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Water-Saving Efficiency and Inequality of Virtual Water Trade in China

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Abstract: Virtual water trade is widely considered as a potential method to solve local water shortage and unequal distribution. However, limited research investigated water-saving efficiency and water inequality of inter-provincial virtual water trade. In this study, we sought to explore this issue within China based on the 2015 input-output data. A multi-regional input-output model and a modified input-output model were used to estimate the virtual water trade and its impact on water-saving and water inequality. Our results suggest that: (1) The total virtual water flow across the country is $200.03 \times 10^9 \text{ m}^3$, which accounts for 32.77% of water withdrawal. The agriculture sector contributes the highest proportion (73.99%) to virtual water flow. (2) Virtual water trade could decrease water withdrawal by $446.08 \times 10^9 \text{ m}^3$ compared with withdrawal under no-trade situation at a national level, and 22 provinces could gain benefits through inter-provincial trade with a positive water-saving efficiency index. (3) Virtual water trade also causes water inequality, which exacerbates water scarcity of exported provinces, especially in northwest provinces. (4) There is a conflict between water conservation and water inequality, but different provinces show significant heterogeneity.

Keywords: virtual water; trade; input-output model; water inequality; water-saving efficiency

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1. Introduction

Severe water shortage in China has led to continuous concerns on the strategies of water resources management. With the increasing water demand from human activity, rapidly developing economic and social systems, and accelerated urbanization, water resources in China are under extreme pressure [1,2]. Moreover, uneven distribution of water resources further aggravated the water shortage in China. For example, the yellow river economic belt has 23.78% of the gross domestic product (GDP) and 25.83% of the population in China, yet only shares 12.26% of the national water resources [3]. Additionally, the quantity of freshwater is decreasing under climate change [4]; six large river basins in China have shown a declining trend over the past 60 years, and the declining trend will be faster in the future [5]. This means that the competition for water resources among different industries and regions will become more intensive. Therefore, it is urgent for China to take more initiatives to conserve domestic water resources.

Numerous studies have explored possible ways to alleviate the water shortage. Three possible solutions are considered to make water resources more sustainable, including technological innovation, physical water transfer projects, and virtual water trade [6,7]. However, physical water transfer projects such as “South to North Water Diversion” are costly and might cause negative influences on the local ecosystem [6]. Regional virtual water trade seems to be another alternative way to generate sustainable water management [8–10]. Virtual water trade is referred to water flow embodied in the trade of products and goods [11]. According to factor endowment theory, importing water-intensive products from areas with abundant water resources can alleviate the water resources pressure of water-poor areas and improve water-saving efficiency [12–16]. For example, Dalin et al. [17] found that the international food trade led to enhanced savings in global water resources

over time, and Zhang et al. [18] suggested that virtual water trade benefits both China and other countries along the Belt and Road.

However, the positive role of virtual water trade has not been unanimously recognized [19–22]. For example, Hoekstra and Mekonnen [19] noted that many exporting countries suffered water problems related to their export position, although importing countries could save water resources. Dalin et al. [21] further pointed out that non-renewable groundwater depletion is highly correlated with global food trade, especially in Pakistan, America, and India. It means that the virtual water trade helps import countries plunder water resources of exporting countries, but may cause regional water inequality.

From the perspective of domestic regional virtual water trade, more studies also found that the virtual water trade is not completely reasonable and even violates the factor endowment principle. Some studies mentioned that northern China, characterized by water-scarce areas, predominantly exports water-intensive products to water-abundant southern areas [23–26]. Zhuo et al. [27] also found that the region's virtual water trade embodied in crop flow in China has been from north to south since 2000. Liu et al. [9] argued that virtual water trade potentially increases the water scarcity in water-scarce provinces, although it helps eastern provinces obtain water resources.

Previous findings clearly reported negative effects of virtual water trade on local water resources, which also deepens our concerns on inter-provincial virtual water trade in China. Researchers highlighted that policy-makers should consider the potential environmental externalities when designing virtual water trade policy [28–30]. However, to the best of our knowledge, limited studies considered the difference between water withdrawal under trade and no-trade. For example, Zhao et al. [29] proposed the indicator of hypothetical virtual water use to calculate the scarce water saving. Relatively, there are still few studies on quantifying water production using the modified input-output model. At the same time, they also do not completely investigate the conflict between water saving and water plunder caused by virtual water trade. The existing research on evaluation of the virtual water-saving effect is based on the water withdrawal under trade situation [9,31], that is, they impose homogeneity on the provincial water-use coefficient. Therefore, the net imported-water is equal to the saved/plundered water through trade. However, they might ignore the difference in water use efficiency among different regions. Since the production efficiency of water resources in different regions is not the same, the amount of water imported by a certain region is not necessarily the same as the amount of water used by the region that is not imported but produced by its own products. This means that the imported water might be larger/less than the water saved through imports.

For the estimation approach, two main methods have been widely used in previous studies. One is the bottom-up approach, which is mostly applied in calculating the virtual water volume of agricultural products [32–35]. The other is a top-down approach represented by input-output (IO) analysis. Based on the input-output table covering the entire production process and final use of economic products, IO analysis can trace the trade-related water resources' effects in the general relationship of various industries [36,37]. Compared with the single regional input-output table, a multi-regional input-output table can reflect economic relations between regions more comprehensively and systematically. Therefore, the application of the multi-regional input-output (MRIO) model in tracing virtual water trade is more common [38–40]. However, the MRIO model cannot trace the virtual water flow under no-trade conditions. A modified input-output (MIO) model can solve this problem by deriving the single regional input-output table without trade from the multiregional input-output table [41]. Therefore, we applied the MRIO model to calculate the provincial virtual water flow under trade condition, and then derived the MIO model based on the traditional MRIO model to calculate water withdrawal of each province under no-trade conditions.

The purpose of this paper is twofold. First, we aimed to investigate the water withdrawal with trade and without trade and explore the impact of virtual water trade on water withdrawal by constructing a water-saving efficiency index. We sought to discover

whether inter-provincial virtual water trade decreases national and local water withdrawal by developing MRIO and MIO models, and then estimate the heterogeneity of provinces and sectors. Second, we explored the water inequality of inter-provincial virtual water trade within China by constructing a water plunder index. Then, we tried to find solutions that can improve water-saving efficiency without widening the regional water inequality by analyzing the conflict between water-saving efficiency and water plunder.

2. Materials and Methods

2.1. Multi-Regional Input-Output Model

Input-output analysis was developed by Leontief [42] in the late 1930s, which is widely applied in the research of trade-related environmental and energy effects. In the multi-regional input-output (MRIO) model, the balance of production activities in province r can be expressed as:

$$x_i^r = \sum_{s=1}^n \sum_{j=1}^m z_{ij}^{rs} + \sum_{s=1}^n f_i^{rs} + e_i^r \quad (1)$$

where x_i^r is the total output of sector i in province r , f_i^{rs} is the final use of sector i from province r to province s , e_i^r is the exports of sector i in province r , z_{ij}^{rs} is the intermediate input from the sector i of province r to the sector j of province s .

The direct input coefficient a_{ij}^{rs} can be calculated as $a_{ij}^{rs} = z_{ij}^{rs} / x_j^s$, where x_j^s is the total output of sector j in province s , and Equation (1) can be written as:

$$x_i^r = \sum_{s=1}^n \sum_{j=1}^m a_{ij}^{rs} x_j^s + \sum_{s=1}^n f_i^{rs} + e_i^r \quad (2)$$

Solving for the total output and expressed by matrix form, Equation (2) can be written as:

$$X^r = (I - A^{rs})^{-1} (F^{rs} + E^r) \quad (3)$$

The water intensity of province r can be calculated as:

$$y_i^r = w_i^r / x_i^r \quad (4)$$

where y_i^r donates the water intensity of sector i in province r , w_i^r is the water withdrawal of sector i in province r , and x_i^r is the total output of sector i in province r .

Then, the water withdrawal of province r expressed by matrix form is equal to:

$$W_T^r = Y^r (I - A^{rs})^{-1} (F^{rs} + E^r) \quad (5)$$

where W_T^r is the matrix of water withdrawal in province r under trade, and Y^r is the matrix of water intensity in province r .

2.2. Modified Input-Output Model

The modified input-output (MIO) model can calculate the water withdrawal for each province under no-trade. According to Yang et al. [19], we derived the single regional input-output table in each region from the multiregional input-output table to guarantee the equality of the final consumption under both trade and under no-trade conditions. The traditional MRIO model can be expressed as:

$$x^r = z^{rr} + f^{rr} + \sum_s z^{sr} + \sum_s f^{sr} + \sum_w z^{wr} + \sum_w f^{wr} + \sum_s ex^{rs} + \sum_s ex^{rw} - \sum_s im^{sr} - \sum_w im^{wr} \quad (6)$$

where x^r is the total output of province r , z^{rr} is the intermediate input from province r to province r , f^{rr} is the final use from province r to province r , z^{sr} is the intermediate input from province s to province r , f^{sr} is the final use from province s to province r , z^{wr} is the intermediate input from foreign country w to province r , f^{wr} is the final use from foreign country w to province r , ex^{rs} is export from province r to province s , ex^{rw} is export from

province r to foreign country w , im^{sr} is import from province s to province r , im^{wr} is import from foreign country w to province r .

Due to $\sum_w im^{wr} = \sum_w z^{wr} + \sum_w f^{wr}$, Equation (6) can be written as:

$$x^r = z^{rr} + f^{rr} + \sum_s z^{sr} + \sum_s f^{sr} + \sum_s ex^{rs} + \sum_s ex^{rw} - \sum_s im^{sr} \quad (7)$$

Using matrix notation, Equation (8) can be shown as:

$$X^r + IM^{sr} = Z^{rr} + F^{rr} + Z^{sr} + F^{sr} + E^{rs} + E^{rw} \quad (8)$$

Under no-trade conditions, we assume that province r has no exports, and the product that needs to be imported is produced locally. Therefore, Equation (9) can be expressed as:

$$\widetilde{X}^r = Z^{rr} + F^{rr} + Z^{sr} + F^{sr} \quad (9)$$

$$\widetilde{X}^r = X^r + IM^{sr} \quad (10)$$

where $\widetilde{X}^r$ is the total output of province r under no-trade, just including output driven by local demand and import from other provinces. Therefore, the direct input coefficient $\widetilde{\alpha}^r$ in the MIO model can be calculated as:

$$\widetilde{\alpha}^r = (z^{rr} + z^{sr}) / (x^r + im^{sr}) \quad (11)$$

Then, Equation (12) can be written as:

$$\widetilde{X}^r = \widetilde{A}^r \widetilde{X}^r + F^{rr} + F^{sr} \quad (12)$$

where $\widetilde{A}^r$ is the matrix of the direct input coefficients. Solving for variable $\widetilde{X}^r$:

$$\widetilde{X}^r = (I - \widetilde{A}^r)^{-1} (F^{rr} + F^{sr}) \quad (13)$$

Since our study aimed at examining the impact of no-trade-induced regional economic input-output structure changes on water withdrawal, we assumed that the water intensity of each province under no-trade was equal to that under trade. Then, the water withdrawal of province r can be calculated by:

$$W_{NT}^r = Y^r (I - \widetilde{A}^r)^{-1} (F^{rr} + F^{sr}) \quad (14)$$

where W_{NT}^r is the matrix of water withdrawal in province r under no-trade conditions, and Y^r is the matrix of water intensity in province r .

2.3. Water-Saving Efficiency Index

Water-saving efficiency index (WEI) of inter-provincial virtual water trade represents whether trade can save water, which can be constructed as follows:

$$WEI^r = \frac{W_{NT}^r - W_T^r}{W_{NT}^r} \times 100\% \quad (15)$$

where WEI^r is water-saving efficiency index of province r , W_{NT}^r represents the water withdrawal of province r under no-trade, and W_T^r represents the water withdrawal of province r under trade. A positive WEI^r means that water withdrawal under no-trade is greater than that under trade in province r and province r will achieve water conservation through inter-provincial virtual water trade; otherwise, there will be a loss of water resources through inter-provincial virtual water trade for province r .

2.4. Water Plunder Index and Water Scarcity Index

As we all know, the spatial distribution of water resources is uneven. Water resources in one region may be plundered by others through inter-provincial trade, and this may exacerbate the water inequality among provinces. According to the environmental plunder index proposed by Yang et al. [41], water plunder index (WPI) is applied to determine water inequality induced by trade. The water plunder index (WPI) of inter-provincial virtual water trade can be calculated as follows:

$$WPI^r = \frac{CW_T^r - PW_T^r}{CW_T^r} \times 100\% \quad (16)$$

$$PW_T^r = Y^r(I - A^r)^{-1}(F^{rr} + EX^{rs}) \quad (17)$$

$$CW_T^r = Y^r(I - A^r)^{-1}(F^{rr} + F^{sr}) \quad (18)$$

where WPI^r is water plunder efficiency index of province r , CW_T^r is consumption-based water withdrawal under trade of province r , and PW_T^r is production-based water withdrawal under trade of province r . If WPI^r is positive, province r will plunder water resources from others to meet its own water demand; otherwise, the water resources of province r will be plundered.

The water scarcity index (WSI) can be used to assess the local water scarcity of each province, and it can be calculated as follows:

$$WSI^r = \frac{W^r}{W_{total}^r} \times 100\% \quad (19)$$

where WSI^r is the water scarcity index of province r , W^r is the total water withdrawal of province r , and W_{total}^r is the total available water resources of province r . If the value of WSI^r is 20–40%, 40–100%, and over 100%, respectively, the province r will be under moderate, severe, and extreme water scarcity [6,43,44]. This study referred to the WSI result estimated by Cai et al. [6] and modified it based on the growth rate of total water resources.

2.5. Data Sources

Our study is based on two types of data:

The first is multi-regional input-output data in China, which can be collected from an inter-regional input-output table in 2015. We obtained this table from China Emission Accounts and Datasets (CEADs) (https://www.ceads.net/data/input_output_tables/, accessed on 25 February 2021). This table quantifies the economic transactions across 31 mainland provinces amongst 42 sectors.

The second is water withdrawal data by different sectors in China. There are no official water withdrawal data for each economic sector. Following Cai et al. [6], Zhang et al. [40], and Sun et al. [45], we collected aggregate water withdrawal data of agriculture, industry, and service sectors for each province from the Chinese Water Resources Bulletin. It is noted that water withdrawal of service sectors was included in domestic water use, and domestic water use was not linked to economic activities. Referring to provincial-level Water Resources Bulletin for each province, we estimated the separate amounts of water withdrawal of service sector. Then, we disaggregated the water withdrawal data of industry and services sector by sectors according to the proportion of sectoral water withdrawal data from the Chinese Economic Census Yearbook (2008).

3. Results

3.1. Inter-Provincial Virtual Water Trade Pattern

In this sector, we first characterize the flow of inter-provincial virtual water trade and differences between provinces and sectors (Figure 1). From the national level, the total flow of virtual water trade was $200.03 \times 10^9 \text{ m}^3$, which accounts for 32.77% of China's total

water withdrawal. It is consistent with previous studies for 2007 and 2012 [6,9]. Among sectors, Agriculture sector and Production and Supply of Electric Power and Heat Power sector are the two dominant sectors in the inter-provincial virtual water trade. The total water flow in Agriculture sector is $148.01 \times 10^9 \text{ m}^3$, accounting for 73.99% of the total water flow. The main reason is that the Agriculture sector has a higher water footprint and larger trade volume. Agricultural production needs to consume a large amount of freshwater due to a higher water-use coefficient and production scale, which leads to a higher water footprint [40]. In addition, the water flow in the Production and Supply of Electric Power and Heat Power sector is $26.53 \times 10^9 \text{ m}^3$, accounting for 13.27% of the total water flow.

Figure 1. Water inflow (a), water outflow (b), and water net flow (c) of inter-provincial virtual water trade in each province. **Note:** We only show the top five sectors with the largest virtual water trade volume, and merge the remaining 36 sectors into “other”. In Figure 1c, negative numbers indicate net outflows, and positive numbers indicate net inflows.

The flow direction of virtual water is mainly from west to east and from north to south. Specific to the provinces, the main inflow provinces include Guangdong, Shandong, Zhejiang, Henan, Shanghai, Anhui, Chongqing, and Jiangsu, which accounts for 51.77% of the national total water inflow. Guangdong is the largest virtual water inflow province, which imports $24.97 \times 10^9 \text{ m}^3$ of virtual water, followed by Shandong ($16.63 \times 10^9 \text{ m}^3$) and Zhejiang ($13.14 \times 10^9 \text{ m}^3$). The main virtual water outflow provinces are Xinjiang, Jiangsu, Heilongjiang, Anhui, Hunan, and Guangxi, accounting for 51.18% of the national total virtual water outflow. Among these provinces, Xinjiang has the largest virtual water outflow ($28.91 \times 10^9 \text{ m}^3$), followed by Heilongjiang, which exports $21.21 \times 10^9 \text{ m}^3$ of virtual water, and Jiangsu ranks third with $16.47 \times 10^9 \text{ m}^3$ of water outflow.

The inter-provincial virtual water trade pattern was further mapped in Figure 2. As the province with the largest water inflow, virtual water of Guangdong mainly comes from Xinjiang, Heilongjiang, Jiangsu, Anhui, Guangxi, and Hunan. The largest water outflow province, Xinjiang, mainly exports virtual water to Guangdong, Shandong, and the provinces in the Yangtze River Delta. In addition, the virtual water trade in the North China Plain was relatively frequent, especially in Jiangsu, Hebei, Henan, and Anhui. In southern China, with abundant water resources, Guangxi, Hunan, and Jiangxi are the main virtual water export provinces, providing water resources to the eastern developed areas such as Guangdong and Shanghai. Figure 2b also marked 10 main virtual water flow routes. The largest virtual water trade occurs in Guangdong, Xinjiang, Heilongjiang, and Shandong (Figure 2b). Guangdong imports $4.72 \times 10^9 \text{ m}^3$ of virtual water resources from Xinjiang. The second is from Xinjiang to Shandong, which exports $4.21 \times 10^9 \text{ m}^3$ of virtual water resources.

Figure 2. Virtual water trade pattern (a) and the main virtual water flow routes (b). **Note:** The regions with one color inside the circle are exporters, and the others are importers; the regions with one color inside the circle represent export; the arrows indicate the virtual water flow direction of the top 10 virtual water trade routes.

3.2. Water Withdrawal without Trade and with Trade

We then simulated the water withdrawal without trade using the MIO model and compared it with water withdrawal with trade (Figure 3). The total water withdrawal without trade in all provinces is $914.33 \times 10^9 \text{ m}^3$, while that with trade in all provinces is $468.25 \times 10^9 \text{ m}^3$. It shows that inter-provincial virtual water trade decreased the national

water withdrawal by $446.08 \times 10^9 \text{ m}^3$, which indicates that inter-provincial virtual water trade saved water resources nationwide. A possible reason is that current virtual water importer regions would be inefficient at carrying out the production they are importing. Our result is also different from the findings of Liu et al. [9], who argued that inter-provincial trade leads to an increase in national water use. An explanation is that Liu et al. [9] directly imposed homogeneity on the water-use coefficient between different provinces, that is, imported water would be equal to the water withdrawal. However, this is not completely consistent with the factor endowment theory. Therefore, we further considered differences in the water use coefficient using the MIO model.

(a)

(b)

Figure 3. Water withdrawal under trade and under no-trade (a) by region and (b) by sector. **Note:** water withdrawal without trade in Zhejiang and Guangdong is $234.92 \times 10^9 \text{ m}^3$ and $202.5 \times 10^9 \text{ m}^3$, respectively; water withdrawal without trade in S1, S2 and S25 is $354.74 \times 10^9 \text{ m}^3$, $380.53 \times 10^9 \text{ m}^3$, $75.59 \times 10^9 \text{ m}^3$, respectively; water withdrawal with trade in S1 and S25 is $343.76 \times 10^9 \text{ m}^3$ and $56.18 \times 10^9 \text{ m}^3$, respectively.

On regional scale, water withdrawal without trade is larger than that with trade in most provinces (22/31), suggesting inter-provincial virtual water trade has decreased water withdrawal in most provinces. Zhejiang has the highest water withdrawal, amounting to $234.92 \times 10^9 \text{ m}^3$ (25.69%) under no-trade, while it has $11.71 \times 10^9 \text{ m}^3$ (2.5%) of water withdrawal under trade. It reflects that Zhejiang would consume a larger amount of its

water to meet regional development and consumption demand when there is no external water supply. In addition, Guangdong has the highest GDP and Jiangsu ranked second in 2015, which indicates its vigorous economic development demand and huge population consumption demand that both require a large amount of water resources. With the larger water demand, water withdrawal of Guangdong and Jiangsu are among the top under both situations. Under no-trade conditions, Guangdong has the second largest water withdrawal amounting to $202.50 \times 10^9 \text{ m}^3$ (22.15%), followed by Jiangsu with $47.60 \times 10^9 \text{ m}^3$ (5.21%). In terms of the trade situation, Jiangsu has the second-largest water withdrawal, amounting to $34.67 \times 10^9 \text{ m}^3$ (7.41%), and Guangdong ranks in third with $27.80 \times 10^9 \text{ m}^3$ (5.94%).

From the sectoral perspective, water withdrawal without trade is larger than that with trade in most sectors (39/42). The highest water withdrawal amounting to $380.53 \times 10^9 \text{ m}^3$ was from the Coal Mining Products sector (S2) without trade. However, it only has $1.92 \times 10^9 \text{ m}^3$ water withdrawal under trade situation, indicating the Coal Mining Products sector (S2) conserves water through trade. In addition, Agriculture (S1) and Production and Supply of Electric Power and Heat Power (S25) sectors have the largest water withdrawal in both no-trade and trade conditions. Without trade, Agriculture sector (S1) holds the second largest water withdrawal with $354.74 \times 10^9 \text{ m}^3$ (38.80%), and Production and Supply of Electric Power and Heat Power sector (S25) ranks third with $75.59 \times 10^9 \text{ m}^3$ (8.27%) of water withdrawal. With trade, Agriculture (S1) has the largest water withdrawal amounting to $343.76 \times 10^9 \text{ m}^3$ (73.41%), followed by Production and Supply of Electric Power and Heat Power sector (S25) with $56.18 \times 10^9 \text{ m}^3$ (12%) of water withdrawal. This suggests that both sectors did not decrease water withdrawal by virtual water trade. The water use efficiencies of these two sectors are relatively low, which makes them become the largest users of water under trade and no-trade conditions [6].

3.3. Water-Saving Efficiency of Virtual Water Trade

The water-saving efficiency index (WEI) in each province is shown in Figure 4a. Most provinces (22/31) could gain benefits through inter-provincial virtual water trade with a positive WEI. Among the 22 benefited provinces, Zhejiang, Guangdong, Shanghai, and Tianjin are the biggest beneficiaries of virtual water trade in terms of water conservation, with higher WEI above 50% (95.02%, 86.27%, 67.75%, and 61.34%, respectively). Furthermore, Zhejiang, Guangdong, Shanghai, and Jiangsu make the greater contributions to national water conservation as they have the largest amount of decreased water withdrawal under trade. However, there are still nine provinces with negative WEI, indicating that they have not gained the water benefit from inter-provincial virtual water trade. Xinjiang, Heilongjiang, and Gansu hold low WEI (−40.24%, −32.79%, and −27.32%), suggesting that they are victims in inter-provincial virtual water trade. Although virtual water trade could achieve water-saving for most provinces, it could not completely increase the sustainability of water use. Because virtual water in China mainly flows from the water-deficient north to the water-rich south, the water shortage in water-scarcity regions increases.

We found that most sectors (39/42) have positive WEI, which reflects that they gained water benefits from inter-provincial virtual water trade. Five sectors, including Coal Mining Products (S2), Petroleum and Natural Gas Extraction Products (S3), and Telecommunications and Electronic Equipment (S20) hold the highest WEI with 99.50%, 90.74%, and 82.09%, respectively, which suggests that these sectors play an important role in water conservation through trade. However, Agriculture (S1) and Production and Supply of Electric Power and Heat Power (S25), with a large amount of decreased water, hold lower WEI. This shows that the improvement of water resources conservation efficiency in these two sectors will have an important impact on national water conservation and should attract sufficient attention from policymakers.

(a)

(b)

Figure 4. Water-saving efficiency of virtual water trade by province (a) and by sector (b). **Note:** The sector classification is listed in Table S1 presented in Supplementary Material. The decreased water under trade in Zhejiang and Guangdong is $223.21 \times 10^9 \text{ m}^3$ and $174.70 \times 10^9 \text{ m}^3$, respectively; the decreased water under trade in S2 and S25 is $378.61 \times 10^9 \text{ m}^3$ and $19.40 \times 10^9 \text{ m}^3$, respectively.

3.4. Water Inequality Embodied Invirtual Water Trade

Based on water plunder index (WPI) and water scarcity index (WSI) under trade conditions (Figure 5), we found that inter-provincial virtual water trade has exacerbated regional water inequality. Fifteen provinces have positive WPI, which suggests that they plunder water resources from other provinces to meet their local water demand. Among these 15 provinces, 11 provinces with WSI above 20% are in a state of water shortage. They relieve local water shortages by importing virtual water from others. As China's economic and political center, Tianjin and Beijing, with high WSI above 100%, both hold the highest WPI, suggesting that they plunder water over 50% of their water consumption from others to alleviate local water scarcity. However, there are four provinces without water shortage (i.e., Zhejiang, Qinghai, Yunnan, and Sichuan) that still plunder water resources from others. This has exacerbated regional water inequality.

Sixteen provinces show a negative WPI, indicating that they lost water resources as a result of inter-provincial virtual water trade. Among these 16 provinces, ten of them have high WSI above 20%, which suggests that trade leads to more severe water scarcity in these provinces. Heilongjiang and Xinjiang had the lowest WPI (-110.30% , -100.32%), which

indicates that they export more than 100% of local water consumption to other provinces. Furthermore, Hebei, Ningxia, Gansu, and Jiangsu with WSI above 70% are virtual water net outflow provinces, implying that virtual water trade has exacerbated water shortages in these provinces. The plunder patterns we estimated were similar to the findings of other studies [25,27].

Figure 5. The water plunder index and water scarcity index of each province. **Note:** The columns marked in red, orange and yellow indicate that provinces are under extreme, severe, moderate water shortage, respectively; and the points marked in blue indicate that there is no water shortage.

4. Discussion

4.1. Water-Saving Efficiency and Water Inequality

To explore the conflict of water-saving effect and water inequality, we compared the water-saving efficiency index (WEI) and water plunder index (WPI) by dividing 31 provinces into four quadrants (Figure 6).

Figure 6. The water plunder index and water-saving efficiency of each province. **Note:** The points marked in red, orange and yellow indicate that provinces are under extreme, severe, and moderate water shortage, respectively; the points marked in blue indicate that there is no water shortage.

Provinces in the first quadrant, including Zhejiang, Guangdong, and Shandong, etc., have both positive WEI and WPI. It means that virtual water trade could help these provinces efficiently save water resources through importing virtual water. Among 13 provinces, 12 provinces (except Qinghai) have a huge demand for water resources due to the large population/economic scale. Therefore, they highly depend on external water resources. It should be also noted that even though Guangdong, Zhejiang, and Hubei have abundant water resources, they still import virtual water from some water-scarce provinces. This might increase the regional water resource inequality.

Shaanxi and Liaoning are in the second quadrant (negative WEI, positive WPI), which means that they plunder water resources from other regions through virtual water trade, but they do not achieve local water conservation from a national perspective. However, as the main imported sources, including Heilongjiang, Jiangsu, and Anhui, which are water-rich provinces, the current trade patterns are beneficial for the two provinces.

The provinces in the third quadrant including Hunan, Guangxi, Gansu, Xinjiang, and Heilongjiang have negative WEI and negative WPI, indicating that they are water-plundered provinces, and the trade patterns are not conducive to water conservation. Moreover, Gansu, Xinjiang, and Heilongjiang are under severe water shortage and need to adjust their trade structure to change the unsustainable trade pattern. Guangxi, with sufficient water resources, can further moderately expand the utilization of water resources and exports.

Twelve provinces (Anhui etc.) are in the fourth quadrant with positive WEI and negative WPI, indicating that they have saved local water resources through virtual water import, and do not plunder water resources for other provinces. From a national perspective, this seems to be beneficial to the sustainable use of water resources, but from a regional perspective, it is not beneficial to provinces with a high WSI. Therefore, water shortage provinces such as Ningxia, Hebei, Jiangsu, Jilin, Anhui, and Inner Mongolia still need to pay attention to the structural adjustment of virtual water trade to prevent the deterioration of regional water shortages, while provinces with lower WPI but abundant water resources such as Sichuan, Guizhou, Fujian, and Jiangxi can moderately expand virtual water exports.

Based on the difference between the four quadrants, we found the provinces show a strong heterogeneity in the association between water conservation and water plunder. Therefore, it is difficult to consistently answer the question of “whether virtual water trade saves water resources?”. Additionally, the endowment of water resources should be taken into consideration when formulating individualized virtual water trading strategies for each province.

4.2. Limitation

Our study estimated water withdrawal under trade and no-trade conditions by developing a modified input-output model. To the best of our knowledge, this is the first attempt in virtual water research. However, there are still some limitations that need to be stated.

First, our study is based on the data from the multi-regional input-output table in 2015, but it is still complicated to obtain the most recent table. Limited by the availability of the multi-regional input-output table, the data used for analysis in this study have an obvious time lag.

Second, water intensity of each province under no-trade was assumed to be similar to that under trade conditions. However, the water intensity of each province might be changed if there is no trade, and estimated water resources under no-trade conditions may be larger than the actual value. Therefore, the variations of water intensity under no-trade conditions need to be further studied.

5. Conclusions

Severe water shortage in China has led to continuous concerns on the strategies of water resources management. Virtual water trade has been considered as an alternative way to generate sustainable water management. However, limited studies have estimated the difference between water withdrawal under inter-provincial trade and no-trade, and they did not investigate the water-saving effects and water inequality caused by virtual water trade. In this study, a multi-regional input-output table in 2015 was used to investigate this issue, and the main findings are summarized as follows:

The total water flow within China is $200.03 \times 10^9 \text{ m}^3$, accounting for 32.77% of water withdrawal nationwide. Moreover, the Agriculture sector contributes to the highest proportion (73.99%) of virtual water flow. The main virtual water flow is from the northeast and northwest regions with the Agriculture sector as the leading industry to the more economically developed southern regions and eastern coastal regions.

Inter-provincial virtual water trade could achieve water conservation at the national scale, which decreased water withdrawal by $446.08 \times 10^9 \text{ m}^3$ compared with the no-trade conditions. Furthermore, 22 provinces could decrease the local water withdrawal through trade, indicating inter-provincial virtual water trade is also conducive to local water conservation in most provinces within China. However, inter-provincial virtual water trade also leads to water inequality, which would exacerbate water scarcity of exported provinces (i.e., Xinjiang, Heilongjiang, Jiangsu, Gansu, Hebei, and Anhui). In addition, the conflict between water conservation and water plunder actually exists because of the difference in water resources endowments of each province, but different provinces show significant heterogeneity.

Based on these findings, our implication is that the province's water resources policies and trade strategies should be adjusted according to local water resource endowment. This may be an effective way to resolve the conflict between water conservation and water inequality caused by trade. In the water-scarce northwest and northeast regions, the water productivity of the agricultural sector needs to be improved and the virtual water export from the Agriculture sector needs to be controlled to ensure water balance while reducing water consumption. For the provinces with a developed economy and a high degree of external dependence on water resources, such as Beijing, Tianjin, Guangdong, Chongqing, and provinces in eastern regions, water resources marketization, including water pricing and water rights, can further improve water conservation and reduce the water plunder. As for regions with rich water resources, such as Yunnan, Jiangxi, Guangxi, and Hunan, the water resources utilization and export can be moderately strengthened to alleviate the water pressure of water-poor regions.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/w13212994/s1>, Table S1: Economic sector classification in this study. Table S2: Basic table of MRIO model. Table S3: Basic table of MIO model.

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