w}'_i = w'_i (I - \alpha A)^{-1} \quad (2)$$

where, w'_i is the direct water system row vector, α is the diagonal matrix of gross domestic product (GDP), whose value is equal to the quotient of the sum of total output and import plus total output, and A is the direct water consumption coefficient matrix.

Table 1 | Summary of interregional input and output including water consumption

		Intermediate use						End use						
		Area 1			Area m			Zone		Area	Export	Total		
		Industry	...	Industry	...	Industry	...	Industry	Zone	Area	Export	Total		
		1	...	n	...	1	...	n	1	...	m	Export	output	
Intermediate input	Area 1	Industry 1	x_{11}^{11}	...	x_{1n}^{11}	...	x_{11}^{1m}	...	x_{1n}^{1m}	F_1^{11}	...	F_1^{1m}	E_1^1	X_1^1
		Industry n	x_{n1}^{11}	...	x_{nn}^{11}	...	x_{n1}^{1m}	...	x_{nm}^{1m}	F_n^{11}	...	F_n^{1m}	E_n^1	x_n^1
	Area m	Industry 1	x_{11}^{m1}	...	x_{1n}^{m1}	...	x_{11}^{mm}	...	x_{1n}^{mm}	F_1^{m1}	...	F_1^{mm}	E_1^m	x_1^m
		Industry n	x_{n1}^{m1}	...	x_{nn}^{m1}	...	x_{n1}^{mm}	...	x_{nm}^{mm}	F_n^{m1}	...	F_n^{mm}	E_n^m	x_n^m
	Import	AM_1^1	...	AM_n^1	...	AM_1^m	...	AM_n^m	FM^1	...	FM^m			
Initial investment		V_1^1	...	V_n^1	...	V_1^m	...	V_n^m						
Total investment		X_1^1	...	X_n^1	...	X_1^m	...	X_n^m						
Water consumption		W_1^1	...	W_n^1	...	W_1^m	...	W_n^m						

x_{ij}^{rs} is the input or use of product in department i of sector r to department j of sector s ; F_i^{rs} is the final demand of s provided by products in department i of sector r ; V_j^s is the initial input of department j in sector s ; X_i^r is the total output (total input) of department i in sector r ; and W_i^r is the water consumption of department i in sector r .

Dividing the total water consumption coefficient by the direct water consumption coefficient gives the demand coefficient of water consumption in this industry, which reflects the driving effect of the output of this sector on the use of water resources in all areas:

$$\delta_i' = \frac{\bar{w}_i'}{w_i'} \tag{3}$$

where w_i' is the direct water coefficient row vector, and δ_i' indicates the driving effect of the sector's output on water use in all regions.

The latent water content in single sector trade is as follows:

$$v_{ij}^{rs} = \bar{w}_j^s \times c_{ij}^{rs} \tag{4}$$

where, v_{ij}^{rs} is the virtual water trade volume of the products imported from sector r of area r and sector j of area s , and c_{ij}^{rs} is the import volume of the products imported from sector i of area r and sector j of area s . Since this paper studies the relationship of virtual water mobilization through trade at the national level, it is more appropriate to use the water intensity of production land to calculate it than to calculate it from the perspective of each area in order to study the local water saving through virtual water trade (Duchin & Lopez 2019).

2.2. Data sources

China adopts a system of compiling input-output questionnaires every two or seven years, but so far the official input-output table of 2020 has not been published, so the input-output table of China in 2019 is the latest data available at present (Melgarejo *et al.* 2019). In order to ensure the timeliness of the research data, the data in this paper is updated to the data of China's interregional input-output table in 2019 based on the latest input-output table. The data used in this paper is from the 'China interregional input-output tables of 2014–2019', which were calculated by the Chenery Moses model through a combination of typical survey and non-survey methods, with good accuracy and authority. The regional input-output table is divided into 8 areas and 17 'sectors', comprising the Northeast area, Beijing-Tianjin area, Northern coastal area (Hebei-Shandong), Eastern coastal area (Jiangsu, Shanghai and Zhejiang), southern coastal area (Fujian, Guangdong and Hainan), central area (Shanxi, Henan, Anhui, Hubei, Hunan and Jiangxi), Northwest area (Mongolia, Shaanxi, Ningxia, Gansu, Qinghai and Xinjiang) and Southwest area (Sichuan, Chongqing, Guangxi, Yunnan, Guizhou and Tibet). Because the liquidity of the

products provided by the construction industry and the service industry is poor compared with the industrial and agricultural products, and the water consumption data is difficult to obtain, this paper only analyzes the situation of the 14 industrial sectors other than the construction industry and the two service industries (Zhang *et al.* 2017). However, with more detailed information of department classification, we can get more accurate conclusions by analyzing the existing sub-departments.

The coefficient of agricultural water consumption can be calculated by Equations (1)–(3). In order to get the direct water consumption coefficient of different industrial departments in different areas, this paper first calculates the national average level of the direct water consumption coefficients of various industrial departments, multiplies and sums up the output value of corresponding departments in each area to get the water consumption of each area under the national average water consumption intensity, and then uses the industrial water consumption of each area to correct. The ratio of industrial water consumption in each region to the water consumption under average water consumption intensity is used as the adjustment coefficient, which is multiplied by the national average water consumption coefficient to obtain the revised direct water consumption coefficient of the different departments in each region, and then the complete water consumption coefficient and demand coefficient are obtained by using Equations (2) and (3). The year of industrial and agricultural water consumption, output value and direct water consumption coefficient of each department in each region of China are consistent with the regional input-output table, which are all from the China Statistical Yearbook and China Environmental Statistical Yearbook, or calculated from relevant data.

2.3. Analysis of the direct water use, complete water use and demand multiplier of different departments

Due to the expansion or compression of the water use coefficients of different industrial sectors in different areas by using the calculated regional adjustment coefficients, it can be seen that the Northeast, Beijing-Tianjin, Northern coastal and Northwest areas with higher water use efficiency in 2019 are almost all areas with water shortage in China, and the adjustment coefficients are less than 1, while the adjustment coefficients of the other four areas are all greater than 1. The direct water consumption coefficient of different departments in each area can be obtained by using the adjustment coefficient, and the complete water consumption coefficient can be obtained by combining with Leontief inverse matrix (Dan *et al.* 2020). On average, the direct consumption coefficient of the 14 industrial sectors in 2019 is higher in turn: power, steam and hot water, gas and tap water production and supply, agriculture, papermaking, printing and stationery manufacturing, chemical industry, and metal smelting and products industry, with the direct water consumption coefficient exceeding $150 \text{ m}^3/10,000 \text{ yuan}$. Among the top five sectors with a large total consumption coefficient, the food manufacturing and the tobacco processing industry replaced the chemical industry, while the other four sectors remained unchanged. In addition, the total water consumption coefficient of the textile and clothing industry and chemical industry also exceeded $500 \text{ m}^3/10,000 \text{ yuan}$ (Peters *et al.* 2010).

From the perspective of regional sector production driving the consumption of water resources in all sectors of the country, the average demand coefficient value of the machinery industry, transportation equipment manufacturing industry, wood processing and furniture manufacturing industry, other manufacturing industry, electronic machinery and electronic communication equipment manufacturing industry is relatively large, all exceed 30 (Yang *et al.* 2019). The demand coefficients (as shown in Table 2) in 3 sectors in Northeast China are larger, including in the food manufacturing and tobacco processing industry, textile and clothing industry, and the wood processing and furniture manufacturing industry, with demand coefficients of 92.9, 65.5 and 156.7 respectively, which are much higher than the average demand coefficients of 28.3, 26.0 and 52.7 in the 8 regions. The demand coefficients of the mechanical industry, electrical machinery and electronic communication equipment and other manufacturing industries in Northeast China and Northern coastal areas are 126.3, 73.0 and 101.9, and 110.5, 65.5 and 94.2, respectively, which are far higher than the average demand coefficients of 66.4, 33.7 and 50.9 in the 8 regions. Relatively speaking, the demand coefficient of areas with abundant natural water resources is generally low, such as the eastern coastal, southern coastal, southwest and central areas. The difference of demand coefficient among different departments is mainly caused by the difference of input raw materials and production process, while the difference of demand coefficient in different areas of the same department is mainly due to the relative difference of water use efficiency between local and intermediate production places. The coefficient of variation of industrial and agricultural production water in 8 regions of China is shown in Table 2.

From the perspective of change trend, from 2014 to 2019, the coefficient of direct water use for production in China's industrial and agricultural sectors decreased significantly, with an average decrease of 57.4%. Except for the wood processing and furniture manufacturing industries in the eastern coastal, southern coastal and central areas, the direct water use coefficient

Table 2 | Demand coefficients of industrial and agricultural production water in 8 areas of China

Time	Sector name	Northeast area	Beijing and Tianjin area	Northern coast	Eastern Coast	Southern coast	Central area	Northwest China	Southwest China
2014	A	1.3	2.1	1.5	1.7	1.4	1.6	1.3	1.6
	B	6.4	4.6	3.6	3.2	2.5	2.8	3.8	3.0
	C	49.7	9.9	8.4	5.4	6.1	4.8	17.2	4.4
	D	46.3	14.5	15.5	8.5	8.7	8.0	22.9	10.0
	E	304.3	94.5	61.9	39.9	33.4	30.8	75.0	46.3
	F	8.1	4.2	3.4	2.5	2.5	2.5	3.9	2.7
	G	3.9	2.9	2.4	1.9	1.7	1.9	2.6	2.1
	H	28.7	13.1	7.9	7.2	7.7	6.4	9.7	6.8
	I	4.1	3.8	3.1	2.5	2.3	2.3	3.6	2.8
	J	54.5	47.0	35.8	23.9	18.7	24.4	42.1	28.7
	K	50.5	19.0	20.7	13.9	9.8	12.8	17.3	13.7
	L	36.0	15.5	31.4	15.9	10.0	17.8	28.1	20.9
	M	102.4	65.4	78.7	58.5	48.4	48.1	101.2	52.9
	N	1.3	1.2	1.1	1.2	1.3	1.2	1.2	1.1
2019	A	1.4	1.5	1.6	1.3	1.3	1.5	1.3	1.4
	B	10.9	7.8	16.9	6.8	4.5	5.1	3.8	4.8
	C	92.9	28.8	29.8	7.4	9.0	6.5	23.4	6.0
	D	65.5	27.8	31.6	8.9	9.2	8.1	31.1	8.8
	E	156.7	52.8	50.0	17.7	20.1	16.6	50.5	17.6
	F	9.2	5.1	5.7	2.4	2.5	2.5	4.0	2.5
	G	5.0	4.0	5.5	2.6	2.5	2.5	4.0	2.5
	H	22.3	18.1	19.7	9.4	12.5	7.5	9.2	9.9
	I	7.5	5.2	7.2	3.0	3.2	2.8	3.6	3.2
	J	126.3	71.4	110.5	34.6	36.1	30.2	55.8	30.0
	K	94.9	59.2	99.7	33.5	28.7	33.0	41.4	29.7
	L	73.0	26.8	65.5	16.5	14.0	17.0	23.1	19.6
	M	101.9	44.1	94.2	26.7	32.1	26.5	30.5	19.7
	N	2.2	2.3	1.7	1.6	1.8	1.3	1.4	1.5

A: Agriculture; B: Mining and dressing industry; C: Food manufacturing and tobacco processing industry; D: Textile and garment industry; E: Wood processing and furniture manufacturing; F: Paper printing and stationery manufacturing industry; G: Chemical industry; H: Non-metallic mineral products industry; I: Metal smelting and products industry; J: Machinery industry; K: Transportation equipment manufacturing industry; L: Electrical machinery and electronic communication equipment manufacturing industry; M: Other manufacturing industries; N: Production and supply of electric steam hot water, gas and tap water

of production in all other areas and departments decreased significantly. The direct water use coefficient of transportation equipment industry, metal smelting and products industry, chemical industry, mining industry and machinery industry decreased by more than 70%. The average decline rate of the total water use coefficient also reached 51.1%. The chemical industry, with the largest decline rate, dropped by 65.1%, and the textile and garment industry, with the smallest decline rate, dropped by 34.9%. In contrast, the water demand coefficient of agriculture, wood processing and furniture manufacturing industry, non-metallic mineral products industry, electrical machinery and electronic communication equipment manufacturing industry and other manufacturing industries in some areas has decreased, while the water demand coefficient of other areas and departments is increasing, with an average increase of 43.5%. In some areas, the demand coefficient of the mining and dressing industry, food manufacturing and tobacco processing industry, machinery industry and transportation equipment manufacturing industry increased rapidly. The increase of demand coefficient can be explained by the relative water use efficiency of different sectors in different regions and the change of interregional trade structure.

3. ANALYSIS ON KEY SECTORS OF INTERREGIONAL VIRTUAL WATER TRADE

In order to investigate which sectors play an important role in local virtual water trade, it is necessary to study the intermediate use and input of virtual water trade among different sectors. In 2019, the key sectors of virtual water trade in each area were different (as shown in Figure 1, which shows the share of virtual water trade in the top five sectors in each area). Among them, metal smelting and products trade plays an important role in the virtual water input of various areas. In addition, the production and supply of electric steam, hot water, gas and tap water in the northeast area, the electrical machinery and

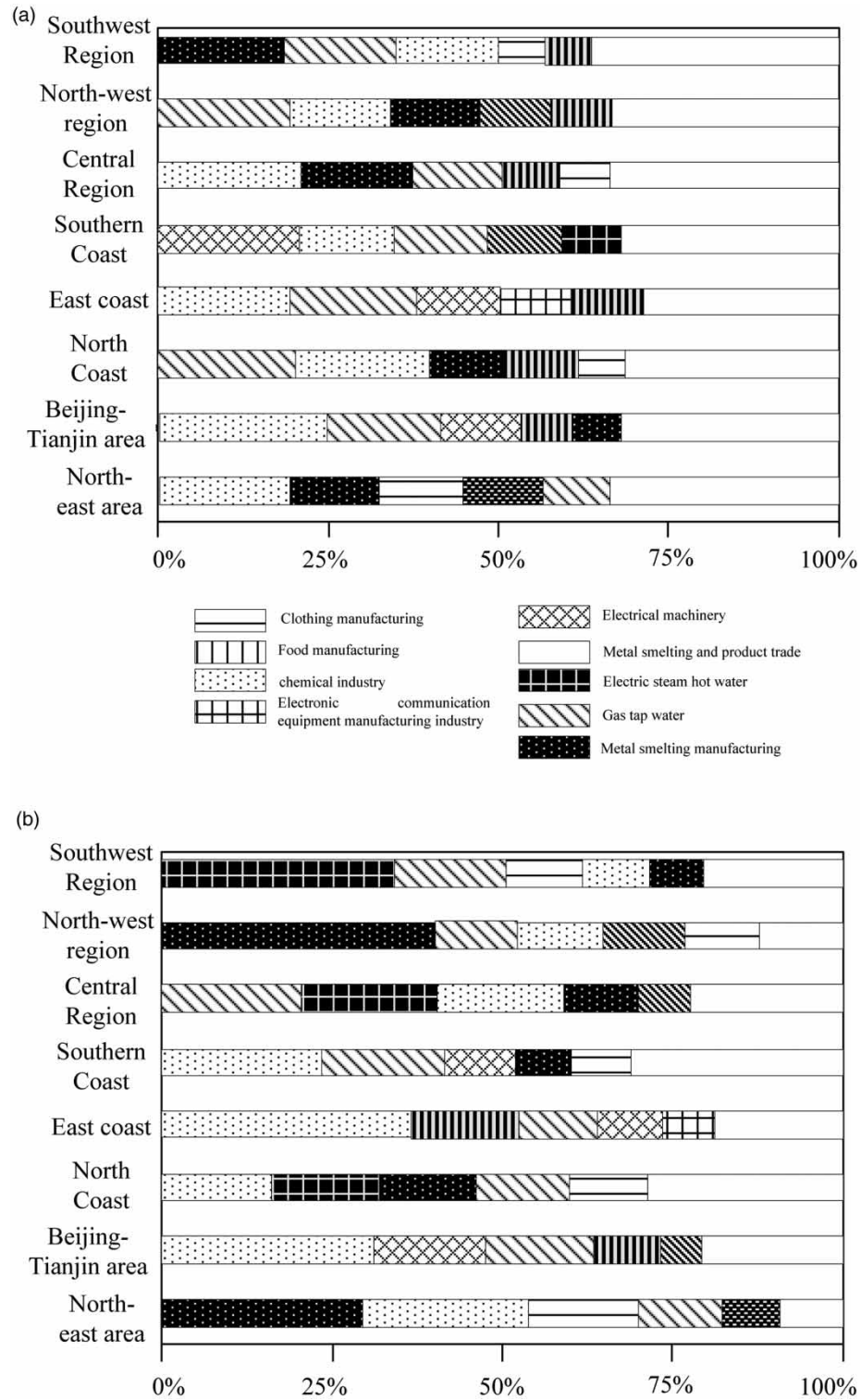


Figure 1 | The import and export of virtual water by key sectors of China's Interregional virtual water trade in 2014 and 2019. (a) Virtual water used in production in 2014. (b) Output of virtual water in 2014. (c) Virtual water used in production in 2019. (d) Output of virtual water in 2019. (continued.)

electronic communication equipment manufacturing industry in Beijing and Tianjin area, the chemical industry, electrical machinery and electronic communication equipment manufacturing industry in the southern coastal area, and the chemical

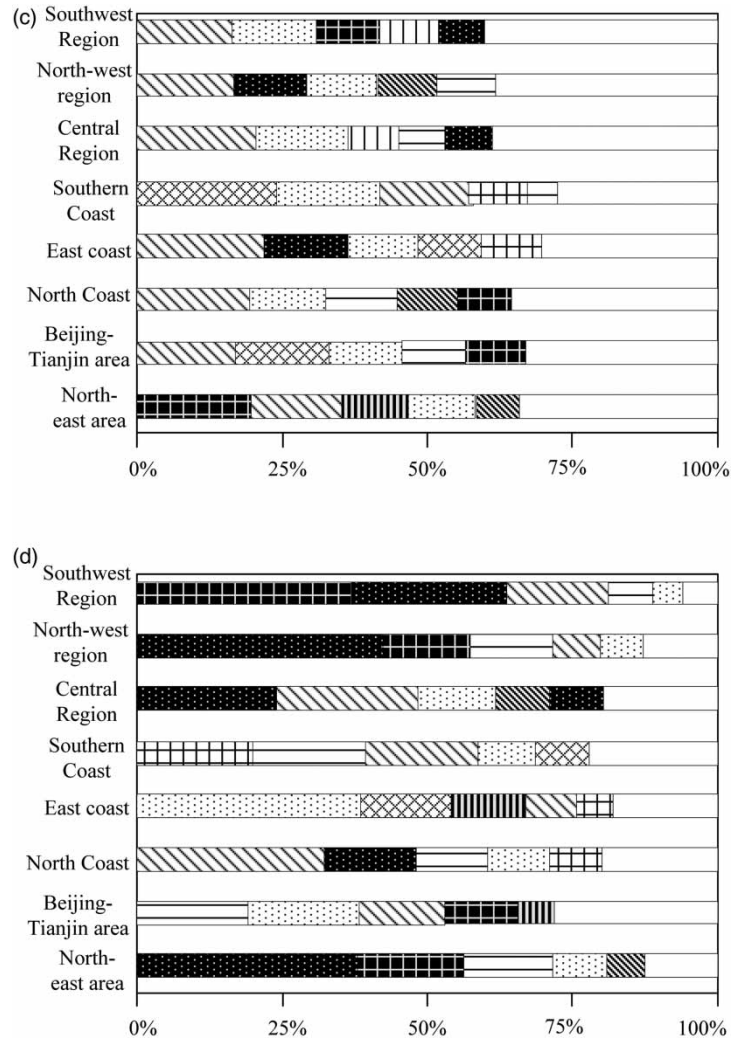


Figure 1 | Continued.

industry in the central area are the key sectors of virtual water import. On the other hand, the key sectors that export virtual water through trade in different areas are quite different. The northeast, northern coastal, northwest and southwest areas export a large amount of virtual water through agricultural trade, as do the food manufacturing industry in the northeast and Beijing-Tianjin area, the clothing manufacturing industry in southern coastal, and the chemical industry in Beijing-Tianjin and eastern coastal, northern coastal, southern coastal, central and western coastal areas. The metal smelting and manufacturing industry in the southern area, the machinery industry in the southern coastal area, the electrical machinery and electronic communication equipment manufacturing industry in the eastern coastal area, and the production and supply industries of electric steam, hot water, gas and tap water in the northeast, central, northwest and southwest areas are the key sectors for each area to export virtual water through trade.

Combined with the comparison of water use intensity of various departments, we can see that the northeast, northwest and northern coastal areas with water shortage and the southwest areas which are water rich account for a large proportion of the trade output of agricultural products with the highest water use coefficient for the products of electric steam hot water, gas and tap water production and supply industries, while the southern coastal areas which are water rich and eastern coastal areas have strong output strength in the electrical machinery and electronic products communication equipment manufacturing industry, machinery industry, metal smelting and products industry with low water use coefficient. High water consumption products mainly flow into the northern coastal, eastern coastal and southern coastal areas. Such industrial structure layout will aggravate the problem of water shortage caused by uneven distribution.

From the perspective of development trend, not all the regional sectors show a growth of virtual water trade volume. Especially in the northeast, Beijing, Tianjin and northwest areas where water is scarce, the virtual water input to agriculture, wood processing, furniture manufacturing, chemical industry and non-metallic mineral property is gradually decreasing. On the contrary, the input of virtual water trade in most water rich areas generally increased, especially through the purchase of products from mining and processing, food processing, textile and clothing, non-metallic mineral manufacturing, metal smelting, electric steam and hot water, gas and tap water production and supply. In terms of trade output, the virtual water output of water rich eastern coastal areas, southern coastal areas and southwest areas to agriculture, the mining and processing industry, food manufacturing industry, wood and paper printing and other products gradually decreased, while the virtual water supply of trade in water poor areas increased by quite a large margin, especially the water supply to the water for mining and processing industry and power steam hot water, gas and tap water production and supply industry in northeast China. Therefore, the water supply to the wood processing and furniture manufacturing products in the northern coastal areas should be strengthened. This trend of industrial structure adjustment is not conducive to alleviate the water shortage in poor water areas.

4. RESULTS AND DISCUSSION

In 2019, China's trade in industrial and agricultural products includes 3.09 trillion (3.09×10^{12}) m^3 of virtual water, of which 0.54 trillion m^3 was transferred through trade among eight areas, accounting for 17.32%. The net flow direction and quantity of virtual water trade in different regions are different: the virtual water from the northeast region to Beijing and Tianjin, northern coastal, eastern coastal and central region has net outflow whilst it has a net inflow to other regions; the Beijing-Tianjin region has a net inflow to all regions; the virtual water from the northern coastal region to Beijing-Tianjin region is a net outflow, and it is a net inflow to other regions; the east coast has a net outflow to Beijing-Tianjin, the north coast and the south coast, and a net inflow to other regions; the south coast has a net outflow to the northeast, Beijing-Tianjin and the north coast, and a net inflow to other regions; the central region has a net outflow to Beijing-Tianjin, the north coast and the south coast, and a net inflow to other regions; and the northwest region has a net outflow to all regions. For virtual water in agricultural and industrial trade, analysis shows that in 2019 China's trade contained 0.50 trillion m^3 and 2.60 trillion m^3 of virtual water for each of them, respectively, and the virtual water transferred through the eight inter-regional trade accounts for 17.1% and 17.4% of the total to each of them, respectively. The volume of virtual water trade between agricultural areas is about 20% of that of industry. Different from the overall situation of industry and agriculture, except for the net inflow of agricultural virtual water to the northwest and the net outflow of trade to other areas, the net outflow of agricultural virtual water from Beijing-Tianjin area to the southeast coastal area is small, and there is also a net outflow of agricultural virtual water from the northern coastal area to the southeast coastal area. In terms of industry, the direction of virtual water trade among areas is basically the same as that of industry and agriculture, except that the northeast area has a net inflow of virtual water to the central area, and the southern coastal area has a net outflow of virtual water to the southwest area.

To sum up, in 2019, a large proportion of virtual water input in Beijing-Tianjin, the northern coastal areas and eastern coastal areas of China was used for local consumption, and was not fully returned to other areas through further processing; by contrast, the northeast, central, northwest and southwest areas use more local water resources for production and then trade export, while the difference between the average (mean) use and input of virtual water in southern coastal areas is not significant. It can be seen that virtual water trade alleviates the poor water situation in Beijing-Tianjin and the northern coastal areas to a certain extent, but the water resources in the northeast and northwest areas, which are also poor in water resources, flow out with trade, while the eastern and southern coastal areas have rich water flow in virtual water through trade, or just maintain the balance of inflow and outflow.

From the perspective of development trend, from 2014–2019, with the continuous expansion of China's interregional trade, the total amount of virtual water of industrial and agricultural products increased by 97.9%, of which the content of agricultural products increased by 87.9%, and the content of industrial products increased by 100.6%. The volume of virtual water trade among most areas showed the same trend. The supply of virtual water for industrial and agricultural products in the northeast, northwest and northern coastal areas increased by 349.5%, 219.3% and 216.4% respectively, while that in the central, southwest and eastern coastal areas increased by 34.6%, 63.5% and 67.9% respectively. The virtual inflow of the central, northwest and southwest areas to the northeast area decreased by 24.9% and that to the

northwest area by 33.8%, on average. Besides the northeast and southern coastal areas, the virtual inflow of Beijing-Tianjin trade also decreased, with an average decrease of 32.1%. This trend is mainly determined by the situation of industrial products trade. On the other hand, the input of virtual water of agricultural products from northeast China to other areas increased rapidly, with an average increase of 504.6%. The growth rates of virtual water input of agricultural products from northwest and northern coastal areas to other areas reached 245.6% and 191.3% respectively, while that from southern coastal areas, eastern coastal areas and central areas to other areas decreased by 57.5%, 14.4% and 10.9% respectively. This development trend leads to the virtual net outflow of some water resource poor areas and the net inflow of water rich areas.

The reasons and trends of the formation of China's virtual water trade relationship can be explained by the differences of water use efficiency, industrial distribution and trade relationships within different areas. Firstly, due to the superposition of the natural distribution of water resources in China, which is more in the south and less in the north, and the increasing population density and economic development level from west to east, the water use efficiency of the regions with relative shortage of water resources for population and economic growth is higher, such as Beijing and Tianjin, northeast, northern coastal and northwest regions; however, due to the excellent natural conditions of water resources, population growth and economic development in the eastern coastal area, southern coastal area, southwest area and some central areas, these areas do not have the necessary driving force to improve water use efficiency, and water use efficiency is low. However, natural factors are an important reason for Beijing and Tianjin to adjust their industrial structure and import virtual water through trade. Secondly, China's industrial distribution and interregional trade interact and mainly depend on local comparative advantages. High quality soil in the north and sufficient light and water resources in the south are important capital for the development of agricultural production, while rich resources in the west are essential for economic development. However, in terms of policy conditions, the eastern and southern coastal areas changed to the market economy development mode earlier, and gained more preferential policies, development opportunities and development resources. Compared with the traditional departments, they are bound to choose the industrial departments with higher added value, more high-tech content and more investment. At this time, the market they withdrew from is occupied by productive areas such as the northeast and northwest. This process also needs to be supported by low water prices. As a populous country, China must pay attention to ensuring the production of self-produced grain, so the water price of agricultural water has always been low. In addition, China has not yet popularized the awareness of water rights and established a perfect water market and ladder water price system, which is also an important reason for the low water price. In view of this, due to the multiple reasons of nature, economy and policy, the interregional virtual water trade relationship, which is contrary to the natural conditions of water resources, has emerged.

5. CONCLUSIONS

This paper proposed a study of the relationship and trend of inter-regional virtual water trade based on the MRIO model, and uses the inter-regional input-output model to study the relationships and trends of virtual water flows generated by China's inter-regional trade from 2014 to 2019. The research results show that water resources utilization efficiency is higher in impoverished water areas such as the northeast, Beijing-Tianjin, northern coastal and northwestern areas. Among the 14 industries considered, the industries with higher direct consumption coefficients are: electricity, steam and hot water, gas and tap water production and supply, agriculture, papermaking, printing and stationery manufacturing, chemical and metal smelting, and product industries. Virtual water trade has alleviated the water shortage in Beijing-Tianjin and the northern coastal areas to a certain extent. However, the northeast and northwest regions where water resources are also scarce have seen virtual water outflows, while the eastern and southern coastal areas have seen virtual water shortages. From the perspective of national overall planning, timely adjustment of the industrial layout and formulation of corresponding industrial trade policies need to be considered according to the local water resources. For example, it is necessary to promote the development of low-intensity water-consuming industries in water poor areas and promote the development of sustainable water use, in order to reduce the burden of water use on impoverished water areas and ensure the healthy and orderly development of the national economy. The limitation of this study is that the fitting method is used to obtain the approximate value of production water consumption in different regions and different departments, ignoring the different degrees of differences between each department and the national average level, which will become the direction of further research. Further improvements can be made when more accurate statistics are available in the future.

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DATA AVAILABILITY STATEMENT

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

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