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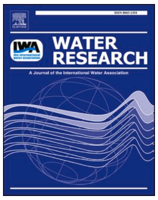

Water transfer infrastructure buffers water scarcity risks to supply chains

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ABSTRACT

Inter-basin water transfer (IBWT) infrastructure has been expanding to deliver water across China to meet water demands in populated and industrial areas. Water scarcity may threaten the ability to produce and distribute goods through supply chains. Yet, it is not clear if IBWTs transmit or buffer water scarcity throughout supply chains. Here we combine a national database of IBWT projects and multi-region input-output analysis to trace water transferred by IBWT and virtual scarce water (scarcity weighted water use) from IBWT sourcing basins to production sites then to end consumers. The results indicate that production and final consumption of sectoral products have been increasingly supported by IBWT infrastructure, with physically transferred water volumes doubling between 2007 and 2017. Virtual scarce water is about half of the virtual water supporting the supply chain of the nation. IBWT effectively reduced virtual scarce water supporting the supply chains of most provinces, with the exposure to water scarcity reduced by a maximum of 56.7% and 15.0% for production and final consumption, respectively. IBWT Infrastructure development can thus buffer water scarcity risk to the supply chain and should be considered in water management and sustainable development policy decisions.

1. Introduction

Water resources underpin human livelihood, economic growth and ecosystem health (Vorosmarty et al., 2000), but their spatial distribution is highly unequal and often mismatches water demands in many countries (Oki et al. 2006; Tang 2020). Inter-basin water transfer (IBWT) infrastructure is often constructed to bring freshwater supplies to locations that do not have enough water to support their population or economic activities (Shumilova et al., 2018; Rising et al., 2022). Global cumulative IBWT capacity has been risen since the 20th century and is projected to grow into the future (Rollason et al., 2022). China has invested heavily in IBWT infrastructure to redistribute water across different river basins with varied levels of water endowment (Zhang et al., 2015; Sun et al., 2021), often with economic, social and environmental costs, particularly for IBWT source basins (Ding et al., 2020). For example, China has spent more than 500 billion RMB yuan on the South-to-North Water Diversion Project to connect the Yangtze River to North China, which is to date the largest IBWT scheme in the world in terms of the construction scale, water transfer volume and distance (Nong et al., 2020).

Water used throughout the production process of a good is referred to as virtual water (Allan 1992; Hoekstra and Mekonnen 2012), so the transfer of agricultural and industrial products between regions through trade implies virtual water transfer (Dalin et al., 2014; D'Odorico et al., 2019). Water can be spatially redistributed physically through IBWT projects (Gohari et al., 2013) and virtually through embodied water in traded products and services (Suweis et al., 2011; Konar et al., 2016). Most previous research focused on the effect of physical or virtual water transfer alone (Yang et al., 2013; Li et al., 2016). One exception by Zhao et al. (2015) has examined physical and virtual water transfers within China, revealing their respective effects on water stress alleviation. However, we still do not understand well to what extent IBWT supports

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production, supply chains, and consumption.

Water scarcity may threaten the ability to produce and distribute goods through supply chains, when natural water availability is not able to meet water demand in a sustainable manner (Mekonnen and Hoekstra 2016). Therefore, regions, industries and people may be vulnerable not only to local water scarcity, but also to water scarcity facing upstream suppliers that are geographically distant (Qu et al., 2018). To quantify water risks due to unsustainable water use in supply chains, it is important to analyze virtual scarce water (i.e. scarcity weighted water use) instead of total virtual water volumes (Feng et al., 2014; Weinzettel and Pfister 2019). The structure of virtual water networks may change significantly after adjusting for water scarcity (Zhao et al., 2018). IBWT water replaces physical water use for production in water receiving basins with water from sourcing basins. In this way, IBWT generally increases water scarcity risk from sourcing basins by increasing water withdrawal in these basins, and buffer water scarcity risk in water receiving basins by reducing local water use. The changing water scarcity in IBWT sourcing and receiving basins is then transmitted throughout the supply chain. Whether IBWT transmits or buffer water scarcity in supply chains, which is an important research question, remains not addressed.

The goal of this study is to answer two important research questions: 1) to what extent IBWT supports production and consumption of different regions? and 2) does IBWT transmit or buffer water scarcity in supply chains? Distinguished from a previous study that focused on the impact of IBWT on regional water scarcity (Sun et al., 2021), the novelty of this study lies in connecting physical water transfer with production, trade and consumption through supply chains. We trace physically transferred water from sourcing basins to recipients and then to end consumers through the supply chain in China from 2007 to 2017. This enables us to evaluate the role of IBWT in transmitting or buffering water scarcity along the supply chain at regional and sectoral levels. To this end, a database of IBWT projects in China was linked to a multi-region input-output (MRIO) analysis to track physically transferred water embedded in various products for inter-provincial and international trade. The supporting role of IBWT in the supply chain was quantified from both the production and consumption perspectives. The role of IBWT in either transmitting or buffering water scarcity along the supply chain was addressed using virtual scarce water analysis. The results advance our understanding of the relationship between IBWT infrastructure and supply chains, with implications for managing water scarcity risks in supply chains.

2. Materials and methods

2.1. Data

We compiled a new dataset consisting of inter-basin water transfer projects in China, based on a previous dataset (Sun et al., 2021) and a few more projects across third-order river basins (Supplementary Information Table S1). Key information on IBWT projects, including source and recipient provinces (they might be the same in a project as a province often contains a number of river basins), installed IBWT capacity, project completion year, target sectoral water uses (agricultural, industrial and domestic use) was collected. China's multi-region input-output (MRIO) tables in 2007, 2010, 2012, 2015 and 2017 (Liu et al., 2008; Liu et al., 2014; Liu et al., 2018; Zheng et al., 2020), which characterize transaction relations of products and services for both intermediate and final uses between sectors and provinces in monetary unit, were used to simulate domestic virtual water transfer and export in China. Because these MRIO tables have different sectoral divisions, sectors of all the tables were harmonized into 30 sectors (Supplementary Information Table S2). Agricultural, industrial and domestic water uses at the provincial level were referenced from China Water Resources Bulletins (MWRC 2007-2017). These three categories of water use were disaggregated at the detailed sectoral level that is consistent to that of the MRIO tables, according to survey-based fine sectoral-level reconstruction water use data (Zhou et al., 2020) and the intermediate input relationship of "water production and supply sector" in the MRIO table. As the operation data of water transfer projects are not available, projects (except the South-to-North water transfer project) were assumed to operate at 80% installed capacity, following a previous study (Sun et al., 2021). Considering that the South-to-North water diversion project was operated at a testing stage since 2014, we assumed that it operated at 50% installed capacity in 2017 according to online reports. IBWT was also disaggregated into sectoral uses at a high resolution based on the project target water uses and quantitative sectoral water uses of the recipient province.

Annual provincial-level natural water availability and sectoral water use data between 2007 and 2017 (MWRC 2007-2017) were downscaled at the 0.25 × 0.25 arc-degree grid level, based on Variable Infiltration Capacity (VIC) hydrologic model simulation results and other multiple-sourced information, following previous studies (Ma et al., 2020; Sun et al., 2022). The grid-level water availability and water uses were then aggregated at the sub-basin level to assess water scarcity in the 76 sub-basins of China's mainland.

2.2. Virtual water transfer accounting and IBWT embedded in the supply chain

The estimation of China's domestic virtual water transfer and export follows the environmentally extended MRIO analysis framework applied in many previous studies (Zhang and Anadon 2014; Sun et al., 2017; Zhao et al., 2018). In the MRIO table with r regions and n economic sectors, the total economic output X (a column vector comprised of rn elements) can be expressed as a function of final consumption of different products Y (a column vector of rn elements):

$$X = (I - A)^{-1} Y \tag{1}$$

where I is the unit matrix, A is the matrix of technical coefficients, $(I - A)^{-1}$ is the Leontief inverse matrix. The sectoral water use vector W for sectoral production (consisting of rn elements) is introduced as:

$$W = DX = D(I - A)^{-1} Y = TY \tag{2}$$

where D is a dialogical matrix of direct water use intensity representing the direct water use per unit output in each sector, and T is an $rn \times rn$ matrix of total water use intensity, signifying total water use per unit product for final consumption. Virtual water transfer embedded in domestic and international supply chain can be derived based on Eq. (2) (see Supplementary Information).

We also combined the multi-regional input-output table and IBWT data under the environmentally extended MRIO analysis framework to trace physically transferred water along the supply chain. In this way, water was traced from sourcing basins to production sites (according to the IBWT project database), and then to domestic and international end consumers (based on the MRIO analysis). When replacing general water use W in Eq. (2) with the use of IBWT (denoted as W_T), IBWT for production use can be written:

$$W_T = D_T X = D_T (I - A)^{-1} Y = T_T Y \tag{3}$$

where D_T is a dialogical matrix of direct IBWT intensity, and T_T is a matrix of total IBWT use intensity. Elements in D_T and T_T is not larger than corresponding ones in D and T, because IBWT comprises only a share of sectoral water uses for production activities. Because MRIO tables are available in 2007, 2010, 2012, 2015 and 2017, water volumes from IBWT in corresponding years were introduced in Eq. (3) to track physically transferred water from production to final consumption.

2.3. Measuring the supporting role of IBWT for production and consumption

IBWT supports both production activities and final consumption in China's supply chain. Here we developed two indicators to quantify the reliance of the supply chain on physical water transfer across different regions, from both the production and consumption perspectives:

$$\begin{aligned} S^i_{\text{prod}} &= w^i_{\text{T}} \Big/ w^i \\ S^i_{\text{cons}} &= wf^i_{\text{T}} / wf^i \end{aligned} \tag{4}$$

where S^i_{prod} and S^i_{cons} are the supporting role of physical water transfer in the supply chain from the production and consumption perspectives in region *i*, respectively; w^i_{T} is physically transferred water for production; and wf^i_{T} is physically transferred water embedded in products for final consumption. These two indicators S^i_{prod} and S^i_{cons} are represented by a percentage value ranging from 0 (indicating no support) to 1 (complete support).

2.4. Virtual scarce water accounting

Virtual scarce water is defined as scarcity weighted virtual water following previous research (Pfister et al., 2009). Water scarcity, which is commonly demand driven (Liu et al., 2017; Sun et al., 2021), is measured as the ratio of water use to water availability (referred to as WTA), following many previous studies (Wada et al., 2011; Hejazi et al., 2014; Vanham et al., 2018; Zhao et al., 2018; Liu et al., 2019). Because a smaller grid scale may not capture possible substantial distance between water abstraction and use within a grid cell, and a larger scale may not be able to consider heterogeneity of spatial water resource and use (Ma et al.2020), sub-basins are spatial units at which water scarcity assessment is considered adequate (Sun et al., 2021). Water scarcity in the year *t* is assessed for a sub-basin of interest using the equation below:

$$WTA_t = wu_t / wa \tag{5}$$

where wu_t indicates water use in year *t*, and *wa* is the mean natural water availability in the sub-basin of interest between 2007 and 2107. When IBWT is implemented, WTA_t in one sub-basin can be calculated, following the previous study (Sun et al., 2021):

$$\begin{aligned} WTA_t &= \left(wu_t + \sum_i \beta wt_{i,t} \right) \Bigg/ wa \\ \beta &= \begin{cases} -1, & \text{water received from project } i \\ 1, & \text{water delivered in project } i \end{cases} \end{aligned} \tag{6}$$

where $wt_{i,t}$ is the IBWT volume of project *i* in year *t*, and $\sum_i \beta wt_{i,t}$ denotes net IBWT volume of the sub-basin of interest in year *t*. A positive net IBWT volume indicates net delivering water volume to other sub-basins, and a negative net IBWT volume indicates net receiving water volume. *WTA* is then converted to water stress index (*WSI*) using a logistic function, following a previous approach (Pfister et al., 2009):

$$WSI = \frac{1}{1 + e^{-11.5WTA}\left(\frac{1}{0.01} - 1\right)} \tag{7}$$

WSI ranges from 0.01 (assuming any water withdrawal has marginal local impact) and 1. *WSI* is tuned to be 0.5 for a *WTA* of 0.4, which is often considered as the threshold between moderate and significant water stress.

When replacing general water use *W* in Eq. (2) with the scarce water use (i.e. water use weighted with *WSI*, denoted as *WS*), scarce water for production use can be written:

$$W_{\text{S}} = D_{\text{S}} X = D_{\text{S}} (I - A)^{-1} Y = T_{\text{S}} Y \tag{8}$$

where D_{S} is a dialogical matrix of direct scarce water use intensity, and T_{S} is a matrix of total scarce water use intensity. Similarly, virtual scarce water embedded in domestic and international supply chain can be computed based on Eq. (8). Provincial-level scarce water uses are needed in Eq. (8). Within the boundary of each province, water uses in different sub-basins (aggregated from grid-level water uses) are weighted by water stress index of corresponding sub-basins, and are then summed up to obtain scarce water use for that province.

2.5. Assessing the exposure of production and consumption to water scarcity

The supply chain is exposed to water scarcity risk, as the supply chain relies on scarce water resources. Two indicators are developed to quantify the exposure of the supply chain to water scarcity across different regions, from both the production and consumption perspectives:

$$\begin{aligned} E^i_{\text{prod}} &= w^i_{\text{S}} \Big/ w^i \\ E^i_{\text{cons}} &= wf^i_{\text{S}} / wf^i \end{aligned} \tag{9}$$

where E^i_{prod} and E^i_{cons} are the exposure of production and final consumption to water scarcity in the supply chain of region *i*, respectively, w^i_{S} is scarce water resources used for production, and wf^i_{S} is virtual scarce water embedded in products for final consumption. These two indicators E^i_{prod} and E^i_{cons} are represented by a percentage value ranging from 0 (indicating no exposure) to 1 (complete exposure).

3. Results

3.1. IBWT increases as infrastructure expands in China

IBWT infrastructure has been increasingly built in China since the 1950s to meet growing water demands for cities and irrigation. Most IBWT projects have been constructed in the East of China, where cities, industries and croplands are concentrated. These projects are distributed in 22 of 30 provincial-level administrative units (hereafter referred to as provinces for short) in 2017. Tibet, Hong Kong, Macao and Taiwan are not considered due to lack of data (Fig. 1 and Supplementary Information Fig. S1). The installed IBWT capacity has reached 25.2 billion m^3 yr^{-1} by 2007, and 57.8 billion m^3 yr^{-1} by 2017 (Figs. 1 and 2A), which is equivalent to ~9% of the national water use (Fig. 2B). The majority of IBWT projects were constructed within provincial boundaries. Technological and economic development has enabled water to be transferred along increasing distances (IBWT length in 1950 was less than 1000 km growing to more than 14,000 km in 2017). When the South-to-North Water Diversion Project started to deliver water from downstream Yangtze River to Beijing, Tianjin, Hebei, Jiangsu and Shandong Provinces in 2014, the share of installed IBWT capacity across different provinces was increased to nearly one third (the share of IBWT capacity within provincial boundaries about two thirds). Provinces receiving the most water through inter-provincial IBWT were Tianjin, Beijing and Hebei, located in water scarce North China plain, whereas inter-provincial IBWT sourcing provinces were Hubei, Jiangsu, Shandong and Hebei.

Human water use is categorized into agricultural, industrial, domestic and eco-environmental compensation uses within China (MWRC, 2007-2017). Domestic water use include tertiary and household water uses. An IBWT project may be designed for a specific water use or combination of uses. In China, IBWT are most often designed to provide urban water supplies to support important social functions and economic benefits. There is an increasing trend in percentages of sectoral water uses that can be met by installed water transfer capacity. The installed IBWT capacity is able to meet ~16.4% domestic water demand

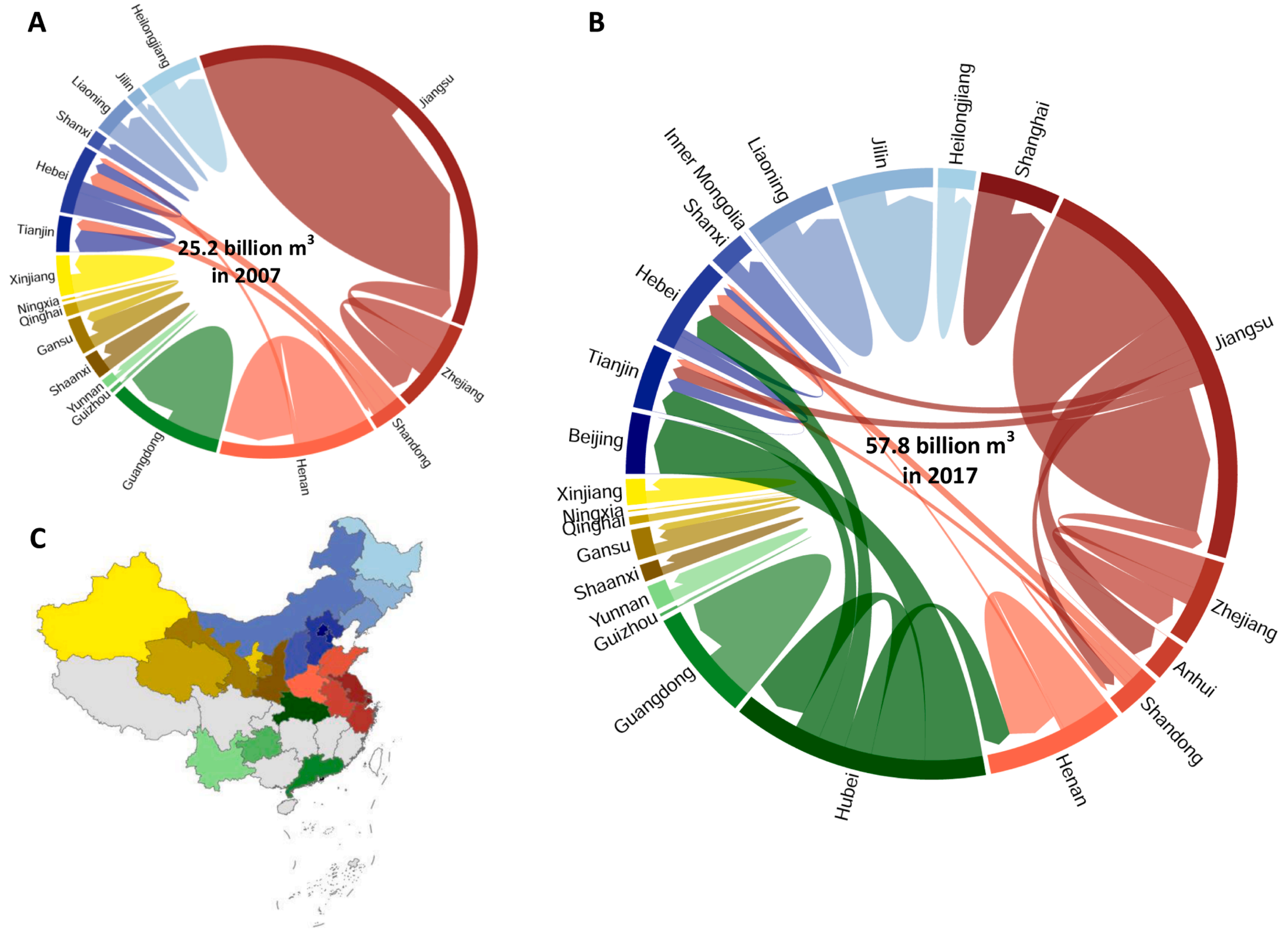

Fig. 1. Installed physical water transfer capacity between and within provinces in 2007 (graph A) and 2017(B). The insert map (C) indicates the location of provinces, with colors corresponding to those in the cord diagram (gray indicates there is no inter-basin water transfer in that province). The size of cord diagrams is scaled based on installed water transfer capacities in 2007 and 2017.(For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and 13.0% industrial water demand of the nation in 2017, which are higher than that for agricultural water demand 6.5% (Fig. 2B). Industrial and domestic water uses comprised 30.5% and 22.7% IBWT water, which were higher than the shares of total water for industrial and domestic water uses (21.2% and 13.9%, Fig. 2C). This highlights that water from IBWT sources is particularly important to certain economic sectors, i.e. to economic production in industrial and tertiary sectors.

3.2. IBWT plays an increasing role in supporting the supply chains

The majority of water transferred by IBWT in China (over three quarters) supports the production of primary, secondary and tertiary goods (with the remainder of IBWT volumes supporting household and eco-environmental compensation uses). Here we traced physically transferred water through the supply chain using an environmentally extended MRIO analysis. In 2007, about 19.1 billion m^3 water (lower than the IBWT installed capacity) was diverted among 18 provinces through tunnels, channels and pumping schemes that connect different basins, in which 15.5 billion m^3 (81.2%) entered the supply chain and was virtually embedded in various products for final consumption (Supplementary Information Fig. S2). In 2017, 39.5 billion m^3 water was diverted through IBWT to 21 provinces. Of this, 30.9 billion m^3 (78.2%) was used for production and supported the supply chain (Fig. 3). Although only 18 provinces physically received IBWT water in 2007 – growing to 21 provinces in 2017 – all of the other provinces and international consumers received virtual IBWT water in their receipts of products through the supply chain (Fig. 3). The volume of IBWT water embedded in inter-provincial trade through supply chains grew from 4.8 billion m^3 in 2007 to 11.2 billion m^3 in 2017, showing a 133% increase. Similarly, IBWT water volumes transferred to international consumers through supply chains grew from 4.0 billion m^3 in 2007 to 4.8 billion m^3 in 2017 (increase of 20%). This constitutes ~25.9% and ~15.5% of China's IBWT water for production purpose in 2007 and 2017, respectively. Key provinces exporting IBWT water to international end consumers through the supply chain were Jiangsu, Guangdong, Shanghai and Henan, all of which are recipients of large volumes of IBWT water.

IBWT supports both production activities and final consumption. The volume of IBWT water doubled between 2007- 2017, leading to increased support of IBWT in China's supply chain (Supplementary Information Fig. S3). At the national level, IBWT supported 5.9% of the water demand from the production perspective and 5.7% from the consumption perspective in 2017. The support of IBWT to China's export was higher ($S_{cons} = 7.3\%$) than the domestic supply chain.

According to indicators that quantify supporting roles of IBWT for production and consumption, IBWT water supports production and the supply chain in a varied manner across provinces. A few provinces are heavily reliant on IBWT. For example, Tianjin's production was mostly supported by IBWT, with more than half of the water demand met by

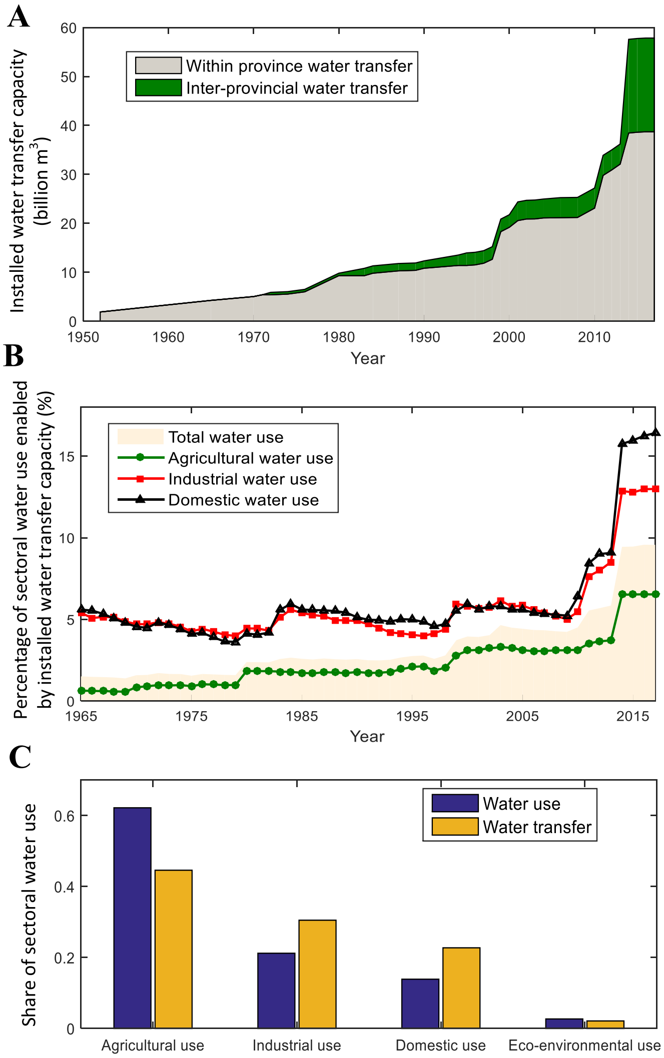

Fig. 2. Physical inter-basin water transfer in China: (A) increasing installed water transfer capacity since 1950s; (B) percentages of sectoral water uses that can be met by installed water transfer capacity; and (C) fractional water uses by sector from physically transferred water in comparison to total water in 2017.

IBWT in 2017 (S_{prod}=76.9%), followed by Beijing, Jilin and Shanghai (S_{prod}= 56.2%, 21.7% and 20.2%, respectively, Table 1). There was increased support of IBWT in production in 18 provinces from 2007 to 2017, with the largest increase occurring in Beijing (Supplementary Information Fig. S3). Physical recipients of IBWT water were concentrated in a few provinces, but virtual IBWT water was spread across China through the supply chain. Notably, production in 8 provinces did not depend on IBWT in 2017, but they were all supported by IBWT from the consumption perspective. End consumers in Tianjin relied the most on IBWT in 2017, with virtual IBWT water constituting 16.5% virtual water embedded in the products for final consumption, followed by Beijing, Shanghai and Henan (S_{cons}= 12.7%, 12.5% and 11.8%, respectively, Table 1). End consumers of all the provinces were increasingly supported by IBWT between 2007 and 2017 (Supplementary Information Fig. S3). There are more economic connections between provinces than physical IBWT transfers, so IBWT support of the supply chain from the consumption perspective has less skewness (with S_{cons} ranging between 1.5% and 16.5% in 2017) than the production perspective (with S_{prod} ranging between 0 and 76.9% in 2017).

IBWT heterogeneously supports sectors throughout China's economy (Supplementary Information Fig. S4 and S5). IBWT provides larger support to production and consumption of industrial ($S_{prod} = 11.6\%$ and $S_{cons} = 6.5\%$) and tertiary ($S_{prod} = 9.4\%$ and $S_{cons} = 7.4\%$) goods than to the agricultural production and consumption of the nation ($S_{prod} = 4.5\%$ and $S_{cons} = 3.6\%$) in 2017. There are important differences in the support of IBWT to sectoral supply chains across provinces (Supplementary Information Fig. S6 and S7). For example, IBWT has little support to agricultural production but high support to industrial and tertiary production in Guangdong (where the center of China's manufacturing industries is located). Export of industrial and tertiary products from China was particularly supported by IBWT, with IBWT water comprising 11.3% and 13.8% of total virtual water exports in 2017 (in comparison to agricultural $S_{cons} = 5.1\%$).

3.3. *IBWT decreases the exposure of supply chains to water scarcity*

Water scarcity poses risks to supply chains and economic prosperity. IBWTs will impact water scarcity risk by physically relocating water from sourcing basins to different destinations for production uses (Sun et al., 2021). While IBWT directly mitigates water shortage in water receiving basins, it also likely intensifies water stress in sourcing basins. It is unclear if the role of IBWTs is to buffer water scarcity risk (e.g., by reducing water scarcity in production sites) or to transmit water scarcity risk (e.g., by introducing water scarcity from their sourcing basins) in the supply chains. Here we traced virtual scarce water (i.e. scarcity weighted water use, which is considered as an indicator for unsustainable water use) embedded in the supply chains from production to final consumption. When total water use for production increased from 507.8 billion m^3 in 2007 to 526.5 billion m^3 in 2017 (with an increase of 3.7%), virtual scarce water embedded in the supply chain showed a smaller increase of 1.1% (from 243.8 billion m^3 to 246.6 billion m^3). The expansion of IBWT infrastructure largely explains the difference between the trends of total virtual water and virtual scarce water in the supply chains. Importantly, a decreasing trend of virtual scarce water for production is observed in water-scarce provinces in North China that are recipients of IBWT waters. In spite of increasing total water uses, Tianjin and Beijing had decreased scarce water use in production by 42.4% and 35.8% between 2007 and 2017. However, more than half of the provinces in China needed more scarce water to support their production or consumption between 2007- 2017 (Supplementary Information Fig. S8).

A hypothetical no-water-transfer scenario, which assumes water receiving basins would use the same amount of IBWT water from local resources, is used to quantify the impacts of IBWT on changing the risk of the supply chain exposed to water scarcity. In 2007, IBWT scenario saved 8.1 billion m^3 virtual scarce water required for the supply chain, in comparison to the hypothetical no-water-transfer scenario with virtual scarce water reaching 255.2 billion m^3 (Fig. 4). Virtual scarce water required for the supply chain in 2017 would reach 262.7 billion m^3 under the hypothetical no-water-transfer scenario, which was 16.2 billion m^3 more than the IBWT scenario (Fig. 4). This means that IBWT overall reduces the reliance of the supply chain on scarce water resources. However, different provinces may benefit or suffer changing virtual scarce water volumes due to IBWT. Jiangsu Province benefited most from IBWT with the largest volume of scarce water saved for both production (saving 6.2 billion m^3) and final consumption (saving 3.6 billion m^3), followed by Shandong, Liaoning, Shanghai, Heilongjiang, Beijing and Tianjin in 2017. These provinces were the top recipients of IBWT waters (Fig. 1). In contrast, Shanxi, Jilin and Qinghai included more scarce water in their production in IBWT scenario in comparison to hypothetical no-water-transfer scenario. Some provinces that did not directly receive IBWT water also benefited from IBWT with reduced reliance of final consumption on virtual scarce water. Virtual scarce water embedded in export for international end consumers was 32.4 billion m^3, but would have been 36.1 billion m^3 in the no-water-transfer scenario in 2017 (with a saving of 3.7 billion m^3 scarce water through IBWT).

Virtual scarce water represents about half of the virtual water supporting Chinese supply chains, confirming the prevalence of water stress

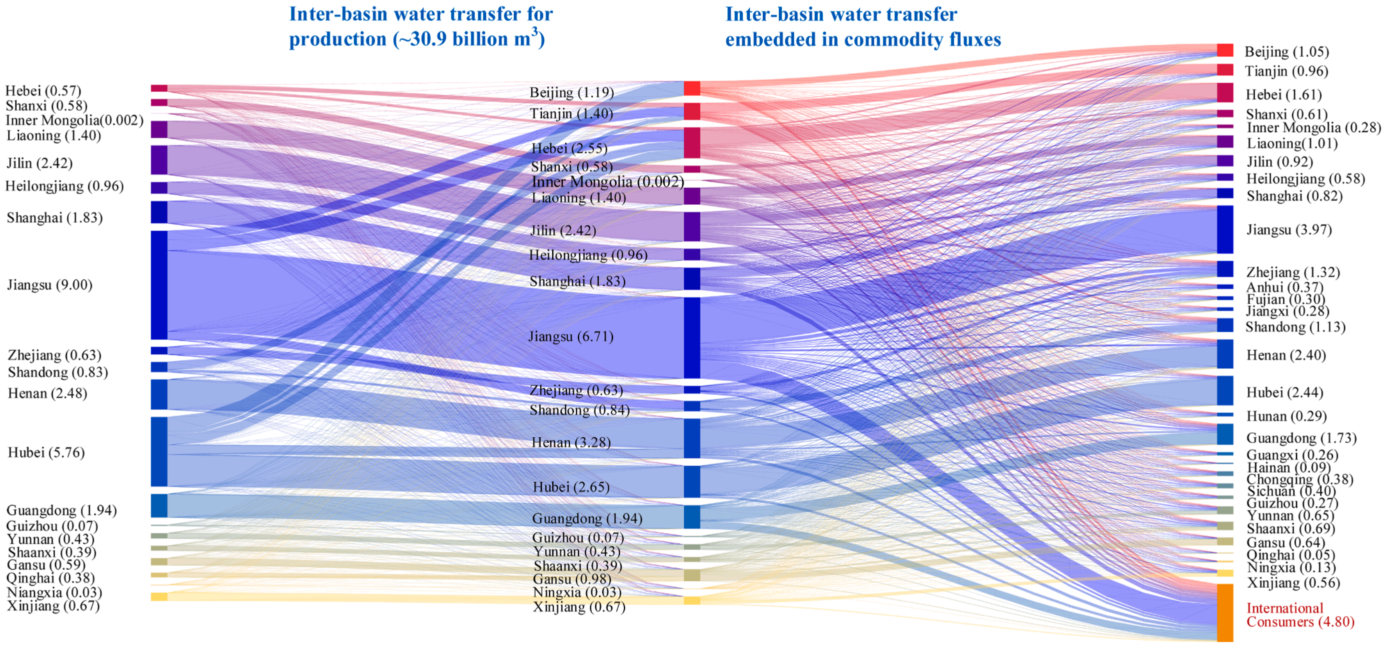

Fig. 3. Inter-basin water transfer volumes embedded in China's supply chain in 2017. The left part of the Sankey graph shows the direction and scale of physically transferred water, and the right part of the Sankey graph shows the direction and scale of physically transferred water embedded in the supply chain and transferred between provinces and international consumers in the form of virtual water. The numbers in the brackets indicate inter-basin water transfer volumes (unit: billion m^3).

Table 1
Supporting role of inter-basin water transfer in China for production and consumption of provinces and export in 2007 and 2017.

Province or export	In 2007 Support for production	Support for consumption	In 2017 Support for production	Support for consumption
Beijing	0%	2.4%	56.2%	12.7%
Tianjin	36.8%	4.9%	76.9%	16.5%
Hebei	3.7%	3.8%	16.9%	11.0%
Shanxi	3.3%	2.5%	9.4%	5.2%
Inner Mongolia	0%	1.2%	0%	2.5%
Liaoning	3.0%	2.8%	12.9%	8.5%
Jilin	2.5%	3.1%	21.7%	10.1%
Heilongjiang	3.4%	3.5%	2.8%	4.2%
Shanghai	0%	2.1%	20.2%	12.5%
Jiangsu	13.2%	9.4%	12.2%	10.1%
Zhejiang	0.1%	2.3%	4.3%	5.6%
Anhui	0%	1.3%	0%	1.9%
Fujian	0%	0.7%	0%	1.7%
Jiangxi	0%	0.7%	0%	1.8%
Shandong	0.5%	1.8%	4.9%	6.0%
Henan	12.9%	8.5%	17.6%	11.8%
Hubei	0%	0.7%	10.2%	8.9%
Hunan	0%	0.5%	0%	1.2%
Guangdong	3.5%	2.4%	5.4%	4.9%
Guangxi	0%	0.5%	0%	1.5%
Hainan	0%	0.2%	0%	3.1%
Chongqing	0%	1.1%	0%	3.9%
Sichuan	0%	0.8%	0%	1.7%
Guizhou	0.7%	1.3%	0.7%	3.2%
Yunan	1.0%	1.3%	3.1%	5.1%
Shaanxi	5.1%	3.8%	5.0%	6.4%
Gansu	7.2%	6.9%	9.2%	8.0%
Qinghai	0%	0.8%	0.0%	2.4%
Ningxia	0.5%	1.0%	0.5%	2.3%
Xinjiang	1.4%	1.8%	1.3%	2.2%
Export	–	4.3%	–	7.3%

facing China's water supply systems. We assessed the ratio of scarce water to total virtual water embedded in the supply chain to quantify the exposure of the supply chain to water scarcity. The comparison between IBWT and hypothetical no-water-transfer scenarios showed that IBWT reduced the exposure of the supply chain to water scarcity from 50.8% to 50.1% at the national level in 2017. Because the exposure showed high spatial heterogeneity, IBWT was particularly important in reducing the exposure to water scarcity in a few provinces that received IBWT water. Tianjin, Shandong, Beijing and Shanghai were the provinces benefitting most from IBWT in terms of reduced exposure of the supply chain to water scarcity, from both the production and final consumption perspectives in 2017 (Fig. 5). IBWT reduced water scarcity exposure of production between 0.1% and 56.7% across 20 provinces, but increased water scarcity exposure of production in 3 provinces (i.e. Shanxi, Jilin and Qinghai). IBWT did not impact water scarcity exposure of production in the remaining 7 provinces in 2017 (which changed water scarcity exposure less than 0.1%, Fig. 5A). IBWT have reduced exposure of end consumers to water scarcity across 29 provinces, with the reduced exposure distributed in a less wide range, i.e. between 0.7% and 15.0%. Qinghai, which is faced with lower water scarcity exposure (38% under the IBWT scenario) than national average (51%), is the only province exposed to increased water scarcity for consumption in 2017 (Fig. 5B). The exposure of export through international supply chains to water scarcity was reduced from 51.7% to 47.3% by IBWT in 2017. Exposure to water scarcity of provinces has been involved since 2007 (Fig. 5) as an increasing number of IBWT projects were built.

Production and final consumption of sectoral products benefited from IBWT to different degrees. The exposure of agricultural, industrial and tertiary production in China to water scarcity was reduced by 3.3%, 4.9% and 7.4% through IBWT in 2017 (E_{prod}= 48.7%, 42.5% and 41.3% for these three sectors in water transfer scenario). Because agricultural products are important intermediate inputs to other sectoral goods, final consumption of industrial and tertiary products in China was exposed to higher water scarcity than corresponding exposure in production (E_{cons}= 46.7% and 46.1%, reduced by 3.8% and 4.9% through IBWT in comparison to no-water-transfer scenario, see Supplementary Fig. S9). Final consumption of agricultural goods is subject to lower exposure to

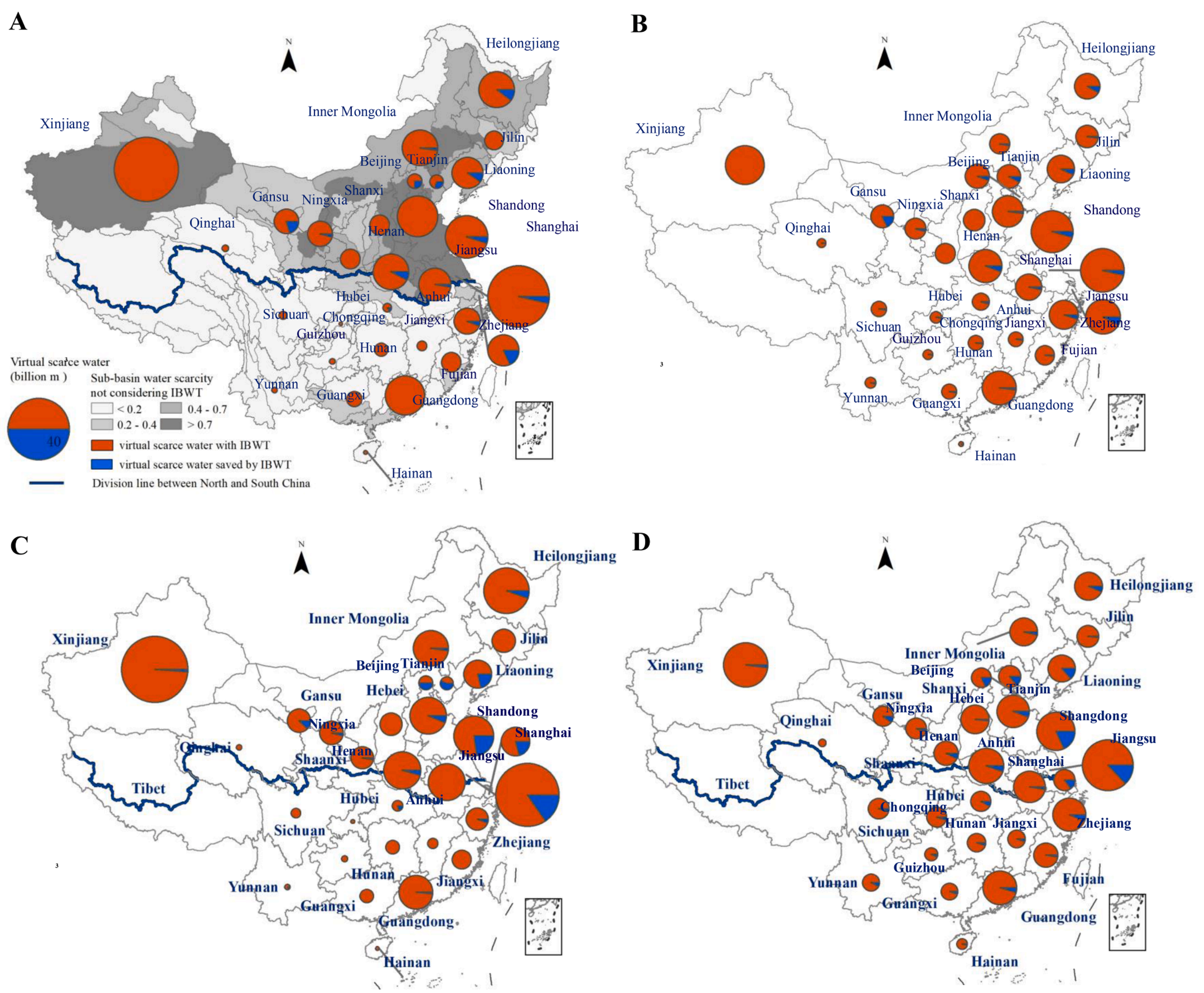

Fig. 4. Virtual scarce water embedded in the supply chains of provinces in China: (A) and (B) show virtual scarce water for production and consumption respectively in 2007; (C) and (D) show virtual scarce water for production and consumption respectively in 2017. The size of circles indicates virtual scarce water under no water transfer scenario. Virtual scarce water in provinces increased due to inter-basin water transfer (IBWT) is not shown.

water scarcity than production ($E_{\text{cons}} = 46.4\%$, reduced by 2.7% through IBWT).

4. Discussion

As the reach of IBWT infrastructure expands, it is playing an increasingly important role in reducing direct and indirect water stress in China. IBWT supported ~6.5% of the total water use in China's supply chain in 2017, and the reliance of the supply chain on IBWT water can be much higher in a few provinces. Final consumption of economic goods has been increasingly supported by IBWT between 2007 and 2017. Though a number of provinces did not receive IBWT water directly in their production activities, physically transferred water has been indirectly incorporated in their supply chain of various products and increasingly supported the end consumers. International end consumers have also witnessed an increase of support by IBWT infrastructure with increasing IBWT water embedded in exported products from China.

What matters in water use management is scarce water resources rather than neutral or abundant water (Weinzettel and Pfister 2019), due to the scarcity value of water and different impacts of water use on local water resources and ecosystems (Feng et al., 2014; Zhao et al., 2018). It is therefore important to see how IBWT impacts scarce water use throughout the supply chains. Our assessment showed that IBWT saved 20.6 billion m^3 scarce water use in the supply chain in 2017 in comparison to no-water-transfer scenario, and end consumers of all the provinces (except Qinghai) benefited from IBWT with scarce water saving throughout the supply chains. International end consumers were exposed to reduced water scarcity in the receipt of sectoral goods embedding physically transferred water. This means that, IBWT infrastructure allows water stressed regions to exploit new sources of surface water and hence allow sustainable water use to be institutionalized in a wider spatial range (than river basin level) through hydraulically connecting different basins. Thus, we concluded that IBWT plays a crucial role in reducing water scarcity risks in supply chains and providing water security to economies and society.

In this study, we measured virtual scarce water using average water availability information (between 2007 and 2017), which shows virtual scarce water flows during average water balance conditions. River basins may experience more extreme water scarcity in certain years, such as during drought conditions (Huang et al., 2021). Our results on water

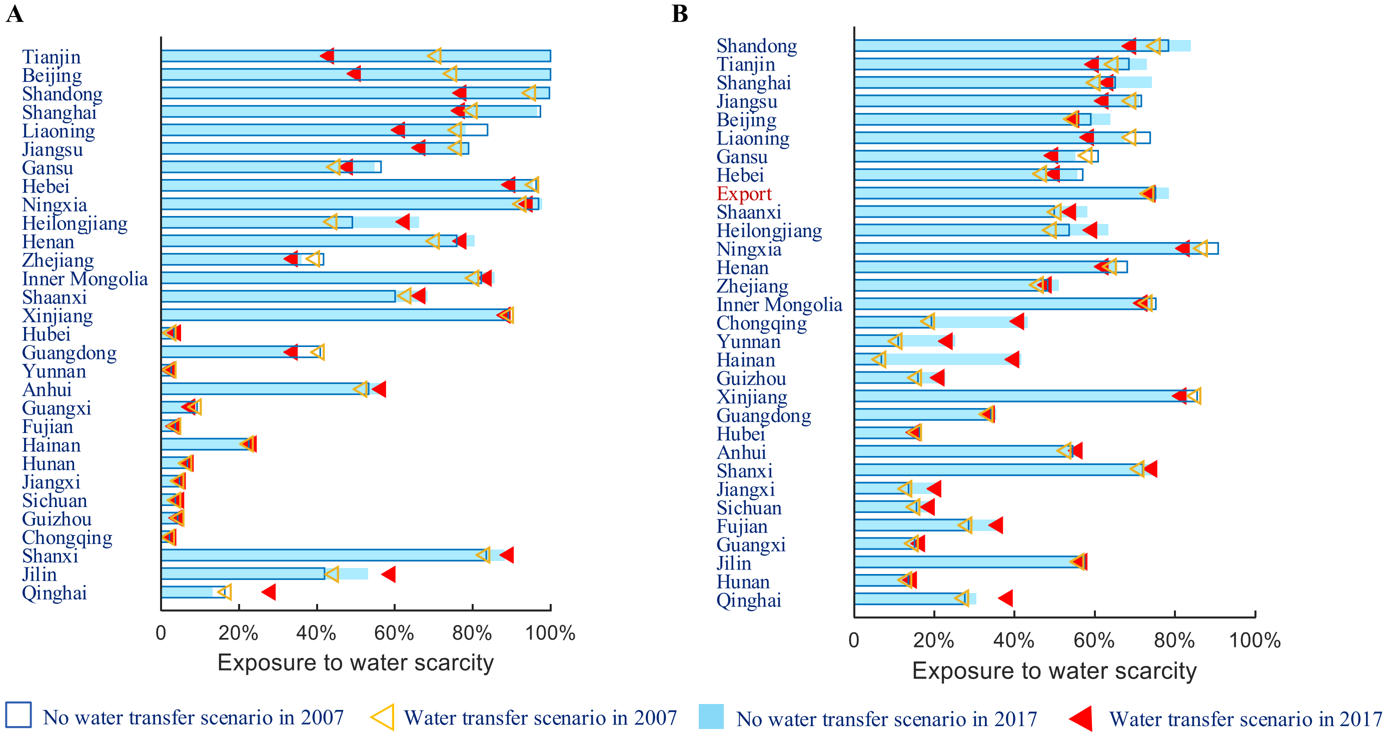

Fig. 5. Ranking provinces in China with their exposure of the supply chain to water scarcity in 2007 and 2017: (A) exposure of production; and (B) exposure to of final consumption. Provinces are ranked with a decreasing magnitude of reduced exposure to water scarcity due to inter-basin water transfer in 2017.

scarcity risks should thus be understood in the context of average conditions, during which water demands are typically more than 40% of average available supplies (Liu et al., 2017). The results highlight the long-term risks facing economic production and supply chains from chronic water stress in the basins of China, rather than from short-term water hazards such as droughts and floods. We find that IBWT serves as a buffer to supply chains against such long-term average water scarcity risk. During short-term drought conditions, IBWT should also be effective in reducing virtual scarce water use through optimized allocation of water.

A few water-stressed basins (e.g. sub-basins along the Yellow River) are IBWT sourcing basins that may transmit water stress through physical water transfers (Sun et al., 2021). Though water is physically transferred to more water scarce regions (e.g. Hai River sub-basins), IBWT receivers and end consumers should know water scarcity and supply chain risk upstream their supply chain. Production in IBWT sourcing basins is subject to higher exposure to water scarcity risk due to IBWT because providing water supply to external regions aggravates their water scarcity. Particularly, Jilin, Qinghai and Shanxi provinces are faced with higher exposure to water scarcity in their production. Proper compensation from physical water recipients will prevent underestimation of water resources values, and compensate water sourcing regions for their restricted local water development. Because IBWT is usually at high economic cost (construction of conveyance channels, reservoirs and pump stations and maintenance cost) and primarily for industrial and domestic uses with high added values, producers and water managers can signal the economic value of IBWT through the market for this important water input in order to balance the benefits and costs of IBWT. It is important to apply a broad suite of institutions and policies (e.g. demand-oriented measures such as water pricing, water markets, water use efficiency improvements, and water use structure upgrade) to achieve sustainable water use and secure the supply chain of the nation. Optimizing combined IBWT infrastructure (supply side) and demand side measures (e.g., pricing and conservation) to enhance water and supply chain sustainability should be an important area for future research.

There are uncertainties due to data constraints in this analysis. The main sources of uncertainty originate from our assumption of actual IBWT volumes based on installed project capacity (Sun et al., 2021), disaggregation of fine-resolution sectoral water uses based on multiple-sourced data, sectoral aggregation of the MRIO data and tables (Liu et al., 2008; Liu et al., 2014; Liu et al., 2018; Zheng et al., 2020), different sources of the MRIO data and water use disaggregation in the environmentally extended analysis. These uncertainty sources are commonly shared by MRIO based virtual water analysis (Sun et al., 2022). Despite these sources of uncertainty, we used the best available information to enhance our understanding of the role of IBWT infrastructure in supporting supply chains in China. We examined the sensitivity of virtual water accounting results to disaggregation of industrial and tertiary water uses by varying disaggregated sectoral water uses by ±20% using the Monte Carlo method. The results showed that virtual water accounting results are not sensitive to disaggregation of fine-resolution water uses given fixed aggregated industrial and tertiary water use statistics in provinces of China (with relative errors varying within ±3%, Supplementary Information Fig. S10). In addition, we conducted the analysis based on MRIO data from the same data source in a shorter period (between 2007 and 2012, Liu et al., 2008; Liu et al., 2014), which showed a consistent trend of increasing IBWT water volumes embedded in the supply chains (Supplementary Information Fig. S11). Future efforts are needed to monitor high-resolution spatial and sectoral water uses, IBWT water volumes and MRIO relationships towards improved understanding of IBWT roles at fine spatial scale and long time period.

5. Conclusions

Inter-basin water transfer (IBWT) is an important infrastructure component of the coupled human-water system. Here, we provided a first national analysis of the IBWT and supply chain nexus using the environmentally extended MRIO technique combined with project explicit IBWT database in China. We differentiate between the use of scarce water and neutral/abundant water in tracing virtual water along the supply chain, as scarce water has a distinct scarcity value and its use may lead to adverse environmental and/or social impacts.

Based on this IBWT and supply chain nexus analysis, the following conclusions can be drawn: 1) Economic production and final consumption through supply chains have been increasingly supported by IBWT infrastructure in China. Although only a limited number of provinces physically received IBWT water, all of the other provinces and international consumers were supported by virtual IBWT water in a varied manner in their receipts of commodities through the supply chain. 2) IBWT overall reduces the virtual scarce water embedded in sectoral production and final consumption, and thus can buffer water scarcity risks to supply chains. IBWT infrastructure allows water stressed regions to exploit new sources of surface water and hence allow sustainable water use to be institutionalized in a wider spatial range through hydraulically connecting different watersheds. However, it should be noted that IBWT increased water scarcity exposure of production in three provinces and water scarcity exposure of consumption in one province. 3) Virtual scarce water represents about half of the virtual water supporting Chinese supply chains, pointing to the prevalence of water stress facing China's water supply systems. Despite the fact that IBWT overall reduces water scarcity risk in China's supply chain, there is still much unsustainable water use throughout China that policy makers may wish to consider in an effort to secure water supplies.

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.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.watres.2022.119442.

References

Allan, T., 1992. Fortunately There Are Substitutes for Water: otherwise Our Hydropolitical Futures Would Be Impossible in Priorities for Water Resources Allocation and Management (ODA, London), 13–26.

Dalin, C., Hanasaki, N., Qiu, H., Mauzerall, D., Rodriguez-Iturbe, I., 2014. Water resources transfers through chinese interprovincial and foreign food trade. Proc. Natl. Acad. Sci. U.S.A. 111 (27), 9774–9779.

Ding, W., Liu, H., Li, Y., Shang, H., Zhang, C., Fu, G., 2020. Unraveling the effects of long-distance water transfer for ecological recharge. J. Water Resour. Planning Manag. 146 (9).

D'Odorico, P., Carr, J., Dalin, C., Dell'Angelo, J., Konar, M., Laio, F., Ridolfi, L., Rosa, L., Suweis, S., Tamea, S., 2019. Global virtual water trade and the hydrological cycle: patterns, drivers, and socio-environmental impacts. Environ. Res. Lett. 14, 053001.

Feng, K., Hubacek, K., Pfister, S., Yu, Y., Sun, L., 2014. Virtual scarce water in China. Environ. Sci. Technol. 48 (14), 7704–7713.

Gohari, A., Eslamian, S., Mirchi, A., Abedi-Koupaei, J., Bavani, A.M., Madani, K., 2013. Water transfer as a solution to water shortage: a fix that can backfire. J. Hydrol. 491, 23–39.

Hejazi, M.I., Edmonds, J., Clarke, L., Kyle, P., Davies, E., Chaturvedi, V., Wise, M., Patel, P., Eom, J., Calvin, K., 2014. Integrated assessment of global water scarcity over the 21st century under multiple climate change mitigation policies. Hydrol. Earth Syst. Sci. 18, 2859–2883.

Hoekstra, A.Y., Mekonnen, M.M., 2012. The water footprint of humanity. Proc. Natl. Acad. Sci. U.S.A. 109 (9), 3232–3237.

Huang, Z., Xuan, X., Liu, X., 2021. The key drivers for the changes in global water scarcity: water withdrawal versus water availability. J. Hydrol. 601, 126658.

Konar, M., Evans, T., Levy, M., Scott, C., Troy, T., Vörösmarty, C.J., Sivapalan, M., 2016. Water resources sustainability in a globalizing world: who uses the water? Hydrol. Process. https://doi.org/10.1002/hyp.10843.

Li, Y., Xiong, W., Zhang, W., Wang, C., Wang, P., 2016. Life cycle assessment of water supply alternatives in water-receiving areas of the South-to-North Water Diversion Project in China. Water Res 89, 9–19.

Liu, J., Yang, H., Gosling, S., Kummu, M., Florke, M., Pfister, S., et al., 2017. Water scarcity assessments in the past, present, and future. Earth's Future 5 (6), 545–559.

Liu, W., Chen, J., Tang, Z., Liu, H., Han, M., Li, F., 2008. Theory and Practice of Compiling China 30-province Inter-regional Input-Output Table of 2007. China Statistics Press, Beijing.

Liu, W., Tang, Z., Chen, J., Yang, P., 2014. The 2010 China Multi-Regional Input-Output Table of 30 Provincial Units. China Statistics Press, Beijing.

Liu, W., Tang, Z., Han, M., 2018. The 2012 China Multi-Regional Input-Output Table of 31 Provincial Units. China Statistics Press, Beijing.

Liu, X., Tang, Q., Liu, W., Veldkamp, T.I.E., Boulange, J., Liu, J., et al., 2019. A spatially explicit assessment of growing water stress in China from the past to the future. Earth's Future 7, 1027–1043.

Ma, T., Sun, S., Fu, G., Hall, J., Ni, Y., He, L., Yi, J., Zhao, N., Du, Y., Pe, i T., Cheng, W., Song, C., Fang, C., Zhou, C., 2020. Pollution exacerbates China's water scarcity and its regional inequality. Nat. Commun. 11, 650.

Mekonnen, M., Hoekstra, A., 2016. Four billion people facing severe water scarcity. Sci. Adv. 2, e1500323.

MWRC (Ministry of Water Resources of China), 2007. China Water Resources Bulletin. –2017. China Water & Power Press, Beijing. www.mwr.gov.cn/sj/tjgb/szygb/.

Nong, X., Shao, D., Zhong, H., Liang, J., 2020. Evaluation of water quality in the South-to-North Water Diversion Project of China using the water quality index (WQI) method. Water Res 178, 115781.

Oki, T., Kanae, S., 2006. Global hydrological cycles and world water resources. Science 313, 1068–1072.

Pfister, S., Koehler, A., Hellweg, S., 2009. Assessing the environmental impacts of freshwater consumption in LCA. Environ. Sci. Technol. 43, 4098–4104.

Qu, S., Lian, S., Konar, M., Zhu, Z., Chiu, A., Jia, X., Xu, M., 2018. Virtual Water Scarcity Risk to the Global Trade System. Environ. Sci. Technol. 52 (2), 673–683.

Rising, J., Josset, L., Troy, T., Lall, U., 2022. The importance of infrastructure and national demand to represent constraints on water supply in the United States. Global Environ. Change. 73, 102468.

Rollason, E., Sinha, P., Bracken, L.J., 2022. Interbasin water transfer in a changing world: a new conceptual model. Prog. Phys. Geogr. 46 (3), 371–397.

Shumilova, O., Tockner, K., Thieme, M., Koska, A., Zarfl, C., 2018. Global water transfer megaprojects: a potential solution for the water-food-energy nexus? Front. Environ. Sci. 6, 11.

Sun, S., Fang, C., Lv, J., 2017. Spatial inequality of water footprint in China: a detailed decomposition of inequality from water use types and drivers. J. Hydrol. 553, 398–407.

Sun, S., Zhou, X., Liu, H., Jiang, Y., Zhou, H., Zhang, C., Fu, G., 2021. Unraveling the effect of inter-basin water transfer on reducing water scarcity and its inequality in China. Water Res. 194, 116931.

Sun, S., Tang, Q., Konar, M., Huang, Z., Gleeson, T., Ma, T., Fang, C., Cai, X., 2022. Domestic groundwater depletion supports China's full supply chains. Water Resour. Res. 58 e2021WR030695.

Suweis, S., Konar, M., Dalin, C., Hanasaki, N., Rinaldo, A., Rodriguez-Iturbe, I., 2011. Structure and controls of the global virtual water trade network. Geophysical Res. Lett. 38 (10) https://doi.org/10.1029/2011GL046837.

Tang, Q., 2020. Global change hydrology: terrestrial water cycle and global change. Sci. China Earth Sci. 63 (3), 459–462.

Vanham, D., Hoekstra, A.Y., Wada, Y., Bouraoui, F., de Roo, A., Mekonnen, M.M., van de Bund, W.J., Batelaan, O., Pavelic, P., Bastiaanssen, W.G.M., Kummu, M., Rockström, J., Liu, J., Bisselink, B., Ronco, P., Pistocchi, A., Bidoglio, G., 2018. Physical water scarcity metrics for monitoring progress towards SDG target 6.4: an evaluation of indicator 6.4.2 "Level of water stress. Sci. Total Environ. 613–614, 218–232.

Vorosmarty, C.J., Green, P., Salisbury, J., Lammers, R.B., 2000. Global water resources: vulnerability from climate change and population growth. Science 289 (5477), 284–288.

Wada, Y., van Beek, L.P.H., Viviroli, D., Durr, H.H., Weingartner, R., Bierkens, M.F.P., 2011. Global monthly water stress: 2. Water demand and severity of water stress. Water Resour. Res. 47, 17.

Weinzettel, J., Pfister, S., 2019. International trade of global scarce water use in agriculture: modeling on watershed level with monthly resolution. Ecol. Eco. 159, 301–311.

Yang, H., Pfister, S., Bhaduri, A., 2013. Accounting for a scarce resource: virtual water and water footprint in the global water system. Curr. Opin. Environ. Sustain. 5 (6), 599–606.

Zhang, C., Anadon, L.D., 2014. A multi-regional input-output analysis of domestic virtual water trade and provincial water footprint in China. Ecol. Econ. 100 (2), 159–172.

Zhang, L., Li, S.S., Loaiciga, H.A., Zhuang, Y.H., Du, Y., 2015. Opportunities and challenges of interbasin water transfers: a literature review with bibliometric analysis. Scientometrics 105 (1), 279–294.

Zhao, X., Liu, J., Liu, Q., Tillotson, M.R., Guan, D., Hubacek, K., 2015. Physical and virtual water transfers for regional water stress alleviation in China. Proc. Natl. Acad. Sci. U S A 112 (4), 1031–1035.

Zhao, X., Li, Y.P., Yang, H., Liu, W.F., Tillotson, M.R., Guang, D., Yi, Y., Wang, H., 2018. Measuring scarce water saving from interregional virtual water flows in China. Environ. Res. Lett. 13, 054012.

Zheng, H., Zhang, Z., Wei, W., Song, M., Dietzenbacher, E., Wang, X., et al., 2020. Regional determinants of China's consumption-based emissions in the economic transition. Environ. Res. Lett. 15 (7), 074001.

Zhou, F., Bo, Y., Ciais, P., Dumas, P., Tang, Q., Wang, X., et al., 2020. Deceleration of China's human water use and its key drivers. Proc. Natl. Acad. Sci. U.S.A 117 (14), 7702–7711.