



Effects of production fragmentation and inter-provincial trade on spatial blue water consumption and scarcity patterns in China

Quanliang Ye^{a,*}, Ranran Wang^b, Joep F. Schyns^a, La Zhuo^{c,d}, Lan Yang^e, Maarten S. Krol^a

^a Multidisciplinary Water Management, Faculty of Engineering Technology, University of Twente, 7522, NB, Enschede, the Netherlands

^b Institute of Environmental Sciences, Leiden University, 2333 CC, Leiden, the Netherlands

^c Institute of Soil and Water Conservation, Northwest A&F University, Yangling, 712100, China

^d Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, 712100, China

^e Fudan Tyndall Center and Shanghai Key Laboratory of Atmospheric Particle Pollution and Prevention (LAP3), Department of Environmental Science & Engineering, Fudan University, 200438, Shanghai, China

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ABSTRACT

Freshwater resources are used to produce commodities that are traded and consumed elsewhere, which generate virtual water flows. The relation between regional blue water scarcity levels—the degree of competition over limited surface and groundwater flows—and inter-regional virtual water flows has been studied. However, the effects of production fragmentation on this relation are still not properly understood. Production fragmentation is the distribution of the production process across different regions, resulting in inter-regional trade of both intermediate and finished goods and services, which involve different virtual water networks. This study formulates a comprehensive trade disaggregation approach to elaborate the virtual water networks of three trade patterns (i.e., direct final goods trade, intermediate goods trade for the last step of production, and value chain-related trade) within China, and further analyzes the impacts of trade on provincial blue water scarcity by comparing the actual water scarcity with that under a “no-trade” scenario (NTS). In 2012, there was 128 km³ blue water virtually transferred across provinces because of inter-provincial trade. Direct final goods trade contributed the most to the virtual water trade (accounting for 47% of the total), whereas value chain-related trade induced the least (17%). Compared with the results under the NTS, we found that current trade alleviated the water scarcity in provinces under extreme water scarcity, but worsened the water scarcity of this nation from a broader scope. Our study suggests policy makers fully considering specific trade patterns and their impacts on provincial or national water consumption to cope with water scarcity in China.

1. Introduction

China has entered an era of “new normal” economic growth recently, towards more sustainable and environmental-friendly development paths. Yet, the past decades’ socioeconomic development has accompanied with significant resource and environmental consequences (Deng et al., 2015; Feng et al., 2013; Jiang et al., 2019), particularly for freshwater resources that are threatened by the stress of both quantity and quality (Guan et al., 2014; Ma et al., 2020). Over half of the population are affected by either quantity-related (0.9 billion) or quality-related water scarcity (1.2 billion) for at least one month of the year (Ma et al., 2020; Mekonnen and Hoekstra, 2016). Thus, there is an urgent need to improve national or sub-national water resource management to cope with water scarcity in China. Moreover, domestic trade

within China has grown rapidly (NBSC, 2020), which presents new features of environmental pressures because resource use and emissions during the production process of goods and services are virtually transferred along the trade. For example, the intra-national virtual water trade has increased by 90% during the period of 2002–2012, mainly from the water-scarce Northwest and Northeast China to the water-rich South (Cai et al., 2019). As for product-specific environmental pressures, maize-related virtual water flow from the North to the South China has increased by 40%, while pork-related virtual water flow from South to North has increased by 23% over the period of 2000–2013 (Zhuo et al., 2019).

An important debate on virtual water transfers, bilateral or multi-lateral, is their ultimate role in reducing or increasing water consumption of such a system consisting of all related regions (Dalin et al., 2012;

* Corresponding author. University of Twente, the Netherlands.

E-mail address: q.ye@utwente.nl (Q. Ye).

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Hoekstra and Mekonnen, 2012; Zhang et al., 2011). For instance, international trade of crops may help save water at the global scale by exchanging virtual water from highly productive countries to less productive locals, resulting in a smaller water consumption per unit of crop grown (Chapagain et al., 2005). The estimation of virtual water transfers, from the sources to the destinations, has been widely carried out (Chen and Chen, 2013; Chen et al., 2012; Dalin et al., 2014; Han et al., 2017, 2018; Hoekstra and Mekonnen, 2012; Wu et al., 2019; Zhuo et al., 2019), and based on that, relevant research such as the drivers of virtual water flows or the potential water savings have been further addressed (Dalin et al., 2017; Tamea et al., 2014). However, the effects of production fragmentation on virtual water flows are still not properly understood. Production fragmentation is the distribution of production process across different regions, resulting in inter-regional trade by different trade patterns (e.g., the direct trade of final products or the trade of intermediate input products for production) which have different associated virtual water networks. The lack of data that provide sufficient information about the commodity trade and the supply chain-wide transactions among these commodities or economic sectors is the main reason (Feng et al., 2011).

Prior studies (Arce González et al., 2012; López et al., 2013; Wang et al., 2017) disaggregated the bilateral trade from the production perspective into three patterns, i.e., trade of final demand, trade of intermediate products for the last step of production, and trade of intermediate products for the remaining steps of inter-regional production. For the first two patterns of trade, products are absorbed by the trade partners, which also regarded as traditional Ricardian trade that represents the direct value added trade pattern (Borin and Mancini, 2015). The last pattern of trade is regarded as supply chain-wide related trade, as the exported intermediate products are processed and re-exported as inputs for other regions' production (Wang et al., 2017; Zhang et al., 2017). Based on the disaggregation, the contributions of different trade patterns as well as the effects of different socioeconomic factors on the inter-regional virtual water flows could be addressed (Liu et al., 2019), as the cases of carbon transfers by Zhang et al. (2017) and Feng et al. (2020). Although previous studies presented a great framework for trade pattern disaggregation, there was still a calculation error in disaggregating the trade of intermediate products, i.e., neglecting the trade of intermediate products for the last step of final goods production that are further traded to trade partners. Without capturing this trade pattern, the actual inter-provincial trade values within China would be underestimated (a simple example demonstrating the underestimation could be found in Supplementary Information B).

Apart from the research gap on the effects of production fragmentation on virtual water networks, the effects of trade (compared to a situation without trade) on national water consumption and provincial water scarcity are not sufficiently assessed either. With more attention on carbon emissions and carbon transfers, previous studies have made great contributions to reveal the effects of trade on global and regional carbon emissions, mainly using three methods—decomposition analysis (Arto and Dietzenbacher, 2014; Hoekstra et al., 2016; Jakob and Marchinski, 2012; Jiang and Guan, 2017; Jiang et al., 2018; Zhu and Jiang, 2019), the pollution haven hypothesis (López et al., 2018; Zhang et al., 2017), and the no-trade scenario (NTS). However, two totally opposite conclusions have been summarized from the studies relying on the first two methods. That is, a general net positive effect was found by decomposition analysis, whereas the current international trade generating global emission savings was revealed by the pollution haven hypothesis. This suggested that to comprehensively understand the effects of trade on global or national environmental performances (not only air pollution emissions but other environmental pressures like blue water consumption), the NTS method would be the most appropriate one compared with the other two methods. However, the existing NTSs, with the core of reallocating the supply chain-wide environmental pressures for product production into consuming region itself, had main limitations such as still using with-trade economic structures or neglecting the

differences in commodity prices and production efficiencies among regions (Wu et al., 2021). In addition, most of the previous NTSs were developed to re-construct the international (Duchin, 2007; Wang and Zimmerman, 2016; Wu et al., 2021; Xu et al., 2020) or bilateral trade (Liu et al., 2010; Shui and Harriss, 2006; Tan et al., 2013) across countries. Little is known about the effects of domestic trade on sub-national environmental pressures, especially for vast countries with great spatial variations in socio-economic development patterns and resource endowments such as China.

In summary, although existing literature has addressed the changes in provincial water consumption and inter-provincial virtual water trade in China yielding novel insights and policy suggestions, the effects of product fragmentation and trade (compared to an NTS) on shaping the national water consumption and provincial water scarcity are not properly understood. Therefore, the objectives of this study are: 1) to formulate a comprehensive trade disaggregation approach to elaborate the virtual water networks of three trade patterns (i.e., direct final goods trade, intermediate products trade for the last production, and value chain-related trade) within China; and 2) to analyze the impacts of trade on provincial water scarcity by comparing the actual water scarcity with that under the NTS. In this analysis we include blue water consumption (BWC, the consumptive use of surface water and groundwater) as indicator for water-related pressures. Data availability at provincial level for BWC is better than for possible additional indicators such as the green water footprint (consumptive use of rainwater) or the grey water footprint (the volume of fresh water required for assimilation of pollutants Hoekstra et al. (2011)). Also BWC is relevant for both agricultural and other economic sectors, is less controversial and is more widely discussed in previous studies, allowing to compare our results to others. The remainder of this paper is organized as follows: Section 2 elaborates the trade disaggregation approach and the NTS we formulate. Section 3 presents the key results about the virtual water trade embodied in different trade patterns and the effects of trade on provincial water consumption as well as water scarcity. Section 4 discusses our results and potential policy implementation. Conclusions will be summarized in Section 5.

2. Methods

The methodology improvements in this study include: 1) formulating a more accurate disaggregation approach to capture the three inter-provincial trade patterns in China, which addresses the underestimation issue of existing trade disaggregation approaches (Feng et al., 2020; Liu et al., 2019; Zhang et al., 2017); and 2) developing a novel NTS with the core of reallocating the supply chain-wide indirect inputs for the production of province m 's final demand into province m itself, whilst considering the distinctions of production structures and coefficients between provinces as well as the local production factor endowments (Duchin, 2007; Wu et al., 2021).

2.1. Disaggregation of trade patterns

Provinces are connected through the inter-provincial trade of intermediate and final products, and each province is connected with the global economy through international imports and exports. The exports from province m to province n (T^{mn}) include the exports of final demands (Y^{mn}) and intermediate inputs (Z^{mn}), i.e., $T^{mn} = Y^{mn} + Z^{mn}i$, where i is a summation vector of appropriate length. The intermediate input (Z^{mn}) can be calculated by $Z^{mn} = A^{mn}x^n$, where A^{mn} is the input coefficient matrix that represents the direct economic requirements for one-unit output. The total output x^n equals to the sum of intermediate inputs, final demands and international exports (EX^n), i.e., $x^n = \sum_{r=1}^g Z^{rn}i + \sum_{r=1}^g Y^{rn} + EX^n = \sum_{r=1}^g A^{nr}x^r + \sum_{r=1}^g Y^{nr} + EX^n$, where g is the number of regions.

$$\begin{bmatrix} \mathbf{x}^1 \\ \mathbf{x}^2 \\ \dots \\ \mathbf{x}^g \end{bmatrix} = \begin{bmatrix} \mathbf{A}^{11} & \mathbf{A}^{12} & \dots & \mathbf{A}^{1g} \\ \mathbf{A}^{21} & \mathbf{A}^{22} & \dots & \mathbf{A}^{2g} \\ \dots & \dots & \dots & \dots \\ \mathbf{A}^{g1} & \mathbf{A}^{g2} & \dots & \mathbf{A}^{gg} \end{bmatrix} \begin{bmatrix} \mathbf{x}^1 \\ \mathbf{x}^2 \\ \dots \\ \mathbf{x}^g \end{bmatrix} + \begin{bmatrix} \sum_{r=1}^g \mathbf{Y}^{1r} + \mathbf{EX}^1 \\ \sum_{r=1}^g \mathbf{Y}^{2r} + \mathbf{EX}^2 \\ \dots \\ \sum_{r=1}^g \mathbf{Y}^{gr} + \mathbf{EX}^g \end{bmatrix} \quad (1)$$

$$= \begin{bmatrix} \mathbf{B}^{11} & \mathbf{B}^{12} & \dots & \mathbf{B}^{1g} \\ \mathbf{B}^{21} & \mathbf{B}^{22} & \dots & \mathbf{B}^{2g} \\ \dots & \dots & \dots & \dots \\ \mathbf{B}^{g1} & \mathbf{B}^{g2} & \dots & \mathbf{B}^{gg} \end{bmatrix} \begin{bmatrix} \sum_{r=1}^g \mathbf{Y}^{1r} + \mathbf{EX}^1 \\ \sum_{r=1}^g \mathbf{Y}^{2r} + \mathbf{EX}^2 \\ \dots \\ \sum_{r=1}^g \mathbf{Y}^{gr} + \mathbf{EX}^g \end{bmatrix}$$

In a standard multi-regional input-output (MRIO) modelling, we have $\mathbf{x} = \mathbf{B}(\mathbf{Yi} + \mathbf{EX})$, where $\mathbf{B} = (\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief inverse matrix, representing the supply chain-wide economic requirements to increase a one-unit monetary increase of final demand or exports. \mathbf{I} is an identity matrix. Thus, the equation of total output \mathbf{x}^n can be transformed into $\mathbf{x}^n = \sum_{r=1}^g \mathbf{B}^{nr} (\sum_{v=1}^g \mathbf{Y}^{rv} + \mathbf{EX}^r) = \sum_{r=1}^g \mathbf{B}^{nr} \sum_{v=1}^g \mathbf{Y}^{rv} + \sum_{r=1}^g \mathbf{B}^{nr} \mathbf{EX}^r$, and then the exports \mathbf{T}^{mn} can be calculated by:

$$\begin{aligned} \mathbf{T}^{mn} &= \mathbf{Y}^{mn} + \mathbf{A}^{mn} \mathbf{x}^n = \underbrace{\mathbf{Y}^{mn}}_{\mathbf{T}_f^{mn}} + \underbrace{\mathbf{A}^{mn} \mathbf{L}^{nn} \mathbf{Y}^{nn}}_{\mathbf{T}_i^{mn}} + \underbrace{\mathbf{A}^{mn} \mathbf{L}^{nm} \sum_{v \neq n}^g \mathbf{Y}^{nv}}_{\mathbf{T}_{i^{mn-n}}} \\ &\quad + \underbrace{\mathbf{A}^{mn} \mathbf{L}^{nn} \sum_{r \neq n}^g \mathbf{A}^{nr} \mathbf{B}^{rn} \sum_{v=1}^g \mathbf{Y}^{nv} + \mathbf{A}^{mn} \sum_{r \neq n}^g \mathbf{B}^{nr} \sum_{v=1}^g \mathbf{Y}^{rv}}_{\mathbf{T}_d^{mn}} + \underbrace{\mathbf{A}^{mn} \sum_{r=1}^g \mathbf{B}^{nr} \mathbf{EX}^r}_{\mathbf{T}_g^{mn}} \end{aligned} \quad (2)$$

where \mathbf{L} is the local Leontief inverse matrix. \mathbf{B}^{mn} in Eq. (2) is decomposed into $\mathbf{B}^{mn} = \mathbf{L}^{nn} + \mathbf{L}^{nn} \sum_{r \neq n}^g \mathbf{A}^{nr} \mathbf{B}^{rn}$ according to Wang et al. (2017) and Zhang et al. (2020). We define: 1) \mathbf{T}_f^{mn} as the trade of final products—the trade partner n would directly absorb the exported products from m , and the exporter m is located in the last stage of production; 2) \mathbf{T}_i^{mn} as the trade of intermediate products for the last stage of pro-

duction—finally absorbed by domestic provinces (\mathbf{T}_d^{mn}) or further processed and exported to foreign counties (\mathbf{T}_g^{mn}).

2.2. Supply chain-wide virtual water flows

The BWC coefficients of products and sectors in province m (\mathbf{f}^m) are calculated by $\mathbf{f}^m = \mathbf{F}^m \widehat{\mathbf{x}}^m^{-1}$, where \mathbf{F}^m is a row vector of direct BWC of products and sectors in province m . The total BWC of province m , W^m , including the BWC for household purposes (W_{hh}^m) which accounts for a big part of BWC in some populous provinces but tends to be neglected in previous studies, can be calculated as:

$$\begin{aligned} W^m &= \mathbf{f}^m \mathbf{x}^m + W_{hh}^m = (\mathbf{f}^m \mathbf{L}^{mm} \mathbf{Y}^{mm} + W_{hh}^m) + \mathbf{f}^m \mathbf{L}^{mm} \mathbf{EX}^m \\ &\quad + \mathbf{f}^m \mathbf{L}^{mm} \sum_{n \neq m}^g \mathbf{T}_f^{mn} + \mathbf{f}^m \mathbf{L}^{mm} \sum_{n \neq m}^g \mathbf{T}_i^{mn} + \mathbf{f}^m \mathbf{L}^{mm} \sum_{n \neq m}^g \mathbf{T}_v^{mn} \end{aligned} \quad (3)$$

The total BWC of province m is disaggregated into five terms. The first term represents the BWC assigned to the economic activities and household use within province m , which has no relation with the inter-provincial or international trade. The second term represents the BWC assigned to the direct exports of final products to foreign countries. The last three terms represent the BWC assigned to different trade patterns.

The local BWC embodied in the export, also known as virtual water outflow (Allan, 1998), from province m to province n is:

$$W_{EX}^{mn} = \mathbf{f}^m \mathbf{L}^{mm} \mathbf{T}_f^{mn} = \mathbf{f}^m \mathbf{L}^{mm} \mathbf{T}_f^{mn} + \mathbf{f}^m \mathbf{L}^{mm} \mathbf{T}_i^{mn} + \mathbf{f}^m \mathbf{L}^{mm} \mathbf{T}_v^{mn} \quad (4)$$

The net virtual water flows (NVW) between provinces m and n are calculated by:

$$\begin{aligned} NVW^{mn} &= W_{EX}^{mn} - W_{EX}^{nm} = \underbrace{(\mathbf{f}^m \mathbf{L}^{mm} \mathbf{T}_f^{mn} - \mathbf{f}^n \mathbf{L}^{nn} \mathbf{T}_f^{nm})}_{NVW-1} + \underbrace{(\mathbf{f}^m \mathbf{L}^{mm} \mathbf{T}_i^{mn} - \mathbf{f}^n \mathbf{L}^{nn} \mathbf{T}_i^{nm})}_{NVW-2} \\ &\quad + \underbrace{(\mathbf{f}^m \mathbf{L}^{mm} \mathbf{T}_{i^{mn-n}} - \mathbf{f}^n \mathbf{L}^{nn} \mathbf{T}_{i^{nm-n}})}_{NVW-3} + \underbrace{(\mathbf{f}^m \mathbf{L}^{mm} \mathbf{T}_d^{mn} - \mathbf{f}^n \mathbf{L}^{nn} \mathbf{T}_d^{nm})}_{NVW-4} \\ &\quad + \underbrace{(\mathbf{f}^m \mathbf{L}^{mm} \mathbf{T}_g^{mn} - \mathbf{f}^n \mathbf{L}^{nn} \mathbf{T}_g^{nm})}_{NVW-5} \end{aligned} \quad (5)$$

duction, which includes the last stage of final good production consumed by the trade partner (\mathbf{T}_i^{mn} , with the traded products cross the border of region m once), as well as the trade partner's trade partners ($\mathbf{T}_{i^{mn-n}}$, with the traded products cross the border of regions m and n once) which has not been captured in previous studies (Supplementary Information B); 3) \mathbf{T}_v^{mn} as the value chain-related trade of products—crossing the provincial or national borders more than

The right five terms NVW-1—NVW-5 represent the net virtual water flows in different trade patterns. A positive value of NVW^{mn} indicates that the bilateral trade increases the BWC of province m , and vice versa for a negative value of NVW^{mn} .

2.3. Developing the no-trade scenario (NTS)

Before describing the development of the NTS, it should be clearly noted that the NTS is completely hypothetical, thus based on some key assumptions such as using production factors to constrain the hypothetical production capacities (Wu et al., 2021). To reallocate the supply chain-wide indirect inputs for the production of province m 's final demand into province m itself, we first calculate the supply chain-wide indirect inputs (i.e., the intermediate inputs) for province m 's final demand, $Z^m = AB\hat{Y}^m$ as:

$$\begin{bmatrix} Z^{m1} & \dots & Z^{m1m} & \dots & Z^{m1g} \\ \dots & \dots & \dots & \dots & \dots \\ Z^{m1} & \dots & Z^{mm} & \dots & Z^{mg} \\ \dots & \dots & \dots & \dots & \dots \\ Z^{m1} & \dots & Z^{gm} & \dots & Z^{gg} \end{bmatrix} = \begin{bmatrix} A^{11} & \dots & A^{1m} & \dots & A^{1g} \\ \dots & \dots & \dots & \dots & \dots \\ A^{m1} & \dots & A^{mm} & \dots & A^{mg} \\ \dots & \dots & \dots & \dots & \dots \\ A^{g1} & \dots & A^{gm} & \dots & A^{gg} \end{bmatrix} \times \begin{bmatrix} B^{11} & \dots & B^{1m} & \dots & B^{1g} \\ \dots & \dots & \dots & \dots & \dots \\ B^{m1} & \dots & B^{mm} & \dots & B^{mg} \\ \dots & \dots & \dots & \dots & \dots \\ B^{g1} & \dots & B^{gm} & \dots & B^{gg} \end{bmatrix} \times \begin{bmatrix} Y^{1m} & \dots & 0 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & \dots & Y^{mm} & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & \dots & 0 & \dots & Y^{gm} \end{bmatrix} \quad (6)$$

where Z^{mm} is the indirect inputs for local production of province m 's final demand; Z^{mn} ($n \neq m$) is the indirect inputs exported to other provinces for the external production of province m 's final demand; Z^{nh} ($n \neq m$ and $h \neq m$) is the indirect inputs between other provinces for the external production of province m 's final demand.

Under the NTS, we assume the final demand of province m would not change, but all the outputs of its final demand (i.e., direct final demand Y^m plus indirect inputs Z^m) would be provided by province m itself. The reallocation of direct final demand is straightforward: we sum up the direct final demand by province, i.e., $Y^m = \sum_{n=1}^g Y^{nm}$. The international import of final demand is allocated into each sector by the sectoral share in Y^m . To reallocate the indirect inputs for the production of province m 's final demand, we consider the distinctions of production structures and coefficients between provinces. The indirect inputs for province h 's production of province m 's final demand (i.e., $\sum_{n=1}^g Z^{nh}$) is proportionally reallocated into province m itself according to local technical coefficients, i.e., $D^m \sum_{n=1}^g Z^{nh} / D^h$, where D is the local technical coefficient matrix. Meanwhile, we also generate the national average technical coefficient of product i for one unit output of product j to reallocate the indirect inputs to province m itself in any case that province m requires all the production requirements of product i from other provinces. The indirect inputs for the local production of province m 's final demand under the NTS is:

$$Z^m = \sum_{h=1}^g D^m \sum_{h=1}^g Z^{nh} / D^h \quad (7)$$

The total outputs of province m under the NTS is:

$$x^m = Z^m \mathbf{i} + Y^m \quad (8)$$

We can see that under the NTS, not only the final use part of trade was removed, but also production upstream in the supply chain was shifted to the province of final use.

The next step is to apply the provincial constraints like resources or labour force in the NTS (Duchin, 2007; Wu et al., 2021). We consider three production factors as the main constraints in our NTS, i.e., land, blue water availability, and labour force. The hypothetical provincial economic production capacities under the NTS should be constrained by their territorial production factor endowments.

$$f_{cs}^m x^m \leq F_{cs}^m \quad (9)$$

where f_{cs}^m is the vector of direct coefficient of constraint factor cs (e.g., km^2 per unit of the output for land) for each sector. F_{cs}^m is the provincial

endowment of constraint factor cs . Provincial land endowment, blue water availability, and employment data are collected from the National Bureau of Statistics of China (NBSC, 2020). If $f_{cs}^m x^m$ exceed any provincial factor endowments, we use a scaling factor $F_{cs}^m / (f_{cs}^m x^m)$ to scale down x^m . Z^m and y^m are further balanced using RAS method (Günük-Şenesen and Bates, 1988).

The total BWC of province m under the NTS is:

$$W^m = f^m (\mathbf{I} - Z^m \hat{x}^{m-1})^{-1} Y^m \quad (10)$$

The difference between W^m and W'^m represents the contribution of

province m -related trade to the national blue water consumption (CNW). A positive value indicates that province m -related trade increases the national BWC, and vice versa for a negative value of CNW^m .

2.4. Blue water scarcity index

The blue water scarcity index of province m with and without trade (WSI^m and WSI'^m , respectively) are calculated as the ratio of BWC in province m with and without trade (W^m and W'^m , respectively) to the average annual blue water availability (WA^m), respectively (Eq. (11) and Eq. (12)):

$$WSI^m = \frac{W^m}{WA^m} \quad (11)$$

$$WSI'^m = \frac{W'^m}{WA^m} \quad (12)$$

The differences between the two water scarcity indices represent the effects of virtual water trade in terms of increasing (i.e., $WSI^m > WSI'^m$)



Fig. 1. Geographical location of each province in China as well as local water scarcity level for the year 2012.

or mitigating (i.e., $WSI^m < WSI^m$) the water scarcity in province m . Low, moderate, severe, and extreme water scarcity levels are typically defined as previous studies did (Wang and Zimmerman, 2016; Zhao et al., 2015). The details about water scarcity level of each province are illustrated in Fig. 1 and Table S1.

2.5. Data sources

The main data sources elaborated in this section include the data sources of multi-regional input-output tables, irrigational BWC of agricultural products, BWC of economic sectors, and annual blue water availability by province.

The hybrid MRIO model developed by Ye et al. (2022) is used in this study. It describes the Chinese economy by 84 agricultural biomass and food commodities and 42 monetary economic sectors in physical (such as tonnes, heads, or m^3) and monetary units at the provincial level for the year 2012. They particularly disaggregated the two highly-aggregated agri-food-related sectors included in the original 42 economic sectors (Mi et al., 2017), i.e., sector “Agriculture, forestry, animal husbandry and fishery products and services” and sector “Food and tobacco manufacturing”, into 84 individual agricultural biomass and food commodities in physical terms. The total 84 agri-food commodities cover the main grain crops (e.g., rice, maize, and wheat), cash crops (e.g., sugar beets, groundnuts, and cotton), fruits (e.g., apples, and citrus), vegetables (e.g., tomatoes), live animals (e.g., cattle, and sheep), livestock (e.g., bovine meat, mutton meat, and pork), fishery, and forestry products, which to our best knowledge formulates the most comprehensive classifications of agri-food commodities for sub-national supply chain analysis.

The total irrigational BWC of each crop in each province is calculated by the provincial crop production multiplied by its average blue water content (in m^3 per ton). The average blue water content of crops are estimated at 5×5 arc-minute grid level following the accounting framework of Hoekstra et al. (2011), which are comprehensively described in Supplemental Information A.

Provincial BWC of five main economic sectors, i.e., irrigation, animal husbandry, industry (including electricity generation), services (including construction), and household, are partially available in the provincial Water Resource Bulletin for the year 2012 (see Table S2). To fill the data gaps of agricultural BWC in the provinces without available data, we use the national BWC coefficient to estimate local BWC of agriculture. For electricity generation sector, we calculate the average BWC coefficient of electricity generation sector in the provinces with available BWC data, and apply the average BWC coefficient in other provinces. For other industrial sectors, we rely on the national BWC data as well as the provincial water withdrawal data of each sector from Chinese Economic Census Yearbook (2008). We allocate the national

BWC of each sector to provinces by the provincial water withdrawal. Here we assume that the more water withdrawn for sectoral production, the more water consumed by that sector. After that, we scale the adjusted industrial BWC into the actual industrial BWC in 2012. For construction sector, we calculate the average BWC coefficient of construction sector in the provinces with BWC data, and apply the average BWC coefficient in other provinces. For household BWC, we calculate the per-capita BWC by the provinces with available data and estimate the household BWC in provinces without available data based on the per-capita BWC and local population.

The average annual blue water availability of province m is calculated from annual water availability data for the period 2007–2017 collected from the provincial Water Resource Bulletin (2012).

3. Results

3.1. Disaggregation of total blue water consumption

At the national scale, blue water is mainly consumed to produce goods and services for local final demands (i.e., without either inter-provincial or international trade) as well as for household use, which together account for 52% of the national BWC (the pie chart in Fig. 2). This can be explained by the relative larger population in China and the higher domestic consumption of water-intensive food products such as rice, maize, and pork by local population (FAOSTAT, 2020). Among all the trade activities, direct final goods trade makes the largest contribution to national BWC (19%), while the other three, intermediate goods trade for the last stage of local production, direct global export, and value chain-related trade, account for 15%, 7%, and 7%, respectively. At the provincial level, Xinjiang, Jiangsu and Heilongjiang are the top three provinces with the largest BWC in 2012, while Beijing, Tianjin and Qinghai have the lowest BWC. The BWC profile in each province has quite different features (the bar chart in Fig. 2 and Table S3). For example, the share of local activities in provincial BWC is only 23% in Hainan, in contrast, this figure in Shaanxi is 77%. Moreover, Hainan has the largest share of both intermediate goods trade and value chain-related trade in its BWC, accounting for 35% and 17%, respectively, whereas Beijing has the lowest, for 7% and 2%, respectively. Direct final goods trade shows a high share in the BWC of provinces, e.g., Xinjiang (34%), Gansu (26%), Heilongjiang (25%) and Guangxi (24%), with land resource endowment whilst low final demand for local population. From the production perspective, highly-developed provinces like Beijing or Shanghai mainly produce to satisfy local demand, and at the same time, import resource-intensive products either as intermediate inputs for local production or direct final products; these imports stem from less-developed provinces such as Xinjiang or Heilongjiang. As for global exports, coastal provinces like Zhejiang (24%), Guangdong

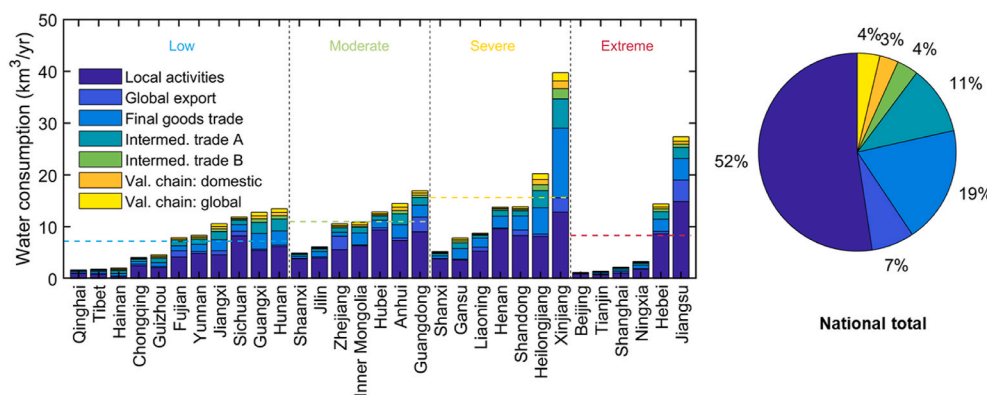


Fig. 2. Provincial (bar chart) and national (pie chart) blue water consumption (BWC) profile by economic activity in 2012. The horizontal dashed lines in the bar chart represent the average BWC of provinces under the same water scarcity level. Local activities include the production of local final demand, and household activities. Global export indicates the direct final goods exported to foreign countries; final goods trade, intermediate goods trade for the last stage of production (Intermed. trade), and value chain-related trade (Val. chain) indicate different trade patterns of inter-provincial trade. Particularly, intermediate goods trade A and B represent the trade of intermediate products for the last stage of production for final demand of the trade

partner and of the trade partner’s trade partners, respectively.

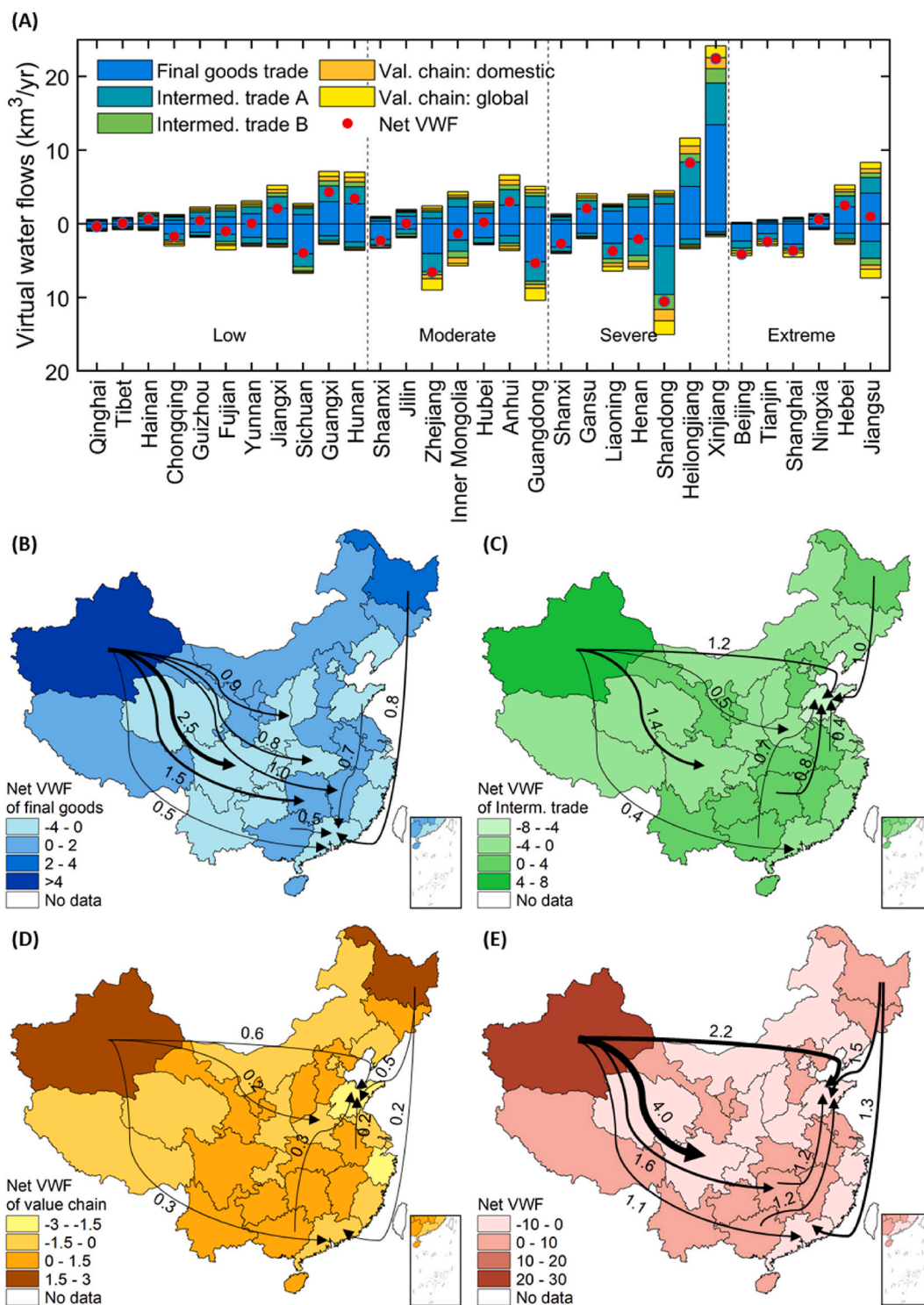


Fig. 3. Virtual water flows related to the exports (above the abscissa in A) and imports (below the abscissa in A), as well as the largest net virtual water exports (red dots in A, and arrow lines in B-E) of 31 provinces in China for year 2012. Final goods trade, intermediate goods trade for the last stage of production (Intermed. trade), and value chain-related trade (Val. chain) indicate different trade patterns of inter-provincial trade. Particularly, intermediate goods trade A and B represent the trade of intermediate products for the last stage of production for final demand of the trade partner and of the trade partner's trade partners, respectively. The negative values in panels B-E indicate that the associated provinces have net virtual water imports. Unit in panels B-E is km^3 per year.

(17%), Jiangsu (15%) and Fujian (15%) have relatively higher shares in their BWC compared with the national total.

Our results also reveal that local water scarcity level possibly plays a role in the provincial BWC profile. That is, provinces under moderate and extreme water scarcity have relatively higher share of local activities in their BWC (58% and 56% as averages, respectively) compared

with the national total, whilst provinces under low water scarcity have relatively higher shares of trade-related activities in their BWC (particularly for intermediate goods trade, and value chain-related trade). Provinces under severe water scarcity do not show similar profiles: for Xinjiang and Heilongjiang, they have higher shares of final goods trade and intermediate goods trade, together accounting for 51% of these two

provinces' BWC; while for others (i.e., Shanxi, Gansu, Liaoning, Henan, and Shandong), a higher share of local activities is observed (62% on average). Last but not least, the average total BWC of provinces under severe and moderate water scarcity are higher than that of provinces under extreme and low water scarcity. Besides the two agriculture-dominated provinces, i.e., Xinjiang and Heilongjiang, other provinces under severe and moderate water scarcity like Guangdong, Anhui, Hubei, and Zhejiang are all economically developed and populous provinces with high blue water requirements for their production of exports and finished goods, and for local household use.

3.2. Provincial balance of virtual water flows by trade pattern

Traditional debates on the displacement of environmental pressures (e.g., carbon emissions) from the consumption sites to the producers are also observed for this water case of China (Fig. 3A). Provinces with high BWC, Xinjiang and Heilongjiang for instance, are those with large net water exports (i.e., $\sum_{n=1}^g NVW^{nm} > 0$), whereas consumption-oriented provinces, such as Zhejiang, Guangdong, Beijing, Tianjin and Shanghai, show net virtual water import (i.e., $\sum_{n=1}^g NVW^{nm} < 0$). The top three provinces with the largest net virtual water exports are Xinjiang (22.4 km³/yr), Heilongjiang (8.3 km³/yr), and Guangxi (4.3 km³/yr), whereas the top three provinces with the largest net water imports are Shandong (10.5 km³/yr), Zhejiang (6.5 km³/yr), and Guangdong (5.3 km³/yr). Among these six provinces, only Guangxi is under low water scarcity level. As for other provinces, generally, provinces under moderate and severe water scarcity have net virtual water imports, while provinces under low water scarcity have net virtual water exports. The number of provinces with net virtual water exports or imports under extreme water scarcity is equal in our analysis. Furthermore, provinces like Jiangsu (under extreme water scarcity), Hubei and Inner Mongolia (both under moderate water scarcity) have relatively high BWC yet low net virtual water flows. To explain this, a high share of local activities in their BWC (Fig. 2) is one factor, the almost even import and export of virtual water is another. It implies that these provinces also act actively in national commodity markets for more bilateral and multilateral collaboration with other provinces, and thus are also important in shaping the virtual water network within China.

The geographical distributions of net water flows related to intermediate goods trade (Fig. 3C), value chain-related trade (Fig. 3D) as well

as the total net water flows of all trade patterns (Fig. 3E) are similar within China, whilst that related to final goods trade (Fig. 3B) shows some differences. Provinces with total net water exports are Xinjiang, Heilongjiang, and those located in the central and southwestern China, whereas provinces with total net water imports are Shandong, Sichuan and those located in southeastern and northern China. In similar distributions with that of the total net water flows, we further find that Xinjiang (7.2 km³/yr and 2.8 km³/yr, respectively), Heilongjiang (3.5 km³/yr and 1.7 km³/yr), and Hunan (2.1 km³/yr and 1.1 km³/yr) are the top three provinces with the largest virtual water exports related to intermediate goods trade and value chain-related trade, whereas Shandong (7.4 km³/yr and 2.9 km³/yr) and Zhejiang (1.8 km³/yr and 1.5 km³/yr) are the top two provinces with the largest virtual water imports related to these two trade patterns. The distribution of the net virtual water flows related to direct final goods trade is a little bit different from those related to other trade patterns. That is, provinces with large virtual water imports of direct final goods trade are those with high level of economic development like Zhejiang (3.3 km³/yr), Guangdong (2.9 km³/yr), and Shanghai (2.4 km³/yr), or with large population like Sichuan (2.8 km³/yr). From the export perspective, besides Xinjiang (12.4 km³/yr) and Heilongjiang (3.0 km³/yr), provinces like Jiangsu (1.8 km³/yr), Guangxi (1.4 km³/yr) and Hebei (1.1 km³/yr) also show large net virtual water outflows of direct final goods trade within China.

Our results also find that direct final goods trade contribute the most to the net virtual water flows within China (accounting for 42% of the total), whereas value chain-related trade induces the least (19%), the rest are associated with the intermediate goods trade (39%). First, the total net water flows embodied in bilateral trade are mainly from Xinjiang to Sichuan and Shandong for fruits and cotton seeds while to Hunan for livestock, as well as from Heilongjiang to Shandong and Guangdong, and from Hunan and Guangxi to Shandong for agri-food products. Direct final goods trade is the major driver of the net virtual water flows. The net virtual water flows embodied in the direct final goods trade are largely from Xinjiang to Sichuan, Hunan, Jiangxi, Shaanxi and Hubei, as well as from Heilongjiang, Shandong, Guangxi and Xinjiang to Guangdong. The major traded commodities are also cotton seeds, fruits, and livestock from Xinjiang, while agri-food products to Guangdong. The net virtual water networks of intermediate goods trade and value chain-related trade look similar to that of the total net water flows. For the former trade pattern, the largest embodied

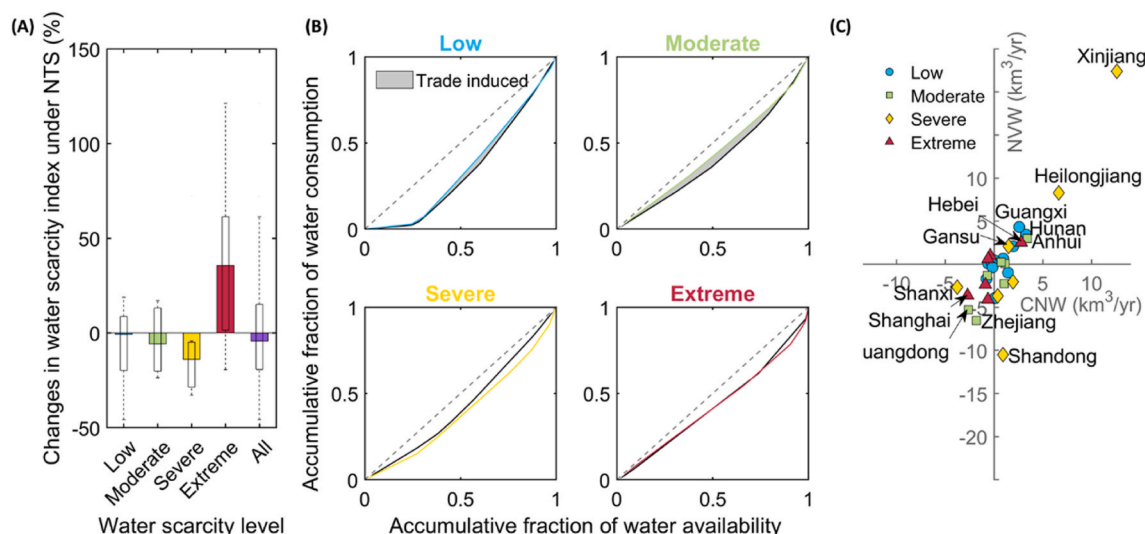


Fig. 4. Effects of trade on the changes in provincial water scarcity index (A) and provincial inequality (B) by water scarcity level, and the trade-related environmental performance of each province on the national and provincial blue water consumption (C). Panel B illustrates the cumulative fraction of water availability against cumulative fraction of water consumption of provinces under the same water scarcity level, sorted by increasing magnitudes of water scarcity index. The deviation between the curved line (black for current with-trade situations while colorful for the NTS) and the diagonal dashed line (of perfect equality) indicates the provincial inequality of water scarcity. NVW and CNW in panel C are the net virtual water flows and the contribution to the national BWC, respectively.

water flow is from Xinjiang to Sichuan mainly for cottonseeds and live animals; moreover, Shandong is distinct for the net virtual water flows embodied in the intermediate goods trade (7.4 km^3), of which 76% is consumed for the last stage of Shandong's production to satisfy the final demand of local population while the rest is consumed for producing goods and services finished by Shandong's trade partners (Fig. 3A). Although value chain-related trade induces the less virtual water flows within China, it is the most complicated trade pattern and hard to be captured. In our analysis, we find that provinces with high virtual water inflows or outflows, notably like Xinjiang and Heilongjiang (for outflows) as well as Shandong, Zhejiang and Guangdong (for inflows), are all with relatively large virtual water flows related to the value chain-related trade (Fig. 3A). It indicates that these provinces are critical to link the intermediate production and product trade that cross borders many times through inter-provincial trade before final products are consumed by the end users, and thus play significant roles in shaping the virtual water network of value chain trade pattern. The associated virtual water flows are mainly from Xinjiang to Shandong and Guangdong for cotton lint and textile-related products, as well as from Heilongjiang to Shandong and Guangdong and from Guangxi to Shandong for agri-food products.

3.3. Effects of trade on provincial blue water consumption and water scarcity

As one of the main commodity-exporting countries, the current trade, both inter-provincial and international, benefits China's economic growth yet with more resource consumption. Under the NTS, China's total outputs would decrease \$4.3 trillion 2012 US dollars (accounting for 16% of the actual national outputs), as a consequence, the national total BWC would decrease $27.4 \text{ km}^3/\text{yr}$ (accounting for 9% of the actual national BWC). This hypothetical deceleration of China's BWC would substantially mitigate the water scarcity in most provinces, particularly in the provinces under moderate and severe water scarcity (Fig. 4A, and Table S4 for province-specific changes). Under the NTS, all provinces are self-sufficient for their finished goods and services, the water scarcity level would reduce (compared to the with-trade case) in seventeen provinces (mostly with net virtual water export like Xinjiang, Heilongjiang, Anhui, Hunan, and Guangxi), whereas it would increase in other fourteen provinces (mostly with net virtual water import like Zhejiang, Guangdong, Sichuan, and Beijing). Out of these fourteen, there are six provinces which are already under severe (Shanxi) or extreme water scarcity (Jiangsu, Ningxia, Beijing, Tianjin, and Shanghai) in reality, indicating that the current inter-regional trade only partially relieves water scarcity in these provinces, including Beijing and Tianjin which are the economic centers of North China meanwhile with limited available water resources.

Our results also reveal that the current trade has influenced the inequality of water scarcity among provinces within China, particularly for the inequality among provinces under low, moderate and severe water scarcity (Fig. 4B). Specified previously, high inequality of spatial water scarcity among provinces exists in China (Ma et al., 2020; Zhao et al., 2015), which is also confirmed in this study (Fig. S1). As illustrated in Fig. 4B and Fig. S1, the curves of cumulative fractions of water consumption and water availability (sorted in an ascending order of the provincial water scarcity indices) are far from the diagonal dashed line (representing perfect water consumption equality), which implies the high inequality in spatial water scarcity within China. Although effects of current trade on changing the inequality among all 31 provinces is slight, the associated effects on changing the inequality among provinces under low, moderate and severe water scarcity are visible. For the provinces under low and moderate water scarcity, the current trade has increased the water scarcity inequality among them, whereas for the provinces under severe water scarcity, current trade has decreased the water scarcity inequality among them. The reason is that provinces with relatively larger (smaller) water scarcity indices under low or moderate

water scarcity are those with net virtual water exports (imports), such that under the NTS, their BWC would reduce (increase) and the associated water scarcity indices would reduce (increase). The situations among provinces under severe water scarcity are different, mainly because Henan and Liaoning are two provinces with relatively lower water scarcity which would further reduce their BWC under the NTS. The effects of current trade on the water scarcity inequality among provinces under extreme water scarcity is small.

We further examine the trade-induced environmental performances of each province on the provincial (by NVW) and national blue water consumption (by CNW). As illustrated in Fig. 4C, by selecting CNW as the horizontal axis and NVW as the vertical axis, 31 provinces are sorted into four categories (or quadrants). Distinctly as the provinces located in the upper right quadrant, such as Xinjiang, Heilongjiang, Anhui, and Hunan, the trade related to these provinces increases both provincial and national BWC. Ideally as the provinces located in the lower left quadrant, mostly are affluent provinces like Shanghai, Zhejiang, Beijing and Tianjin, of which the related trade contributes to a reduction in both provincial and national BWC. Other provinces like Shandong, Jiangsu, and Henan have different environmental performances on the local provincial BWC and the national total. For the future water resource utilization and management towards sustainability, attention should be paid to the provinces in the upper right quadrant. It was already known that the virtual water exports of these provinces are mainly driven by final demand for some low-value-added but water-intensive agricultural (e.g., rice, wheat, cotton seeds, and fruits) and food products (e.g., livestock). Considering that future per-capita incomes in China could further increase and the diet of Chinese could be more westernized, the requirements of these agri-food products could be growing. Thus, it would be more critical for these provinces to sustainably use the limited water resources in the locals, meanwhile to contribute to the food security of China.

4. Discussion

We have assessed the effects of production fragmentation and trade on provincial blue water consumption and scarcity in China using an improved trade disaggregation approach and a novel "no-trade" scenario. In this section we first reflect on the potential implications of this study's finding for water management and policy making in China. Subsequently, we address the limitations of this study and provide recommendations for future research.

4.1. Potential policy implications

Although current trade alleviates the water scarcity in provinces under extreme water scarcity, it is worsening the water scarcity of this nation from a broader scope, i.e., the national water scarcity would be less if there is no trade. This finding is consistent with the previous analysis by Zhao et al. (2015), Zhao et al. (2018), and Zhuo et al. (2016). Given that future inter-provincial trade will further increase due to the development of multiple urban agglomerations (e.g., Jing-Jin-Ji, the Yangtze River Delta, and the Pearl River Delta) in China, the embodied virtual water flows will also be intensified. Previous policy suggestions for water saving and water scarcity alleviation mainly focused on supply-side measures, by putting caps to water consumption by river basin (Mekonnen and Hoekstra, 2016), increasing water-use efficiencies of sectors (Zhou et al., 2020), and better sharing of the limited freshwater resources (Zhao et al., 2015). Based on our more accurate trade disaggregation, the purpose of traded commodities like for final consumption or as intermediate inputs for further production, and the effects on provincial water consumption and scarcity in China are now better understood. This knowledge can be used to consider re-organization of production sites and trade patterns among provinces to affect spatial water consumption and scarcity patterns. We have shown that the final demand-related trade contributes the largest part of

China's virtual water flows (Fig. 2), and is mainly related to agri-food products. The first suggested measure is to enhance local production of final commodities or decrease the final demand of water-intensive products like livestock, especially in provinces with high final goods-related virtual water import such as Guangdong, Jiangsu, and Sichuan. For provinces currently under extreme water scarcity like Beijing, Tianjin or Shanghai, their development under NTS would increase local water scarcity (as shown in Fig. 4A); thus to enhance the trade with adjacent provinces or co-development with adjacent provinces will be the potential measures to improve their self-sufficient capacities as well as decrease the economic and resource cost for trading products. To optimize spatial cropping patterns with more production in rainfed areas for primary crops like rice, wheat and maize, or in places with higher irrigation efficiencies relying on more advanced irrigation technologies would also be potential options (Chouchane et al., 2020). A recent study showed that the massive investment on irrigation infrastructure in water-scarce regions of China during the period of 2002–2017 has driven a substantial reduction in the BWC of staple crops (Huang et al., 2021). Yet, how to formulate the cropping patterns should consider multiple social-economic-environmental factors to avoid the extra increasing in BWC due to the rebound effects arising from the improvement in water productivity and economic benefits by extending farming areas. This may be more important for less developed provinces located in the northwestern (with a relatively slow-growing economy and serious water shortages), central and northeastern China (major provinces for blue water export). The last is to promote better measures of water conservation, unconventional water resources (e.g., rainwater, seawater or reclaimed water), and industry productivity locally by all parties. This would help decrease national water use and enhance industrial commodity supplies in locals. For household BWC, which accounted for 9% of the national total in 2012, we suggest that formulating a rational water price system in urban areas as well as better managing the self-withdrawn groundwater in rural areas would be the options to reduce this part BWC.

Literature estimating water use and virtual water flows in different terms, such as “water withdrawal” (Liu et al., 2019; Zhao et al., 2015) or “water consumption” (Dalin et al., 2014; Zhuo et al., 2016), may come up with quite different policy suggestions. Estimating water use in “water withdrawal”, Liu et al. (2019) found that electricity generation sector was another key sector besides agriculture sector with high water withdrawal in China, and then suggested future measures to reduce water withdrawal by shifting electricity generation system into air cooling systems. It is true that electricity generation sector abstracts a large quantity of water for cooling purpose. In Jiangsu for instance, water withdrawal by electricity generation sector ($14 \text{ km}^3/\text{yr}$) was around three times of that by other industrial sectors ($5 \text{ km}^3/\text{yr}$). Yet, the actual water consumption (i.e., loss of water from the available ground-surface water body in a catchment area) of this sector is relatively low in China (around 10% of its water withdrawal), and has been decreasing by adopting air-cooling or seawater-cooling technologies (Zhang et al., 2018). Other key sectors besides agriculture with high “water consumption”, e.g., chemical industrial sector, metal smelting and rolling sector, and food manufacturing sector, should be paid more attention to for China's green-economic transition in future. Furthermore, other literature also weighted virtual water flows with the “water scarcity” concept and estimate as scarce virtual water flows (Feng et al., 2014; Liao et al., 2020; Zhao et al., 2018). The interdependence between “water scarcity index” and “water use” would make this indicator estimated based on a main assumption that “water scarcity index” is an independent and unchanged variable. Therefore, in some cases, the interpretation of scarce virtual water flows would be controversial, and hard for comparison with other studies.

4.2. Limitations and future work

The almost 10-year time lag of our analysis (for year 2012) should be

noted when interpreting the main results. The most recent year for which inter-provincial MRIO tables of China are known is 2015 (Li et al., 2020; Zheng et al., 2020), but with high uncertainty arising from the main assumptions on provincial production structures and inter-provincial trading patterns in order to fill the data gap of actual inter-provincial transactions across industries. On the other hand, the hybrid MRIO model (Ye et al., 2022) relies on food and agricultural biomass input-output model that is developed based on the production, trade and use data of crops, livestock, and foods from FAOSTAT, which only reported the associated data with high reliability by the year 2013. While other production and consumption data of crops, livestock and food products were also relatively comprehensively recorded for year 2012 by the Chinese National Bureau of Statistics. We also realized that where data on macro-economic structure in general do bear uncertainty and are experienced to undergo changes until far after the year of reference, the main results on virtual water trade networks are largely robust to such uncertainty. Therefore, we stick to use the best available MRIO tables of Mi et al. (2017) and carry out this study in 2012. Lastly, the distribution of freshwater resources within the nation as well as the economic structures especially for main water-consuming provinces like Xinjiang, Jiangsu and Heilongjiang have not changed significantly in the past decades (NBSC, 2020). The main water scarce regions are still located in the North (Beijing, Tianjin, and Hebei), Northeast (Heilongjiang, Jilin and Liaoning) and Northwest (Ningxia, Xinjiang, and Gansu) China. Thus, the analysis of current virtual water networks associated different trade pattern may have small changes as 2012 did. Yet we still believe a more recent analysis of trade effects on national or provincial water consumption and water scarcity changes will be more reliable for future policy and decision making.

There exist other potential limitations in this study. To better simulate provincial economic structure and consumption patterns under the NTS, we need to analyze the changes in product-specific production, trade and consumption by one province. In this context, time-series MRIO tables should be constructed. Based on that, we could capture the key products that are increasingly imported to substitute associated products that are previously produced by the province itself. Yet, if we rely on the monetary MRIO table (in a relatively low resolution of sectors or product categories) to develop the no-trade scenario, although with high uncertainty, this misallocation issue (i.e., misallocating the products to the consumers that cannot produce them locally) may not influence the results by a big margin. When associated products, like crops, fruits and livestock, are aggregated into few product categories, the hypothetical inputs and outputs of these categories would be determined by the main crops that dominate local production. Future studies could focus on establishing such a database with time-series product-specific MRIO tables that give sufficient information about the development of provincial and national economy. Second, in this NTS analysis we selected three production factors as the main constraints on the provincial production capacities under the NTS. It should be noted that the hypothetical results of economic production, human consumption, and water consumption would highly depend on the constraint factors applied in the NTS. Future work needs to apply more resource and social constraints on the NTS, especially for key production factors and inputs such as materials or fuels, to simulate the production and environmental impacts under the NTS more comprehensively. Lastly, trade also impacts on economic structure, consumption patterns, and technology development (Jiborn et al., 2018), and therefore on provincial BWC. However, the economic structure, consumption patterns, and technology development cannot be simulated dynamically based on a static MRIO model. Insights from dynamic economic modelling could, to some extent, generate assumptions for altered MRIO model parameters in simulating scenarios with trade scenarios. Further integrating the static MRIO model with a dynamic economic model, to some extent, can reduce the uncertainty from these factors in the hypothetical BWC modelling. This line of research is beyond the scope of this analysis but worth future explorations.

5. Conclusions

Production fragmentation has been changing the traditional production and consumption models of commodities as well as the associated resources inputs and pollution emissions. In this study we formulated a comprehensive trade disaggregation approach to elaborate the virtual blue water networks of three trade patterns (i.e., final goods trade, the trade of intermediate products for the last stage of production, and value chain-related trade) within China, and further examined the impacts of trade on provincial blue water scarcity by comparing the actual water scarcity with the hypothetical results under the NTS. In 2012, there was 128 km³ blue water that virtually transferred among provinces because of inter-provincial trade. Direct final goods trade contributed the most to the virtual water trade (accounting for 47% of the total), whereas value chain-related trade induced the least (17%), the rest are associated with the intermediate goods trade (36%). Compared with results under the NTS, we found that the current trade, both inter-provincial and international, benefits China's economic growth yet with more resource consumption. Furthermore, the current trade has influenced the inequality of water scarcity among provinces within China, particularly for the inequality among provinces under low, moderate and severe water scarcity. Our analysis enables the consideration of specific trade patterns and their impacts on provincial and national water consumption to cope with water scarcity in China, such as enhancing local production of final commodities or decreasing the final demand of water-intensive products like livestock, especially in provinces with high final goods-related virtual water import such as Guangdong, Jiangsu, and Sichuan, while promoting better measures of water conservation, unconventional water resources, and industry productivity locally by all parties.

CRedit authorship contribution statement

Quanliang Ye: Conceptualization, Data curation, Methodology, Writing – original draft, Writing – review & editing, Funding acquisition. **Ranran Wang:** Conceptualization, Methodology, Writing – original draft, Supervision. **Joep F. Schyns:** Writing – original draft, Writing – review & editing, Supervision. **La Zhuo:** Writing – original draft, Writing – review & editing. **Lan Yang:** Data curation, Writing – original draft, Writing – review & editing. **Maarten S. Krol:** Supervision, Writing – original draft, Writing – review & editing.

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

Nomenclature

A	technical coefficient matrix
B	the Leontief inverse matrix
BAE	Balance of Avoided Emissions
BWC	blue water consumption
CNW	national blue water consumption
cs	constraint factor

D	local technical coefficients matrix
EX	a column vector representing international exports
f	a row vector representing blue water consumption coefficients of products and sectors
F	provincial endowments of constraint factors
F	a row vector representing direct blue water consumption of products and sectors
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
g	number of regions
h	a certain province in China
i	a certain product or sector
i	a summation vector of appropriate length
I	an identity matrix
L	local Leontief inverse matrix
m	a certain province in China
MRIO	multi-regional input-output
n	a certain province in China
non_n	other provinces in China except province n
NTS	no-trade scenario
NVW	net virtual water flows
T	a column vector representing exports from province
T_d	a column vector representing value chain-related trade of products finally absorbed by domestic provinces
T_f	a column vector representing trade of final products
T_g	a column vector representing value chain-related trade of products further processed and exported to foreign counties
T_i	a column vector representing trade of intermediate products for the last stage of production
T_v	a column vector representing value chain-related trade of products
W	total blue water consumption
W'	total blue water consumption under the no-trade scenario
W_EX	local blue water consumption embodied in the export
W_hh	blue water consumption for household purposes
WA	blue water availability
WSI	blue water scarcity index
WSI'	blue water scarcity index under the no-trade scenario
x	a column vector representing total outputs
x'	a column vector representing total outputs under the no-trade scenario
Y	a column vector representing final demands
Y'	a column vector representing final demand under the no-trade scenario
yr	year
Z	intermediate input matrix
Z'	intermediate input matrix under the no-trade scenario
Zm	a square matrix representing supply chain-wide indirect inputs for province m's final demand

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2021.130186>.

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