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Unveiling the inequalities in virtual water transfer in China: The environmental and economic perspectives

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ABSTRACT

To alleviate the geographical mismatch between supply and demand of water resources, virtual water trade had attracted extensive attention. Many studies had estimated the virtual water flow and measured the virtual water inequality using Environmental Input-Output (EIO) model. However, EIO model ignores the feedback effect in the trade, which may lead an overestimation or underestimation of virtual water transfer. Moreover, while considering the relation between economic benefits and environmental costs, the studies of virtual water inequality are still limited in both number and methodology. Here, to address these gaps, we recalibrated the virtual water and value-added transfer in China's 30 provinces in 2017 using a new Environmental Spillover-Feedback Effects (ESFEs) model, and then measured the inequality between virtual water transfer and the resource endowments taking the value-added into account. Our results show that the virtual water transfer of half of provinces changed exceeding 50 %, with a maximum of 428 %. The ratio of net virtual water outflow to one-way virtual water inflow (which is called virtual water plunder index in this study) in Xinjiang is up to 935 %, which directly contributing to the inequality among regions. Moreover, the virtual water transfer in different regions is not compensated equally from the perspective of economy. As a result, some regions are getting both water resources and economic benefits, while others are getting the opposite. Our study highlights the importance of considering both the pressure on water resources and economic benefits when measuring the virtual water inequality. Our findings support policymakers in developing adequate responses, i.e., clarifying regional responsibilities of virtual water trade, building a whole industrial chain, and balancing the transfer of value-added and virtual water.

1. Introduction

As a way to alleviate the geographical mismatch between supply and demand of water resources, virtual water trade had attracted extensive attention (Zhao et al., 2018). If we take water conservation as the ultimate target, then water resources in water-sufficient regions are supposed to be directed to water-deficient regions through virtual water trade. However, the current virtual water trade literature on the global scale (Chen et al., 2021a; Cai et al., 2019; Wang et al., 2019) and national scale (Zhuo et al., 2016; Wang et al., 2020 and Li et al., 2022) have found that virtual water transfer showed a general trend from water-deficient regions to water-sufficient regions, and in another context, the regions which supply water to the water-deficient regions were also under an ultimate water stress (Zhang et al., 2011). From a national perspective, this virtual water transfer pattern only made a futile transfer of the pressure on water resources instead of meeting the water resources sustainability goals (Song et al., 2020). It was the virtual water plunder among regions that pushed a virtual water inequality by imported considerable amount of water-intensive goods and services through virtual water trade. It did dominate virtual water transfer pattern due to multiple factors such as economic stages, soil resources and policy elements, rather than the water resource endowments which were supposed to be considered first (Tian et al., 2022). Significantly, if failure to allocate responsibilities for water stress mitigation rational, it is likely to exacerbate this inequality under the discrepancy of water resource endowments.

However, if the water resource costs of the resource-plundered

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Nomenclature

A^{mm}, A^{nn}	The matrix of intra-regional direct consumption coefficient
A^{mn}, A^{nm}	The matrix of inter-regional direct consumption coefficient
EIO	Environmental Input-Output model
ESFEs	Environmental Spillover-Feedback Effects model
FFW_i^{mm}	The feedback effects of water resources
FFV_i^{mm}	The feedback effects of value-added
F^{mm}, F^{mn}	The feedback effects in economic field
L^{mm}, L^{nn}	The Leontief inverse vector
$NVAT_{RF}{}^{mn}$	Net value-added transfer revised by feedback effect
$NVWT_{RF}{}^{mn}$	Net virtual water transfer revised by feedback effect
$NVAI_{RF}{}^{mn}$	Net value-added inflow revised by feedback effect
$NVAO_{RF}{}^{mn}$	Net value-added outflow revised by feedback effect
$NVWI_{RF}{}^{mn}$	Net virtual water inflow revised by feedback effect
$NVWO_{RF}{}^{mn}$	Net virtual water outflow revised by feedback effect
Q_i^m	The water consumed column vector
SFW_i^{mn}	The spillover effects of water resources
SFV_i^{mn}	The spillover effects of value-added
S^{mn}, S^{mn}	The spillover effects in economic field
TI_i^m	The total input vector
TO^m, TO^n	The total output column vector
VWI	Virtual water inequality index
$VWP1_i^m$	Virtual water plundering
$VWP2_i^m$	Virtual water plundered
$VWPI_i^m$	Virtual water plunder index
V_i^m	The value-added coefficient column vector
WSI	Water scarcity index
W_i^m	The direct water use coefficient column vector
Y^m, Y^n	The final demand column vector
γ	The slope of absolute equality line

regions are compensated for, it can be understood that trade still brings benefits to them (Zhang et al., 2018). Thus, a more comprehensive discussion of 'inequality' in the processes of virtual water trade requires an understanding of the relation between economic benefits and environmental costs, which was ignored by existing studies. The value-added in economic field was similar to virtual water in that it flowed cross regions following goods and services in trade. Due to differences in industry structures and development stages, there were great disparities in the intercourse on economic benefits and environmental costs among regions, resulting in a potential risk in inequality between virtual water and value-added transfer. Many studies had evaluated the inequality between carbon emissions and economic benefits (Mi et al., 2020; Wei et al., 2020; Zhu et al., 2022; Wang et al., 2022), while the studies in virtual water inequality are still limited in both number and methodology.

Multiple studies were linked to Environmental Input-Output (EIO) model to provide estimates of virtual water transfer (Zhang et al., 2020; Zhi et al., 2022). However, this model only focuses on the one-way transfer mechanism of spillover effect, and ignores its secondary effect which do occur in trade namely feedback effect. This will lead an overestimation or an underestimation of virtual water transfer, which may have significant influences on the subsequent trade policymaking. Addressing the above gap present in the EIO model, the Environmental Spillover-Feedback Effects (ESFEs) model allows explicitly distinguishing the two-way impact in trade (Chen et al., 2021b). This makes it possible to obtain a more comprehensive understanding of inter-regional environmental impact mechanisms. The inter-regional spillover effect of region *m* to region *n* means that the consumption of region *m* increases the production of services and goods in region *n*, which makes the pressure on water resources transfer from region *m* to region *n*. This is a one-way impact in trade. The inter-regional feedback effect, as the secondary effect of spillover effect, means that when region *m* has a spillover effect on region *n*, region *n* will further respond to it by increasing the consumption of water resources in region *m*. This can be understood as a two-way impact between regions. Until now, studies have proved that feedback effect cannot be underestimated, due to its large proportion in the spillover effect (Hu et al., 2019; Chen et al., 2021b).

In previous studies, the environmental pressure and economic benefits transfer calculated by EIO model are not accurate enough, as it does not take into account the impact of feedback effect in the trading process. In addition, increasing studies have integrated the mutual interests of economic benefits and environmental pressure. However, most of them focus on carbon emissions and it is still very limited when it comes to virtual water transfer. In this study, we quantified and recalibrated the virtual water and value-added transfer using the ESFEs model, which take the feedback effect into account and make the values more accurate than the one calculated by EIO model. Based on this, we measured the inequality between virtual water transfer and the resources endowment taking the value-added in to account, so as to refine the incomprehensive consideration of 'inequality' in previous studies, filling the gap of virtual water inequality studies. We also explored regional one-way transfer of virtual water to examine the virtual water plunder phenomenon in inter-regional trade. Finally, we thoroughly interpreted the empirical results and made policy suggestions. Our findings support policymakers in developing adequate responses, i.e., clarifying regional responsibilities of virtual water trade, building a whole industrial chain, and balancing the transfer of virtual water and value-added.

2. Methodology and data

2.1. Data

The China multi-regional input-output table in 2017 (Zheng et al., 2020) was chosen in this study, which covers 31 provinces and 42 socioeconomic sectors. The 42 industries were merged into 18 according to the availability of data and the nature of different industries. All water withdrawal data were obtained from China Statistical Yearbook (National Bureau of Statistics of China, 2018). In addition, some data are not directly available. The total water withdrawal of the tertiary industry was calculated by subtracting the urban residential water use from the urban domestic water use. The water use of urban residents was estimated by multiplying the per capita daily water use of urban residents (Ministry of Construction of the People's Republic of China, 2002) and the total population using water (National Bureau of Statistics of China, 2018). Since the data on water withdrawal of various industries in 2017 were not provided in the currently available materials, in this study, the water withdrawal of each secondary and tertiary industries in 2017 was calculated on a year-on-year basis, according to the following three items: (1) the proportion of water withdrawal of the secondary and tertiary industries in 2008 in the Economic Census Yearbook (Office of the Leading Group for the Second National Economic Census of the State Council, 2008), (2) the total secondary industrial water withdrawal in 2017 from the China Statistical Yearbook, and (3) total water withdrawal of the tertiary industry in 2017 which calculated above.

The following is a brief description of the research methods. The ESFEs model can calculate the virtual water transfer between different sectors in two regions, which is presented by spillover effect and feedback effect. Spillover effect refers to the virtual water flow from region n to region m caused by the consumption of one region m to another region n (i.e. the spillover effect from region n to region m). Based on this, the spillover effect will cause a consumption of region n to region m, resulting in the flow of virtual water from region m to region n. This is the 'feedback effect' from region n to region m, which is called the feedback effect.

Virtual water inequality (VWI) index is defined to reveal the transfer mechanism of virtual water and value-added between regions. If region m exports commodities or services (i.e., virtual water), then it should receive a corresponding economic benefit (i.e., value-added). However, due to the different level of economic development in each region, the exchange of commodity and wealth in trade is not necessarily equal. The Virtual water inequality index is used to measure the inequality in this exchange.

2.2. Spillover-feedback effects model in virtual water transfer

The traditional closed two-region input-output model can be expressed as follows (Isard, 1951):

$$\begin{bmatrix} A^{mm} & A^{mn} \\ A^{nm} & A^{nn} \end{bmatrix} \cdot \begin{bmatrix} TO^m \\ TO^n \end{bmatrix} + \begin{bmatrix} Y^m \\ Y^n \end{bmatrix} = \begin{bmatrix} TO^m \\ TO^n \end{bmatrix} \tag{1}$$

Where TO^mdenotes the total output of region m (column vector), including the elements to_i^m which denotes the total output of sector i in region m. Y^m denotes the final demand column vector of region m. A^{mm} denotes the direct consumption coefficient matrix within region m, including it's elements a_{ij}^{mm} which denotes the ratio of the intermediate input of sector i in region m to the total input of sector j in region m. A^{mn} denotes the direct consumption coefficient matrix between region m and region n, including it's elements a_{ij}^{mn} which denotes the ratio of the intermediate input of sector j in region n supplied by the sector i in region m to the total input of sector i in region m. Similarly, TO^n,Y^n,A^{mm},A^{nm},A^{nn} are in the same way.

According to (Pan, 2006), taking the region m as an example, (1) can be transformed into the following expression:

$$\begin{aligned} TO^m = {} & \left[I-(I-A^{mm})^{-1}A^{mn}(I-A^{nn})^{-1}A^{nm}\right]^{-1}(I-A^{mm})^{-1}Y^m + \\ & \left[I-(I-A^{mm})^{-1}A^{mn}(I-A^{nn})^{-1}A^{nm}\right]^{-1}(I-A^{mm})^{-1}A^{mn}(I-A^{nn})^{-1}Y^n \end{aligned} \tag{2}$$

Define $F^{mm} = \left[I-(I-A^{mm})^{-1}A^{mn}(I-A^{nn})^{-1}A^{nm}\right]^{-1}$, $S^{mn} = (I-A^{mm})^{-1}A^{mn}$, $L^{mm} = (I-A^{mm})^{-1}$, then (2) can be simplified as follows:

$$TO^m = F^{mm}L^{mm}Y^m + F^{mm}S^{mn}L^{nn}Y^n \tag{3}$$

where L^{mm} is the Leontief inverse matrix, S^{mn} is the spillover effect from region m to region n, F^{mm} is the feedback effect form region n to region m (which stems from the spillover effect from region m to n).

Similarly, defining $F^{nn} = \left[I-(I-A^{nn})^{-1}A^{nm}(I-A^{mm})^{-1}A^{nm}\right]^{-1}$, $L^{nn} = (I-A^{nn})^{-1}$, $S^{nm} = (I-A^{mm})^{-1}A^{nm}$, the total output column vector of region n can be simplified as:

$$TO^n = F^{nn}L^{nn}Y^n + F^{nn}S^{nm}L^{mm}Y^m \tag{4}$$

After the above, the closed two-region input-output model can be expressed as:

$$\begin{bmatrix} TO^m \\ TO^n \end{bmatrix} = \begin{bmatrix} L^{mm}Y^m \\ L^{nn}Y^n \end{bmatrix} + \begin{bmatrix} S^{mn}L^{nn}Y^n \\ S^{nm}L^{mm}Y^m \end{bmatrix} + \begin{bmatrix} (F^{mm}-I)L^{mm}Y^m + (F^{mm}-I)S^{mn}L^{nn}Y^n \\ (F^{nn}-I)S^{nm}L^{mm}Y^m + (F^{nn}-I)L^{nn}Y^n \end{bmatrix} \tag{5}$$

where $\begin{bmatrix} S^{mn}L^{nn}Y^m \\ S^{nm}L^{mm}Y^m \end{bmatrix}$ denotes the spillover effect from region m to region n in the economy, $\begin{bmatrix} (F^{mm}-I)L^{mm}Y^m + (F^{mm}-I)S^{nm}L^{nn}Y^n \\ (F^{nn}-I)S^{nm}L^{mm}Y^m + (F^{nn}-I)L^{nn}Y^n \end{bmatrix}$ denotes the feedback effect from region n to region m in the economy, which stems from the spillover effect from region m to region n.

If we assume that the final demand of one region does not change when the final use of another region increases (Hu et al., 2019), then (5) can be expressed as:

$$\begin{bmatrix} TO^m \\ TO^n \end{bmatrix} = \begin{bmatrix} L^{mm}Y^m \\ L^{nn}Y^n \end{bmatrix} + \begin{bmatrix} S^{mn}L^{nn}Y^n \\ S^{nm}L^{mm}Y^m \end{bmatrix} + \begin{bmatrix} (F^{mm}-I)L^{mm}Y^m \\ (F^{nn}-I)L^{nn}Y^n \end{bmatrix} \tag{6}$$

In inter-regional virtual water trade, water resources are traded between regions following goods and services in the form of virtual water. An increase in the final demand of region m for a certain product in region n will cause region n consuming more water resources to produce this product to meet the demand. When the products are consumed in region m and produced in region n, it can be understood that the water spillovers from the n region to region m from the perspective of environmental. Moreover, it will also in turn increases the product produced in region m, that is, the water resources are feedback from region m to region n, which is caused by the spillover effect from region n to region m.

To quantify the spillover and feedback effects of water resources, we introduced the direct water use coefficient. The calculation formula can be expressed as:

$$W = [W^m],\ W^m = [W_i^m],\ W_i^m = \frac{Q_i^m}{TI_i^m} \tag{7}$$

where W_i^m is the direct water use coefficient of sector i in region m, Q_i^m is the water consumed volume of sector i in region m and TI_i^m is the total input of sector i in region m. Or in a matrix form as:

$$W = \begin{bmatrix} W^1 & \cdots & W^m & \cdots & W^e \end{bmatrix},\ W^m = \begin{bmatrix} W_1^m & \cdots & W_i^m & \cdots & W_f^m \end{bmatrix} \tag{8}$$

The complete water use coefficient is defined as the increment of the water consumption of the entire economic system required by an industry to increase the output of a unit product. It is negatively related to water use efficiency. According to (8), the calculation formula of the complete water use coefficient can be expressed as:

$$W' = W \cdot (I-A)^{-1} \tag{9}$$

Substitute the direct water coefficient matrix into Eq. (6):

$$SFW = \begin{bmatrix} W_i^m & 0 \\ 0 & W_i^n \end{bmatrix} \begin{bmatrix} S^{mn}L^{nn}Y^n \\ S^{nm}L^{mm}Y^m \end{bmatrix} = \begin{bmatrix} W_i^m S^{mn}L^{nn}Y^n \\ W_i^n S^{nm}L^{mm}Y^m \end{bmatrix} \tag{10}$$

$$FFW = \begin{bmatrix} W_i^m & 0 \\ 0 & W_i^n \end{bmatrix} \begin{bmatrix} (F^{mm}-I)L^{mm}Y^m \\ (F^{nn}-I)L^{nn}Y^n \end{bmatrix} = \begin{bmatrix} W_i^m(F^{mm}-I)L^{mm}Y^m \\ W_i^n(F^{nn}-I)L^{nn}Y^n \end{bmatrix} \tag{11}$$

where SFW and FFW are the spillover and feedback effects of water resources, respectively.

Take region m as an example, the spillover effect and feedback effect are shown in the following two equations:

$$SFW_i^{mn} = W_i^m S^{mn}L^{nn}Y^n \tag{12}$$

$$FFW_i^{mm} = W_i^m(F^{mm}-I)L^{mm}Y^m \tag{13}$$

According to Eq. (12) and Eq. (13), the calculation equation of virtual water plundering (VWP1), virtual water plundered (VWP2), virtual water plunder index (VWPI) and net virtual water transfer revised by feedback effect ($NVWT_{RF}$) integrating spillover effect and feedback effect are shown in the following four equations:

$$VWP1_i^m = SFW_i^{nm} + FFW_i^{mm} \tag{14}$$

$$VWP2_i^m = SFW_i^{mn} + FFW_i^{nn} \tag{15}$$

$$VWPI_i^m = \frac{VWP1_i^m - VWP2_i^m}{VWP1_i^m} \times 100\% \tag{16}$$

$$NVWT_{RF}{}^{mn} = SFW_i^{mn} + FFW_i^{nn} - SFW_i^{nm} - FFW_i^{mm} \tag{17}$$

Here, $VWP1_i^m$, $VWP2_i^m$, and $VWPI_i^m$ represent the virtual water one-way import of region m sector i, the virtual water one-way export of region m sector i, and the percentage of the net virtual water transfer of region m sector i in its virtual water one-way import, respectively.

When $NVWT_{RF}{}^{mn}$ is positive and negative, we defined it as $NVWO_{RF}{}^{mn}$ and $NVWI_{RF}{}^{mn}$, respectively.

Similarly, in order to quantify the spillover and feedback effects of value-added, we introduced the value-added coefficient. The calculation equation can be expressed as:

$$V = [V^m] \text{ , } V^m = \left[V_i^m\right] \text{ , } V_i^m = \frac{v_i^m}{TI_i^m} \tag{18}$$

Take region *m* as an example, the spillover effect and feedback effect in value-added are as follows:

$$SFV_i^{mn} = V_i^m S^{mn} L^{nn} Y^n \tag{19}$$

$$FFV_i^{mm} = V_i^m (F^{mm} - I) L^{mm} Y^m \tag{20}$$

According to Eq. (19) and Eq. (20), the calculation equation of net value-added transfer revised by feedback effect ($NVAT_{RF}$) integrating spillover effect and feedback effect are shown in the following equation:

$$NVAT_{RF}{}^{mn} = SFV_i^{mn} + FFV_i^{mn} - SFV_i^{nm} - FFV_i^{mm} \tag{21}$$

When $NVAT_{RF}{}^{mn}$ is positive and negative, we defined it as $NVAO_{RF}{}^{mn}$ and $NVAI_{RF}{}^{mn}$, respectively.

2.3. Virtual water inequality (VWI) index

In order to measure the inequality in virtual water transfer, a standard between virtual water and value-added is defined (Xin et al., 2021). If the virtual water outflow is taken as the independent variable and the value-added inflow as the dependent variable, a function passing (0,0) can be constructed. The calculation equation of its slope is as shown in Eq. (22):

$$\gamma = \sum_{m=1}^{p} \sum_{n=1, m \neq n}^{p} |NVAT^{mn}| \Big/ \sum_{m=1}^{p} \sum_{n=1, m \neq n}^{p} |NVWT^{mn}| \tag{22}$$

As shown in Fig. 1, the constructed function is called the absolute equality line. This means that only the points falling on the line realize the equality. The horizontal distance from inequality points A, B, C, D to the absolute equality line represents the deviation degree from the standard.

And it can be calculated as follows:

$$Degree = \begin{cases} \dfrac{|NVAT^{mn}|/\gamma - NVWT^{mn}}{NVAT^{mn}/\gamma}, \dfrac{|NVAT|}{\gamma} > NVWT \\ \dfrac{NVWT^{mn} - |NVAT^{mn}|/\gamma}{NVWT^{mn}}, \dfrac{|NVAT|}{\gamma} \leq NVWT \end{cases} \tag{23}$$

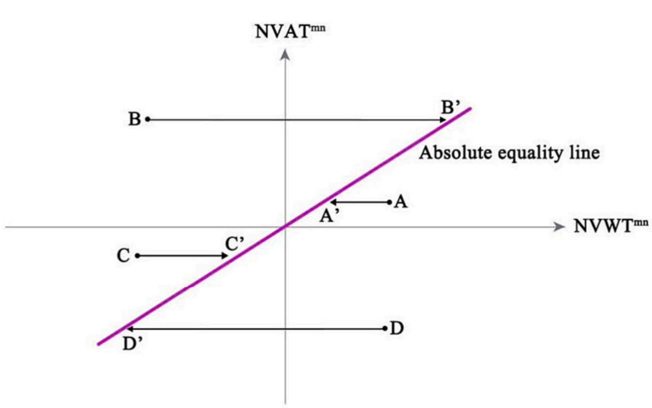

Fig. 1. Relationship between net virtual water and net value-added transfer.

To specify the value interval as (0, 1), introducing the function e^{-x} into Eq. (23), VWI can be calculated as follows:

$$VWI = e^{-Degree} \tag{24}$$

When the VWI value is 1, it means the absolute equality, and 0 means the absolute inequality.

3. Results and discussion

3.1. The necessity of feedback effect in recalibrated virtual water transfer

3.1.1. The spillover and feedback effects

The inter-regional spillover effects in virtual water transfer are shown in Fig. 2, and its specific value are shown in the Supporting Information, Supplementary Table 1 and 2. From the perspective of one region's supply, the spillover effect from Xinjiang to other 29 provinces was the largest at 165.31 × 10^8 m^3, and it was the smallest from Tianjin to the other 29 provinces at 3.49 × 10^8 m^3. This demonstrated that Xinjiang had the largest water withdrawal driven by other regions, resulted from that the massive amounts of virtual water were exported to other regions in the form of water-intensive agricultural products. Tianjin was on the contrary. On the other hand, from the perspective of one region's demand, the spillover effects from the other 29 provinces to Guangdong was the largest at 99.26 × 10^8 m^3, and from the other 29 provinces to Qinghai was the smallest at 3.41 × 10^8 m^3. This situation depended on the high level of regional economic development and opening degree of Guangdong, which enabled it to import a large number of products from other regions. Qinghai was on the contrary.

The inter-regional feedback effects in virtual water transfer are shown in Fig. 3, and its specific value are shown in the Supporting Information, Supplementary Table 3 and 4. From the perspective of feedback effect of one region's own reaction, the province with the largest feedback effect was Jiangsu at 0.15 × 10^8 m^3, and the smallest was Qinghai at 0.004 × 10^8 m^3. From the perspective of feedback effect of other regions' own reaction, the province with the largest feedback effect was Henan at 45.44 × 10^8 m^3, and the smallest was Qinghai at 0.37 × 10^8 m^3. This demonstrated that Jiangsu and Henan were more closely linked to the resource-economy of other provinces, and showed close trade relations with them, therefore the two-way virtual water transfer mechanism is the most obvious. Qinghai was on the contrary.

According to the above, the inter-regional feedback effects were much smaller than the inter-regional spillover effects, which is consistent with the results of Ning et al. (2019) in carbon emissions field and Chen et al. (2021a, 2021b) in virtual water transfer field.

3.1.2. Changes in net virtual water transfer caused by feedback effect

When it comes to inter-regional virtual water transfer, our study mentions two models: EIO and ESFEs. ESFEs is based on EIO through complex transformation, and its structure has changed greatly compared with EIO. ESFEs can be viewed as a two-part structure, one is the calculation of spillover effects, and the other is the calculation of feedback effects. As a result, we have a clearer understanding of the internal mechanisms of virtual water transfer between regions: When region m exports virtual water to region n (which is named spillover effects), a flow of water from n to m is generated, which is named feedback effects. However, EIO does not have such a structure, it can only output virtual water flows from region m to region n, which is equivalent to spillover effects in ESFEs, and do not involve feedback effects. In summary, EIO is able to quantify the primary effects of interregional virtual water transfer, while ESFEs quantifies both the primary effects and the secondary effects (arising from the primary effects). Only when the secondary effect is subtracted, is the real inter-regional virtual water transfer.

Based on the above, we demonstrate the importance of feedback effects by the percentage of the gap between the virtual water transfers

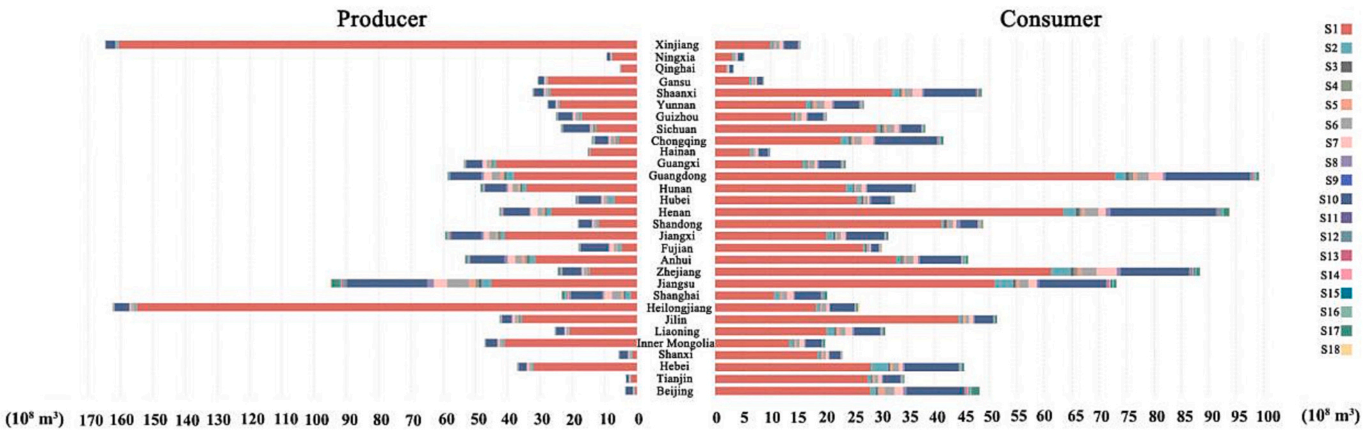

Fig. 2. The inter-regional spillover effects of 30 provinces of China in 2017.
Note: S1-Agriculture, Forestry, Animal Husbandry and Fishery, S2-Extraction of fossil energy and ores, S3-Food and tobacco processing, S4-Textile, leather and other clothing materials, S5-Wood processing, S6-Petroleum, coking, nuclear fuel and chemical products, S7-Metal and non-metallic products, S8-Transportation, communication and other equipment, S9-Other manufacturing, S10-Production and supply of electricity, heat, gas and water, S11-Construction, S12-Wholesale and retail trades, S13-Transport, storage, and postal services, S14-Accommodation and catering, S15-Finance and real estate, S16-Social service, S17-Scientific research, technical services and education, S18-Living standards security.

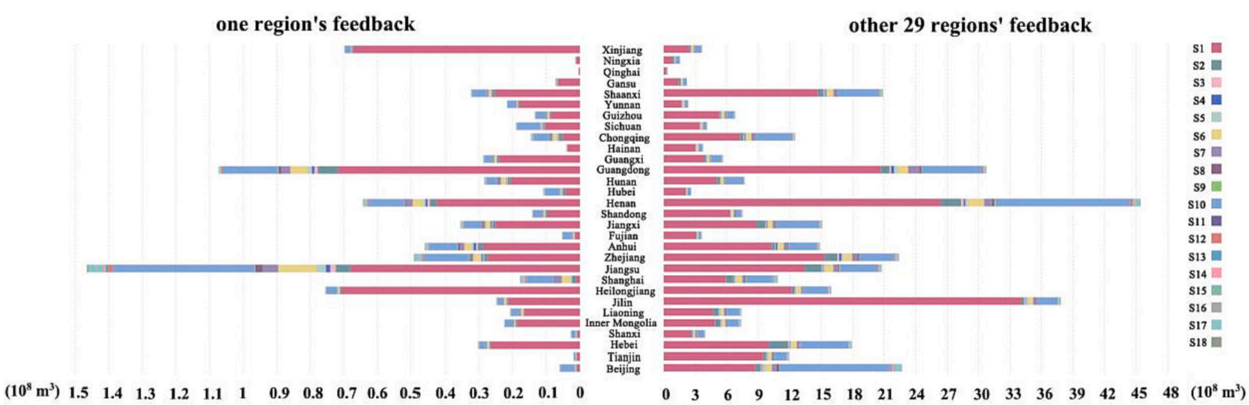

Fig. 3. The inter-regional feedback effects of 30 provinces of China in 2017.

from the two models. As mentioned above, there are two scenarios: (1) the virtual water transfer considering only spillover effect (which is calculated by EIO) and (2) the virtual water transfer considering both spillover and feedback effect (which is calculated by ESFEs). Fig. 4 provides the virtual water transfer change percentage of the above two scenarios. It can be seen that Jilin, Hebei, Liaoning, and Shaanxi provinces had transformed from a net inflow province to a net outflow province of virtual water after the feedback effect were taken into account. Further, there were 15 provinces whose change rate exceeded 50 %, with a maximum of 428 %. Given the significant variation of virtual water transfer, it can be proved that the feedback effect is something cannot afford to be ignored in the two-way impact mechanism of virtual water transfer.

3.2. Virtual water plunder in trade

Virtual water trade resulted in inequalities. Fig. 5(a) reveals that Guangdong was the largest predator in 30 provinces, with 100.33×10^8 m^3 of virtual water flowing in from other 29 provinces. Heilongjiang was plundered the most by other 29 provinces with 178.55×10^8 m^3 of virtual water flowing out. This result is consistent with the conclusion of Xin et al., (2021). With a high population density and rapid agricultural and industrial development, Guangdong has a great demand for water resources. Due to the limited water resources within the region, which cannot meet the development demand, a large amount of virtual water has been introduced from other provinces. On the contrary, Heilongjiang has many large rivers and sufficient annual precipitation, thus the local water resources are abundant. In addition, Heilongjiang is one of China's important agricultural (which is a water-intensive industry) production regions, so a lot of virtual water flows out with agricultural products in trade.

The virtual water plunder index (VWPI) represents the intensity of plundering or being plundered. Fig. 5(b) shows that Shanxi had the highest VWPI at 58 %, implied that Shanxi's plunder intensity on other 29 provinces was strongest, and followed by Tianjin, Shandong, Zhejiang and Beijing. On the other hand, Xinjiang had the lowest VWPI at −935 %, implied that Xinjiang was plundered with the greatest intensity by the other 29 provinces, followed by Heilongjiang, Gansu, Inner Mongolia and Guangxi. From the perspective of sectors, it was remarkable that the regions with VWPI<-100 % for S1 were always plundered in trade, and the absolute value of VWPI up to 935 %. This highlighted that S1 was the predominant industry in determining the intensity of virtual water flow in trade.

3.3. Inequalites in trade

3.3.1. Inequality in $NVWT_{RF}$ under water resource endowments

The map (Fig. 6) gives information regarding net virtual water transfer and water scarcity index (WSI). Among the 19 provinces with net virtual water outflow, there are 8 provinces' (Hebei, Inner Mongolia,

Fig. 4. The percentage change of virtual water transfer in two scenarios.*The two scenarios: (1) the virtual water transfer considering only spillover effect and (2) the virtual water transfer considering both spillover effect and feedback effect.

Liaoning, Shanghai, Jiangsu, Anhui, Ningxia, Xinjiang) with WSI ≥ 0.91, which denotes a status of water scarcity. Such a pattern of virtual water trade undoubtedly created a threat to water security owing to the massive loss of local virtual water under their poor water resource endowments. These regions may obtain economic benefits through virtual water exports, thereby increasing trade income.

Among the 11 provinces with net virtual water inflow, there are 5 provinces (Zhejiang, Fujian, Guangdong, Chongqing, Sichuan) showing a water sufficient status with WSI <0.09. In spite of the water resource endowments in these provinces were rich relatively, their local final demands were still met by exploiting the water resources in other provinces. This caused a risk of water scarcity exacerbated in some water-stressed provinces where the productions were produced. There are two possible reasons for this: (1) Even though these regions have rich water resources, due to geographical location, climate and other factors which are not enough to support the development of industries (such as agriculture which has a great demand for farmland), they have to rely on the imports to meet local demand; (2) the growing population has led to a great increase in the demand for water. Therefore, even if water resources are abundant in water-deficient regions, it is likely to be insufficient to meet local demand.

3.3.2. Inequality between $NVWT_{RF}$ and $NVAT_{RF}$

It can be seen from Fig. 7(a) that the provinces characterized prominent inequality between net virtual water and value-added transfer are Henan, Yunnan and Guangdong, whose VWI were almost 0. The provinces closest to equality were Chongqing, Guangdong, and Inner Mongolia, whose VWI are almost 1.

It can be seen from Fig. 7(b) that 30 provinces were divided into six parts. The provinces in parts (1)~(6) falling outside the absolute equality line demonstrate diverse scenarios. Provinces located in parts (1), (2) and (6) above absolute equality line could be described in a same category. Their actual net virtual water outflow was less than the theoretical value, which matched the corresponding value-added. Taking part (6) as an example, the net virtual water of the provinces located here were in a state of inflow. However, compared with the loss of virtual water, these provinces have gained more economic benefits. As the capital of China, Beijing had developed technology and an excellent industrial structure. Their products exported to other provinces were concentrated in a type of low water-consumption and high value-added, and the high water-consumption and low value-added products were imported. Therefore, Beijing had created a considerable trade surplus at 103.87 billion yuan of value-added, becoming the most outstanding beneficiary in economy.

The provinces of parts (3), (4), (5) below the absolute equality line could be summarized as being in the same category where the actual net virtual water inflow values are less than the theoretical values matching the value-added. Taking part (5) as an example, relative to the amount of economic benefits they obtained, these provinces expensed more water resources outflowing to other regions. That was, they were the victims from the economy perspective. As a major agricultural province in China, owing to the industrial structure, Xinjiang exported substantial water-intensive and low value-added products to other provinces. As a result of this, Xinjiang had 152.7×10^8 m^3 net virtual water outflow, but had only 35.25 billion net value-added inflow, which triggered an excessive economic benefits loss.

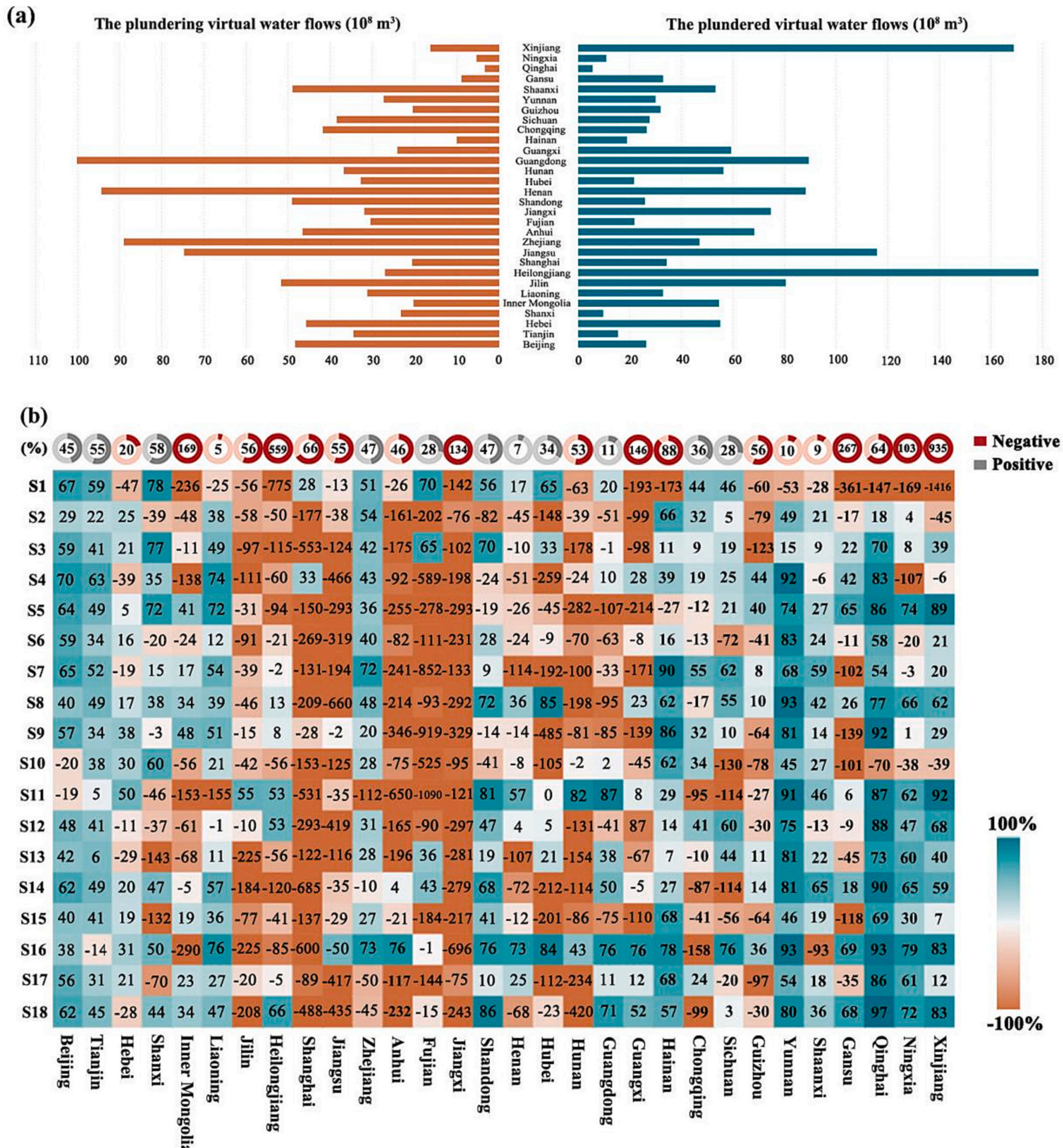

Fig. 5. The plundering and plundered in virtual water transfer and the virtual water plunder index (VWPI) of 30 provinces of China in 2017 (a)The plundering and plundered in virtual water transfer (b) The VWPI by sectors.

3.3.3. *The inequality between $NVWT_{RF}$ and $NVAT_{RF}$ under water resource endowments*

The 8 water-deficient provinces mentioned in Section 3.3.1 face water resources being plundered coupled with economic benefits loss. As shown in Fig. 7(b), the four most prominent such provinces are Hebei, Shanghai, Jiangsu and Xinjiang. According to the value-added, Hebei, Shanghai and Jiangsu were supposed to transfer 59.5 × 10^8 m^3, 73.3 × 10^8 m^3, 66.8 × 10^8 m^3 virtual water to other provinces respectively. However, only 9.3 × 10^8 m^3, 13.7 × 10^8 m^3, 41.2 × 10^8 m^3 were the actually outflows. When it came to Xinjiang, with only 35.25 billion yuan net value-added inflow, it only needed to reach the net virtual water outflow at 4.4 × 10^8 m^3, but the actual amount was 152.7 × 10^8 m^3.

Moreover, the 5 water rich provinces mentioned in Section 3.3.1, which plundered considerable amount of water resources from other provinces, have also obtained economic benefits in trade. Take Zhejiang and Fujian for example. Zhejiang, which had 41.9 × 10^8 m^3 net virtual water inflow, was supposed to bear the economic costs of 337.2 billion yuan. However, the actual value-added outflow was only 118.32 billion yuan. Fujian was supposed to bear 92.1 billion yuan economic costs owing to 8.7 × 10^8 m^3 net virtual water inflow. However, on the contrary, it only obtained an economic benefit of 69.8 billion yuan actually.

To sum up, Hebei, Shanghai, Jiangsu and Xinjiang, with their poor water resources endowments, suffered massive water resources losses in trade. Hebei and Shanghai recived an extra corresponding compensation of economic benefits, while Xinjiang did not receive enough, facing double losses in terms of environment costs and economic benefits. The reason might be that the unbalanced division of labor in the supply chain contributed to the low value-added industrial structure in these regions. That is, the region might undertake the production of low value-added

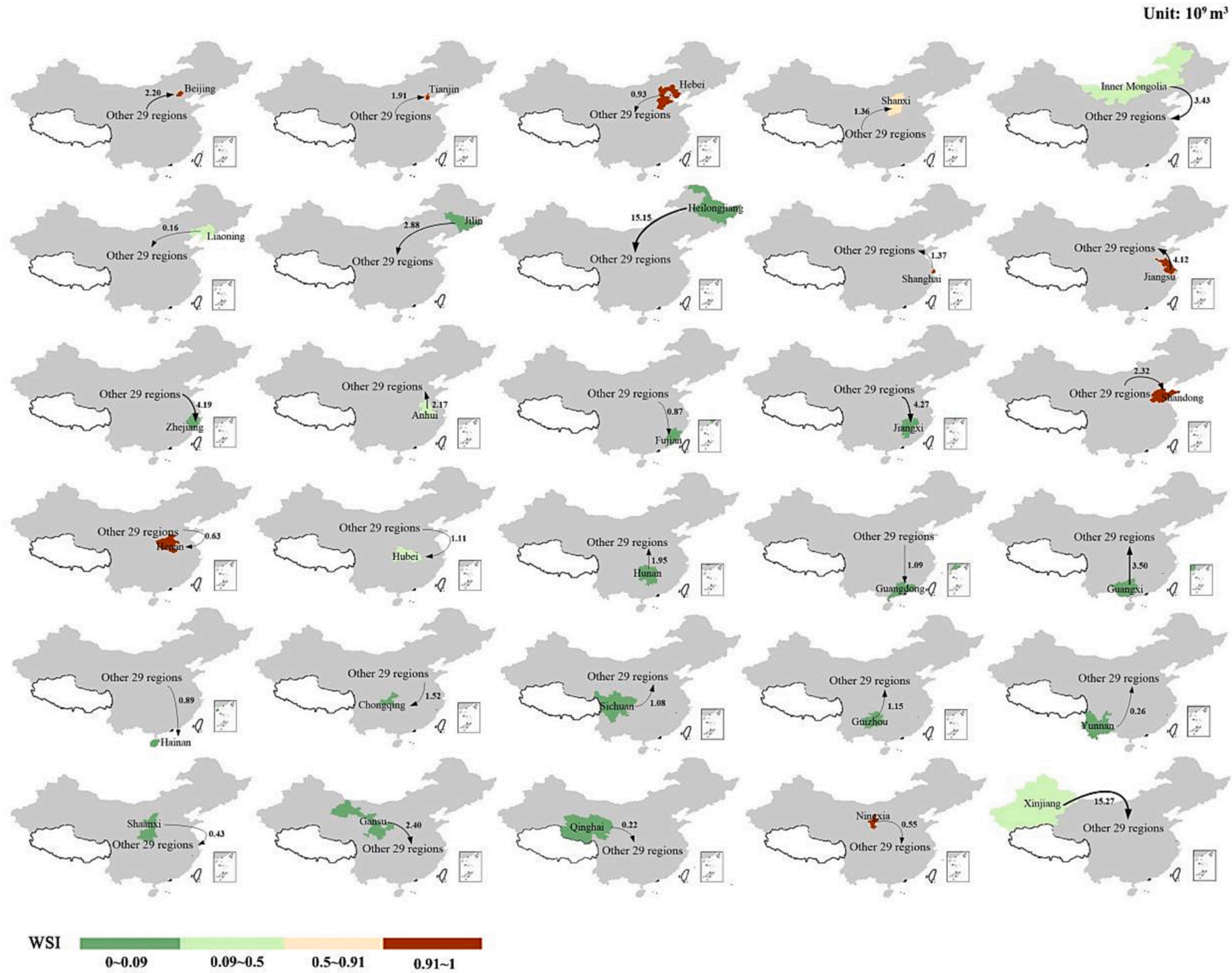

Fig. 6. Water scarcity index (WSI) and $NVWT_{RF}$ in trade of 30 provinces of China in 2017. The direction and thickness of the arrow indicate the direction and size of the virtual water flow, and the color of the panels indicate the WSI of the corresponding region. *The WSI value ranges from 0 to 1. The higher the value, the more serious the water shortage situation is. When WSI $\leq$ 0.09, water resources are abundant. When 0.09 $<$ WSI $\leq$ 0.5, water resources are slightly deficient. When 0.5 $<$ WSI $\leq$ 0.91, water resources are moderately deficient. When WSI $>$ 0.91, water resources are severely deficient.

products in the supply chain, such as assembly, processing, etc., which lead to the region only obtaining less economic benefits in the supply chain. In contrast, under rich water resource endowments, Zhejiang and Fujian were not only a predator of water resources, but also obtained considerable amount of value-added. The underlying reason is that their exports were likely to be concentrated in high value-added products. They tended to have strong technology and innovation ability, so as to develop the market demand of high value-added products. In addition, products from these regions may have high brand value and market position, and their premium effect has contributed to creating a large amount of value-added even if few goods are exported.

3.4. Net virtual water transfer and water use efficiency by sectors

Focusing on the 8 water-deficient provinces with net virtual water outflow mentioned in Section 3.3.1, it can be seen from Fig. 8(a) that the inter-provincial export of S1 were the main cause of net virtual water outflow. Except for Shanghai, in the other 7 provinces, net virtual water outflow caused by S1 accounted for a large proportion of the total virtual water transfer. For example, net virtual water outflow caused by S1 in Hebei was 13.34×10^8 m^3, accounting for 98.16 % of total. Liaoning was 5.10×10^8 m^3, accounting for 99.81 %. Xinjiang was 152.38×10^8 m^3, accounting for 99.22 %. The 5 water-sufficient provinces with net virtual water inflow mentioned in Section 3.3.1 were similar. Their net virtual water inflow were the largest due to S1, which accounted for 74.65 %, 98.47 %, 94.05 %, 63.64 % and 85.78 % of the total of Zhejiang, Fujian, Guangdong, Chongqing and Sichuan respectively. From another perspective, the S1 exported virtual water in Xinjiang, Heilongjiang, Inner Mongolia ranked the top among the 30 provinces, with 152.4×10^8 m^3, 148.1×10^8 m^3, and 32.2×10^8 m^3 respectively. The large share of water flow in S1 was owing to the enormous production scale, which consumed excessive fresh water resources to complete the production of agricultural products (Zhang et al., 2019), especially the irrigation, which is a major water-consuming part of agricultural production (Guan and Klaus, 2007; Chai et al., 2014).

The products of water-inefficient industries export were another important reason for the scenarios of excessive virtual water transfer. If each region produces the goods or services for which they are competitive, it will maximize water use efficiency and decrease water waste (Chapagain et al., 2006; Mubako et al., 2013). Fig. 8(b) represents the complete water use coefficient by sectors, which is negatively correlated with the water efficiency. The complete water use coefficient of S1 in Xinjiang ranked No.1 among the same sectors in 30 provinces, S5 in Anhui ranked No.3, S7 ranked No.2, and S7 in Jiangsu ranked No.1, S10

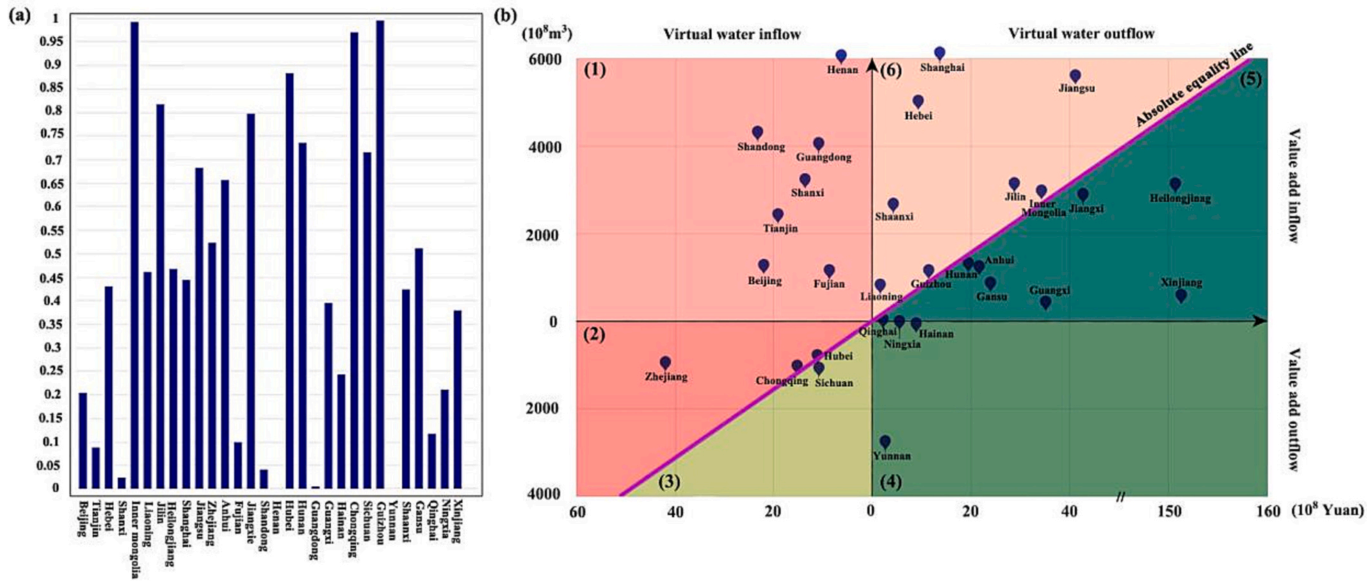

Fig. 7. Virtual water inequality (VWI) index and $NVWT_{RF}$ and $NVAT_{RF}$ of 30 provinces of China in 2017 (a) Virtual water inequality index (b) $NVWT_{RF}$ and $NVAT_{RF}$.

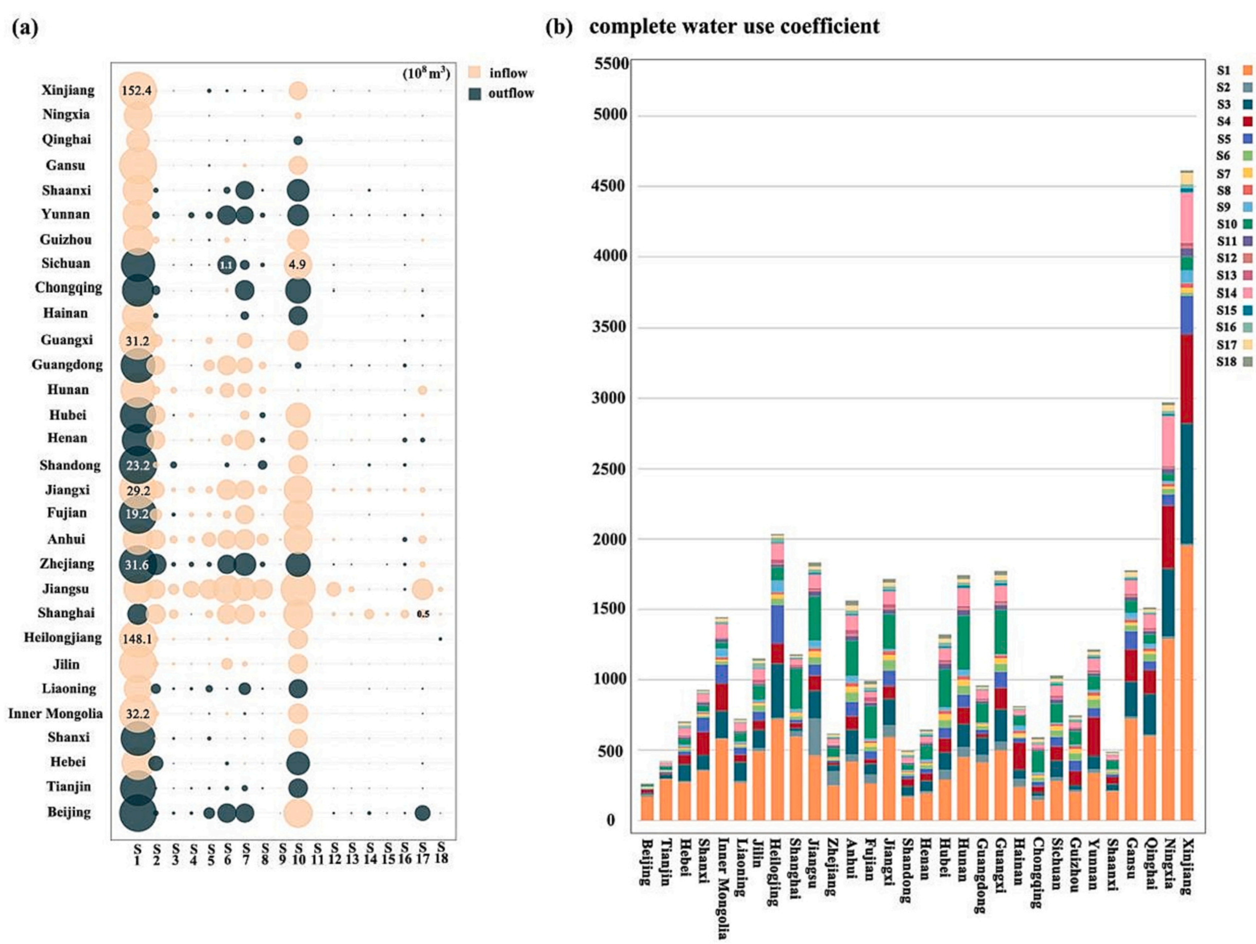

Fig. 8. $NVWT_{RF}$ and the complete water use coefficient by sectors of 30 provinces of China in 2017: (a) $NVWT_{RF}$ by sectors (b) The complete water use coefficient by sectors.

in Shanghai ranked No. 4. These sectors had excessive net virtual water outflow with low water use efficiency. That is, they consumed more water to produce the same products comparing with other regions.

3.5. Uncertainties and limitations

There are also some uncertainties and limitations in our study. The assumptions of the ESFEs model are relatively simplified. The model assumes that the economic system is closed and balanced. However, the actual economic system is often complex and unbalanced. The equilibrium of economic system means that the efficiency of resource allocation and the economic benefits of market participants are maximized. Therefore, these simplified assumptions may lead to uncertainty in the results.

Moreover, due to the limitation of the ESFEs model, it can only be decomposed into two-region or three-region frameworks based on EIO model. When the regions are more than three, we can only address the problem using the same model repeatedly, which limiting our ability to explore environmental pressure transfers between individual regions. The development and application of ESFEs models are complex and meaningful, which is worth further investigating.

4. Policy implications

To respond the UN Sustainable Development Goals (SDGs) 6 and 12, which highlight the sustainability of water and consumption-production patterns respectively, it is essential to constrain the over-exploitation of water resources and balance water sustainability and related economic inequality. Based on our findings, the following policy recommendations are suggested.

Firstly, when commodities are transferred from one region to another, the consumption regions impose an extra water stress for the production regions. Therefore, the regions involved in the trade activities are supposed to share the water stress caused by the virtual water transfer jointly. For example, the regions which outsource water stress should give financial compensation to the contributors of water resources. Our results clarify the regional responsibilities for water stress mitigation, which provide guidance to decision maker to promote inter-regional cooperation.

Secondly, S1 is a water intensive and low value-added industry, which results in the simultaneous loss of virtual water and value-added for Xinjiang, Heilongjiang, Gansu and Guangxi. Thus it is important to balance the transfer of value-added and virtual water. The National Rural Industry Development Plan (2020–2025) of China emphasizes the importance of whole industrial chain, which implies that if high value-added industries can benefit local economy and make up for the deficit caused by S1, then the trade-instigated inequality may be alleviated. Therefore, building a whole industrial chain should be prioritized for above regions.

Thirdly, both the 14th Five Year Plan for the Development of Rural Industries in Heilongjiang and the 14th Five Year Plan for Promoting Agricultural and Rural Modernization in Gansu aim to achieve the agricultural advancement and water conservation simultaneously by industrial upgrading. Developing the deep processing of food and agricultural by-products is a good way to increase the agricultural value-added per unit water use. For example, strengthening the cooperation with upstream and downstream enterprises and extending the value chain, such as agricultural cultivation, processing, packaging, sales, etc., this will narrow the inequality between virtual water and value-added transfer.

Fourthly, our results show that some regions are getting both water resources and economic benefits, while others are getting the opposite. On account of the predicaments of trade structure and water use efficiency, the economic benefits and environment costs among different provinces were significantly different. However, the fairness principle in sustainable development emphasizes an equitable balance of interests and an equitable development in both inter-regional and intra-regional. Therefore, while paying attention to economic growth, policymakers must also concern about resource use inequality.

5. Conclusions

This study quantified and recalibrated the virtual water transfer in association with the feedback effects in 30 provinces of China using the ESFEs model. The virtual water transfers identified this way were then used to measure the inequality between virtual water transfer and the resource endowments taking the value-added into account. The main conclusions are as follows:

(1) The inter-regional feedback effects were much smaller than the inter-regional spillover effects. However, after the revision of the feedback effects, the change rate of the virtual water transfer volumes reached a maximum of 428 %, and the provinces of Liaoning and Jilin changed from a virtual water importer to a virtual water exporter. Therefore, even though the feedback effects are smaller than the spillover effects, the former cannot be ignored in the virtual water transfer process.
(2) Utilizing products produced in water-efficient regions to meet the final demands of water-inefficient regions will reduce the proportion of production water consumption in the total available water. However, the results of this study show that, due to different irrigation measures and crop patterns used in different regions, the complete water use coefficient of sector S1 (agriculture, forestry, animal husbandry and fishery) was widely different in different provinces of China. For example, the value of this coefficient in the massive water export provinces of Xinjiang and Ningxia was ten times higher than the corresponding coefficient value in provinces of Chongqing and Shandong, resulting in a considerable waste of water resources.
(3) The current virtual water trade fails to meet the principle of transferring water resources from water-sufficient to water-deficient provinces. Also, the virtual water transfer in different regions were not compensated equally from the economic perspective. For example, Xinjiang is a water-deficient region but it still transfers large amounts of water to other regions hence it should be compensated for this in terms of economic benefits. However, after taking the value-added into account, we found that there was still a significant gap in the economic compensation this region ought to receive. The above is undoubtedly contrary to the sustainable development strategy. This also hinders the process of poverty eradication to a greater extent, owing to the unequal distribution of natural resources and social wealth in inter-regional trade.

Based on above, it is suggested that policymakers focus on assessing a two-way impact of virtual water transfer, for the purpose of grasping the situation of virtual water trade more accurately. Based on the principle of equity, policymakers should identify regional responsibilities and strengthen the inter-regional coordination through building a balanced inter-regional trade structure that meets the target of synergistic sustainability of water resource and economic development.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2023.09.009.

References

Cai, B., Zhang, W., Hubacek, K., et al., 2019. Drivers of virtual water flows on regional water scarcity in China[J]. J. Clean. Prod. 207, 1112–1122.

Chai, Q., Qin, A., Gan, Y., et al., 2014. Higher yield and lower carbon emission by intercropping maize with rape, pea, and wheat in arid irrigation areas[J]. Agron. Sustain. Dev. 34, 535e543.

Chapagain, A.K., Hoekstra, A.Y., Savenije, H.H.G., 2006. Water saving through international trade of agricultural products[J]. Hydrol. Earth Syst. Sci. 10 (3), 455–468.

Chen, W.M., Kang, J.N., Han, S.M., 2021a. Global environmental inequality: evidence from embodied land and virtual water trade. Sci. Total Environ. 783, 146992.

Chen, Y., Huang, K., Hu, J., et al., 2021b. Understanding the two-way virtual water transfer in urban agglomeration: a new perspective from spillover-feedback effects [J]. J. Clean. Prod. 310, 127495.

Guan, D.B., Klaus, H., 2007. Assessment of regional trade and virtual water flows in China[J]. Ecol. Econ. 61 (1), 159–170.

Hu J R, Huang K, Ridoutt B G, et al. Measuring integrated environmental footprint transfers in China: a new perspective on spillover-feedback effects[J]. J. Clean. Prod., 241, 118375.

Isard, W., 1951. Interregional and regional input-output analysis: a model of a space-economy[J]. Rev. Econ. Stat. 33 (4), 318–328.

Li, H., Liu, X.M., Wang, S., et al., 2022. Impacts of international trade on global inequality of energy and water use. J. Environ. Manag. 315, 115156.

Mi, Z.F., Zheng, J.L., Meng, J., 2020. Economic development and converging household carbon footprints in China[J]. Nat. Sustain. 3 (7), 529–537.

Ministry of Construction of the People''s Republic of China, 2002. Urban Resident Water Consumption Standard. China Construction Industry Press, Beijing. GB/T 50331-2002 [S].

Mubako, S., Lahiri, S., Lant, C., 2013. Input-output analysis of virtual water transfers: case study of California and Illinois. Ecol. Econ. 93, 230–238.

National Bureau of Statistics of China, 2018. China Statistical Year Book[M]. China Statistical Press, Beijing.

Ning, Y., Miao, L., Ding, T., 2019. Carbon emission spillover and feedback effects in China based on a multiregional input-output model[J]. Resour. Conserv. Recycl. 141, 211–218.

Office of the Leading Group for the Second National Economic Census of the State Council, 2008. China Economic Census Yearbook 2008 [M] Beijing: China Statistics Press.

Pan, W.Q., 2006. The feedback and spillover effects among multi-regions in interregional input-output models[J]. Syst. Eng. Theor. Pract. 7, 86–91.

Song, J., Yin, Y., Xu, H., et al., 2020. Drivers of domestic grain virtual water flow: a study for China[J]. Agric. Water Manag. 239, 106175.

Tian, P.P., Lu, H.W., Liu, J.G., et al., 2022. The pattern of virtual water transfer in China: from the perspective of the virtual water hypothesis[J]. J. Clean. Prod. 346, 131232.

Wang, Z.Z., Zhang, L.L., Ding, X.L., et al., 2019. Virtual water flow pattern of grain trade and its benefits in China[J]. J. Clean. Prod. 223, 445–455.

Wang, X.C., Klemes, J.J., Wang, Y.T., et al., 2020. Unsustainable imbalances and inequities in carbon-water-energy flows across the EU27. Renew. Sust. Energ. Rev. 138, 110550.

Wang, Y.H., Xiong, S.Q., Ma, X.M., 2022. Carbon inequality in global trade: evidence from the mismatch between embodied carbon emissions and value added[J]. Ecol. Econ. 195, 107398.

Wei, W.D., Hao, S.J., Yao, M.T., et al., 2020. Unbalanced economic benefits and the electricity-related carbon emissions embodied in China's interprovincial trade[J]. J. Environ. Manag. 263, 110390.

Xin, M.L., Wang, J.G., Xing, Z.C., 2021. Decline of virtual water inequality in China's inter-provincial trade: an environmental economic trade-off analysis[J]. Sci. Total Environ. 806, 150524.

Zhang, Z.Y., Yang, Y., Shi, M.J., 2011. Analyses of water footprint of Beijing in an interregional input-output framework[J]. Ecol. Econ. 70 (12), 2494–2502.

Zhang, W., Liu, Y., Feng, K., et al., 2018. Revealing environmental inequality hidden in China's inter-regional trade[J]. Environ. Sci. Technol. 52, 7171–7181.

Zhang, S., Taiebat, M., Liu, Y., et al., 2019. Regional water footprints and interregional virtual water transfers in China[J]. J. Clean. Prod. 228, 1401–1412.

Zhang, W., Fan, X., Liu, Y.T., et al., 2020. Spillover risk analysis of virtual water trade based on multi-regional input-output model—a case study[J]. J. Environ. Manag. 275, 111242.

Zhao, X., Li, Y.P., Yang, H., et al., 2018. Measuring scarce water saving from interregional virtual water flows in China[J]. Environ. Res. Lett. 13 (5), 054012.

Zheng, H.R., Zhang, Z.K., et al., 2020. Regional determinants of China's consumption-based emissions in the economic transition[J]. Environ. Res. Lett. 15 (7), 1–14.

Zhi, Y., Hamilton, P.B., Wu, G.Y., et al., 2022. Virtual water indicator for comprehensive water pressures: model and case studies[J]. J. Hydrol. 608, 127664.

Zhu, M.C., Zhao, Z.B., Meng, Y., 2022. Unfolding the evolution of carbon inequality embodied in inter-provincial trade of China: network perspective analysis[J]. Environ. Impact Assess. Rev. 97, 106884.

Zhuo, L., Mekonnen, M.M., Hoekstra, A.Y., 2016. Consumptive water footprint and virtual water trade scenarios for China—with a focus on crop production, consumption and trade[J]. Environ. Int. 94, 211–223.