AGU ADVANCING EARTH AND SPACE SCIENCE

Water Resources Research

RESEARCH ARTICLE

10.1029/2021WR030695

Domestic Groundwater Depletion Supports China's Full Supply Chains

Siao Sun[1,2], Qiuhong Tang[2,3], Megan Konar[4], Zhongwei Huang[5], Tom Gleeson[6], Ting Ma[2,7], Chuanglin Fang[1,2], and Ximing Cai[4]

[1]Key Laboratory of Regional Sustainable Development Modeling, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China, [2]University of Chinese Academy of Sciences, Beijing, China, [3]Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China, [4]Civil and Environmental Engineering Department, University of Illinois at Urbana-Champaign, Urbana, IL, USA, [5]School of Hydrology and Water Resources, Nanjing University of Information Science and Technology, Nanjing, China, [6]Department of Civil Engineering, University of Victoria, Victoria, BC, Canada, [7]State Key Laboratory of Resources and Environmental Information System, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China

Key Points:

- Groundwater depletion is traced using a multi-region input-output analysis coupled with the high-resolution groundwater use modeling
- About 21 billion m^3 yr^{-1} groundwater depletion, primarily from water scarce Northern-China, is virtually transferred domestically
- Groundwater depletion supporting export to the Rest of the World is estimated to be 4.8 billion m^3 yr^{-1}

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

S. Sun and Q. Tang,
suns@igsnrr.ac.cn;
tangqh@igsnrr.ac.cn

Citation:

Sun, S., Tang, Q., Konar, M., Huang, Z., Gleeson, T., Ma, T., et al. (2022). Domestic groundwater depletion supports China's full supply chains. *Water Resources Research*, *58*, e2021WR030695. https://doi.org/10.1029/2021WR030695

Received 25 JUN 2021
Accepted 6 MAY 2022

Author Contributions:

Conceptualization: Siao Sun, Qiuhong Tang
Data curation: Zhongwei Huang, Ting Ma
Formal analysis: Siao Sun
Investigation: Qiuhong Tang, Megan Konar
Methodology: Siao Sun
Project Administration: Chuanglin Fang
Resources: Chuanglin Fang
Visualization: Siao Sun, Tom Gleeson
Writing – original draft: Siao Sun

Abstract

Groundwater use underpins much economic production. The unsustainable use of groundwater threatens environmental flows in surface waters, sustainable development, and future food security. The connection between agricultural trade and groundwater depletion has been recently highlighted, but how groundwater depletion supports the production of industrial and tertiary goods, trade, and consumption remains less well understood. Here, we present the first analysis of groundwater use and depletion embedded in the complete supply chain of China (including primary, secondary, and tertiary products). We use a multiregion input-output analysis coupled with the high-resolution groundwater use modeling to track groundwater depletion from production to end consumer. Our modeling results show that groundwater depletion occurred primarily in water scarce North China for agricultural production, but the depleted resource was then incorporated throughout the supply chain and dispersed across Chinese and international consumers. ~64 billion m^3 yr^{-1} (±1 billion m^3 yr^{-1}) groundwater was depleted in China, in which more than a half was from Xinjiang, Hebei, Henan and Heilongjiang Provinces. Approximately 40% of the groundwater depletion can be traced to interprovincial transfer (21 billion m^3 yr^{-1}) and export (4.8 billion m^3 yr^{-1}). The hot spots for final consumption of groundwater depletion were major cities in both North and South China. Importantly, over 60% of the groundwater depletion was embodied in industrial and tertiary products for final consumption, highlighting the importance of tracing groundwater through the full economy. Groundwater depletion represents a long-term risk to supply chains, and policy-makers can use this understanding to sustainably manage groundwater and diversify supply chains.

Plain Language Summary

Groundwater is a critical resource that is under increased pressure due to unsustainable exploitation. Groundwater resources underpin both national supply chains and global trade, but how groundwater supports the full supply chain of a nation remains unresolved. This study traces the groundwater depletion incorporated in the complete supply chain (including industrial and tertiary products, not just primary goods) of China through interprovincial transfers and international exports. The results show how groundwater depletion, which is concentrated in North China, is distributed to domestic and international consumers of final goods. International importers receive China's groundwater in the receipt of industrial products. We highlight that groundwater depletion represents a long-term risk to supply chains.

1. Introduction

Groundwater is a critical resource that is under increased pressure around the world due to unsustainable exploitation for human water uses (Aeschbach-Hertig & Gleeson, 2012; Döll et al., 2014). China withdraws more than 100 billion m^3 groundwater annually (more than 10% of the global total) to support the livelihood and production activities of the largest population in the world and has been reported as one of the major countries depleting its groundwater resources (UNDP, 2006) according to both global and regional hydrological modeling (Famiglietti, 2014; Wada, van Beek, & Bierkens, 2012; Wada, van Beek, Weiland, et al., 2012) and observations (Fang et al., 2019; Tang et al., 2013). Groundwater depletion is defined as groundwater withdrawal (abstraction)

Writing – review & editing: Qiuhong Tang, Megan Konar, Tom Gleeson, Ximing Cai

in excess of the natural recharge rate of groundwater (Döll et al., 2012), which often leads to a decrease in the water storage of aquifers, threatening environmental flows and sustainable development. Groundwater depletion will curb future groundwater availability (Steward et al., 2013), thus reducing future water security (Castle et al., 2014), not only locally but also in places where groundwater intensive products are received via trade.

As groundwater resources underpin both national supply chains and global trade (Gumidyala et al., 2020), the connection between agricultural trade and groundwater depletion has been recently highlighted (Dalin et al., 2017, 2019; Marston et al., 2015). Much research has focused on quantifying total or surface water use embedded in sectoral products within or across countries/regions (Garcia et al., 2021; Richter et al., 2020; Vanham et al., 2018), but less attention has been paid to the role of groundwater withdrawals and related sustainability of the supply chains (Dalin et al., 2019). We do not have a good understanding of how groundwater (and groundwater depletion) is incorporated along the full supply chain of a nation, including industrial products, services, and final consumption. Because the impacts and potential recovery from groundwater depletion often have very different time and space scales in comparison to surface water depletion (Marston & Konar, 2017; Richter et al., 2020), distinguishing groundwater depletion from renewable water use allows us to better understand the overall sustainability and risks of water in supply chains.

Human society has a long history of exploiting groundwater, and our reliance on groundwater is increasing (Gleeson et al., 2020). As the largest stock of liquid freshwater available for human use (Dalin et al., 2019), groundwater availability is often less sensitive to annual and interannual rainfall fluctuations than surface water and is thus a great buffer to climate variability (Gleeson et al., 2020). In addition, the distribution of groundwater is ubiquitous, underlying most of the earth's surface rather than confined river channels and lakes as is surface water (Gleeson et al., 2020). These properties make groundwater an important resource for human use: Groundwater provides approximately 2 billion people with drinking water and supplies ~40% global irrigation and ~27% industrial water uses (Döll et al., 2012; Morris et al., 2003; Siebert et al., 2010). Intensive exploitation of groundwater in many places has caused groundwater depletion and subsequent social and environmental problems (Gleeson et al., 2012; Scanlon et al., 2012).

There is high spatial variability in groundwater use across China with depletion concentrated in a few aquifers in North China (Cai, 2008; Wada et al., 2010), which means that a fine-scale analysis is key to evaluating this uneven groundwater exploitation. Despite the importance of groundwater in supporting domestic and production water uses, spatially explicit groundwater depletion data in China are not readily available due to the difficulty in monitoring large-scale groundwater use. Groundwater withdrawal and depletion in China have been assessed by a number of global modeling studies (Dalin et al., 2017; Dalin et al., 2019; Wada, van Beek, & Bierkens, 2012; Wada, van Beek, Weiland, et al., 2012); yet prior research has not used regional Chinese water use statistics. There has been increasing research into the subnational virtual water transfer (i.e., the water embodied in products used in the production process and transferred domestically, Allan, 1998) in China (Sun et al., 2017; Zhang & Anadon, 2014; Zhang et al., 2012; Zhao et al., 2015). Dalin et al. (2017) quantified groundwater depletion embedded in global crop trade. However, the groundwater depletion associated with interprovincial trade and export for the full supply chain (including industrial and tertiary products) is missing.

The goal of this study is to trace the groundwater depletion of the full supply chain of China embedded in the interprovincial trade and export (as a lumped volume to the Rest of World as given in the MRIO database). Here, we estimate high-resolution groundwater withdrawal and depletion in China using a simulation-based approach that we constrain by provincial-level statistical data. The groundwater withdrawal from locations of depletion in production is traced to the end consumers, using a multiregion input-output (MRIO)-based approach, which is an analytical technique from the discipline of economics that has been widely applied to the use of various natural resources and pollution tracking (T. O. Wiedmann et al., 2015; Oita et al., 2016; Lin et al., 2016; T. Wiedmann & Lenzen, 2018; Xu et al., 2020). According to a summary of relevant studies (Table S1 in Supporting Information S1), a methodological framework that combines the groundwater depletion modeling with the MRIO analysis is missing. Our study presents a methodological framework coupling physical and virtual water analyses (through the high-resolution groundwater use modeling coupled with coupling groundwater use modeling and MRIO analysis) to quantify groundwater depletion in the supply chain. This approach enables us to distinguish groundwater depletion for production and consumption (Garcia et al., 2020; Marston et al., 2018). Specifically, "consumption-based groundwater withdrawal" is the groundwater that is virtually embedded in products throughout the supply chain and consumed by end consumers. To focus on the unsustainable groundwater incorporated in supply chains, we define "consumption-based groundwater depletion" to be depleted groundwater (i.e., groundwater withdrawal minus groundwater recharge) that is embedded in products consumed by end consumers. Commodity fluxes through supply chains enable one location's consumption-based groundwater depletion to be different from its groundwater depletion for production. Consumers who receive groundwater depletion-intensive products should be aware of the risk from groundwater depletion upstream in their supply chain. As such, distinguishing this critical water source along supply chains is a major advancement over other virtual water studies that quantify the total water embodied in supply chains and trade.

2. Materials and Methods

2.1. Data Sources

The data sources used in this study mainly include the latest MRIO table in China, water withdrawal, and water availability data sets. The China MRIO table in 2012 provides the interconnection and interdependence relationships of economic activities between 42 sectors (including 1 agricultural sector, 27 detailed industrial sectors, and 14 detailed tertiary sectors) and 31 provincial administrative unites (hereinafter referred to as provinces, not including Hong Kong, Macao, and Taiwan due to data unavailability) in the monetary unit (Liu et al., 2018). Provincial-level water withdrawal data for agricultural, industrial, domestic and eco-environmental compensation sectors are referenced from China Water Resources Bulletin (MWRC, 2006–2015). Domestic water withdrawal includes tertiary and households water uses, which can be separated referring to Provincial Water Resources Bulletins (PWRB, 2012). The eco-environmental compensation water use is mainly for irrigating urban green space and replenishing dry rivers and lakes in urbanized areas. The provincial-level water supplies from surface water (including both locally generated surface water and transferred water from other basins), groundwater and other sources (mainly including reclaimed water and desalinated water) are also referenced from China Water Resources Bulletin (MWRC, 2006–2015). Provincial-level natural water availability, including surface water resources, groundwater resources (recharge for groundwater), and double-counted water resources (water resources that are counted in both surface water and groundwater) in 2006–2015, is referenced from China Water Resources bulletin (MWRC, 2006–2015). Double counting of surface water and groundwater resources is avoided by deducing the overlap, that is, double-counted water resources, from the sum of the surface water and groundwater resources.

Previous studies of water resources embodied in various products for domestic transfers or international trade—virtual water transfer or trade—have sometimes distinguished between blue water (surface water and groundwater) and green water (soil moisture) sources (Dalin et al., 2014; Hoekstra et al., 2011). Because we focus on groundwater withdrawal and depletion embedded in the supply chain, green water is not considered in this study. Previous virtual water accountings have been conducted based either on water withdrawal (i.e., water use) or water consumption (total water withdrawal subtracted with return flow, e.g., percolation losses from irrigation and wastewater discharges from industries, Zhang & Anadon, 2014). Because return flows may not be recharged back underground (e.g., wastewater discharges from domestic and industrial uses) and the water quality of return flows is usually degraded, here, virtual water accounting is based on water withdrawal, like many previous studies (Sun et al., 2017; Zhang et al., 2012; Zhao et al., 2015).

In addition, Hydrography information that determines the surface flow directions of watersheds in China is derived from the Global Dominant River Tracing-based hydrography data sets (Wu et al., 2011). This data set will be used to determine upstream-downstream hydrographic relations of the grids to calculate the grid-level surface water availability, which is the sum of upstream surface water available (i.e., surface water availability minus local surface water withdrawal) and locally generated surface water. Grid-level population distribution (Ma et al., 2020) is required for disaggregating consumption-based water withdrawal, groundwater withdrawal, and groundwater depletion, assuming equal consumption of sectoral products by end consumers in each province.

2.2. Data Processing and Simulation of Groundwater Withdrawal and Depletion

The main procedure for data processing is shown in Figure 1. Provincial-level groundwater depletion is not readily available from statistics and is thus estimated with spatially explicit groundwater use modeling (the physical

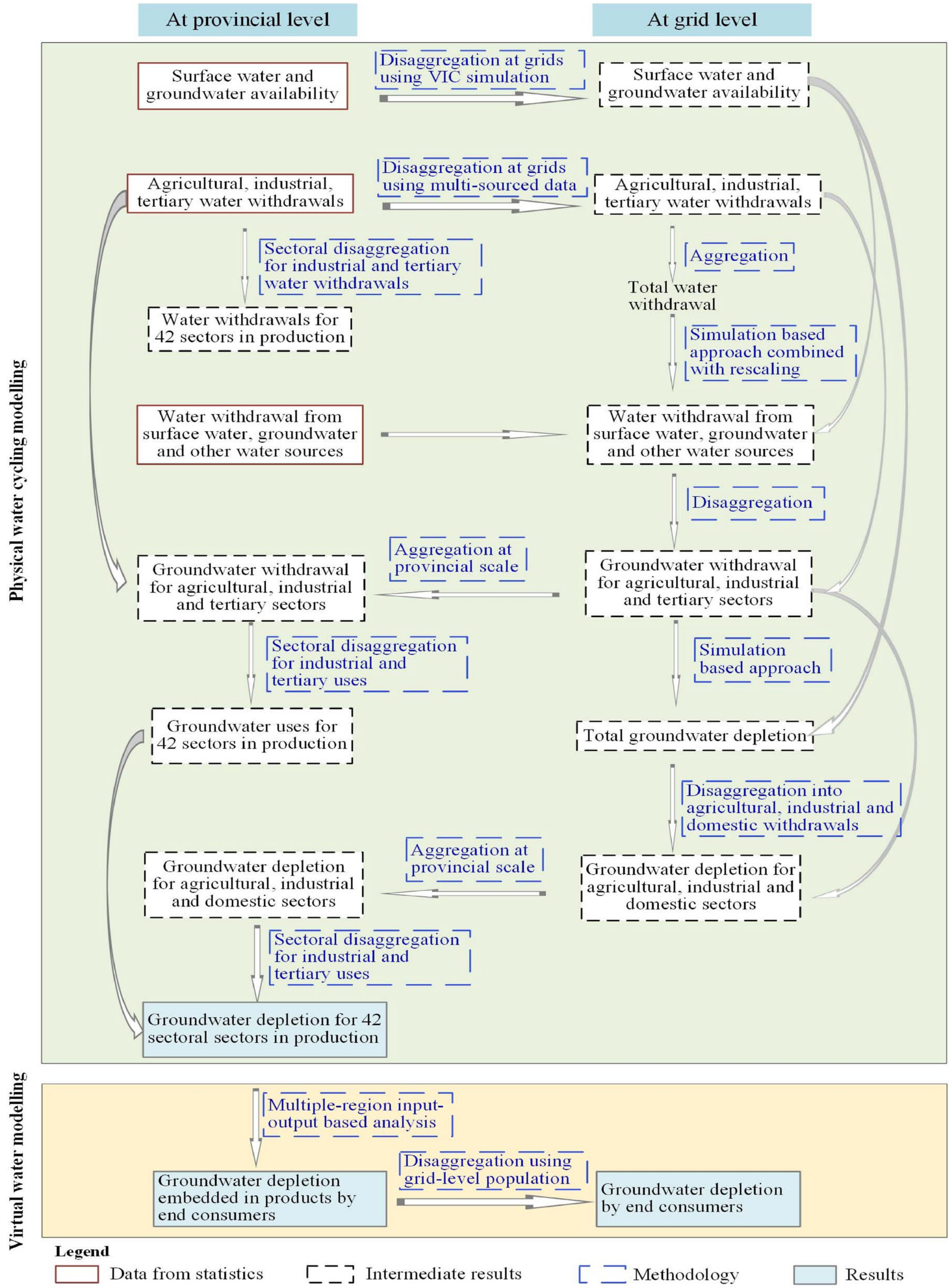

Figure 1. Data processing framework for simulating groundwater withdrawal and depletion. A methodological framework employing hydrology and supply chain modeling is used in this study.

water cycling part in Figure 1). Provincial-level sectoral water withdrawals at an annual basis (i.e., agricultural, industrial, domestic, and eco-environmental compensation water uses) are disaggregated at the 0.25×0.25 arc-degree grid scale based on multisourced data (including grid-level land uses, climatic data, industrial GDP, and population), following a previous analysis (Ma et al., 2020) (please refer to Supporting Information S1 for disaggregation details). This water withdrawal disaggregation based on regionally resolved data should provide a more reliable grid-level sectoral water withdrawal assessment in China in comparison to previous global studies (Huang et al., 2018; Wada, van Beek, & Bierkens, 2012; Wada, van Beek, Weiland, et al., 2012) mostly based on national data (e.g., FAO AQUASTAT country-specific data). Provincial-level water withdrawal data for production purposes are converted to sectoral water withdrawal data in consistence with sectors of the MRIO table, following a previously used approach (Sun et al., 2019; Zhang & Anadon, 2014): The industrial water withdrawal is disaggregated into 27 detailed industrial sectoral data proportional to sectoral industrial water uses in 2008 in Chinese Economic Census Yearbook (SCLGOSCEC, 2008). The tertiary water withdrawal is disaggregated into 14 detailed sectors according to the proportions of the intermediate inputs of the "water production and supply sector" to detailed tertiary sectors in the MRIO table.

Natural water availability at an annual basis in provinces is divided into surface water and groundwater proportional to their quantities. Provincial-level surface and groundwater availability data are then disaggregated into grid-level values based on simulated surface and subsurface runoff using the Variable Infiltration Capacity (VIC) model. In comparison to grid-level water availability simulations in global studies, the VIC hydrological simulation used observation-based meteorological forcings (in contrast, global studies often used reanalysis data), and the simulation results have been validated with more gauge measurements across China (Zhang et al., 2014). This disaggregation makes surface water availability and groundwater recharge to achieve mass balance with the provincial statistics.

Based on grid-level water withdrawal data, surface water and groundwater withdrawals at the grid scale are simulated following a previous approach (Munia et al., 2016). The water demand at a specific grid (except the part met by the other water sources, which constituted only ∼0.7% of the total national water supply and are disaggregated at the grid scale proportional to grid water demand) is first met by the surface water availability (including upstream and locally generated surface water resources based on the hydrography information). We assume that a share of surface water (i.e., 80% here) is for environmental flow requirement (i.e., some water must remain in-stream to maintain environmental flows), which is not available for human water use. If the surface water availability is insufficient for meeting the human water demand at a grid, the water demand greater than surface water supply is from groundwater. Then, the simulated grid-level surface water withdrawal is rescaled to make the aggregated provincial-level surface water withdrawal equal to the provincial statistics. The groundwater withdrawal at the grid scale is derived by subtracting surface water withdrawal from the grid-level total water withdrawal. The rescaling step assures the surface water and groundwater withdrawals by simulation be consistent to provincial statistics.

Groundwater depletion at the grid scale is derived based on the high-resolution groundwater withdrawal and natural groundwater recharge. If the groundwater demand is less than annual groundwater recharge at a grid, no groundwater depletion occurs. Otherwise, the quantity of groundwater depletion is calculated as the difference between groundwater demand and recharge. Groundwater depletion at the provincial scale is calculated by aggregating corresponding values at the grids within the provincial boundaries. The sensitivity of provincial-level groundwater depletion to the share of surface water for environmental flow requirement (80%) is examined by changing this share between 70% and 90%, that is, groundwater depletion is simulated assuming 70% and 90% surface water for environmental flow requirement, and provincial-level groundwater depletion volumes are compared under different scenarios. The rescaling step in this approach makes the provincial groundwater depletion not sensitive to the assumed share of surface water for environmental flow requirement (see sensitivity analysis results in Supporting Information S1).

The grid-level groundwater withdrawal and depletion are disaggregated to agricultural, industrial, and domestic sectors based on their grid-specific sectoral demands, assuming that eco-environmental compensation water demand is met by surface water and other sources. This sectoral partitioning is made based on the assumption that the responsibility of groundwater withdrawal and depletion at one grid is appropriated to sectoral uses proportional to their grid specific demands, which can be justified by the fact that sectoral water demands are competitive (Martina et al., 2018) and altogether, they lead to groundwater withdrawal and depletion. Spatially explicit sectoral groundwater withdrawal and depletion in China are shown in Figures S1 and S2 in Supporting Information S1. The grid-level sectoral groundwater withdrawal and depletion (by agricultural, industrial, and domestic sectors) are aggregated at the provincial scale, which are then disaggregated to provincial groundwater withdrawal and depletion by 42 sectors, proportional to provincial-level sectoral water withdrawals. The sensitivity of the results to this assumption for disaggregation is examined using the Monte Carlo method.

2.3. Groundwater Use Accounting in the Multiregion Input-Output Framework

Based on the MRIO table in China in 2012, 42-sectoral water withdrawal, groundwater withdrawal, and groundwater depletion in the same year can be assigned to final consumers by tracing the linkages among varied industries of different provinces in the production chains. Following many previous studies (Sun & Fang, 2019; C. Zhang & Anadon, 2014; Zhao et al., 2015), in a socioeconomic system with n regions and m sectors, the sectoral water use W (W is an $mn \times 1$ vector, representing either water withdrawal, groundwater withdrawal or groundwater depletion) can be written as

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

where D is the vector of direct water use intensity (or direct groundwater use intensity or direct groundwater depletion intensity corresponding to what W represents), denoting direct water withdrawal (or direct groundwater withdrawal or direct groundwater depletion) per unit output in each sector, X is the vector of total economic output, Y is the vector of final demand, I is the unit matrix, A is the matrix of technical coefficients, $(I - A)^{-1}$ is the Leontief inverse matrix, and T is an $mn \times mn$ matrix of total water use intensity, representing the total water use per unit product for final consumption. Water withdrawal, groundwater withdrawal, and groundwater depletion embodied in various products and services along the production chains can be tracked for provincial units. Virtual water from province r to province s, represented by vw^{rs}, can be computed as

$$vw^{rs} = \sum_k \sum_i t_{ik}^r y_{ik}^s \tag{2}$$

where t_{ik}^r represents the total water withdrawal (or total groundwater withdrawal or groundwater depletion) in province r for producing one unit product i in region k (can be calculated from elements in T in Equation 1) and y_{ik}^s is the amount of product i produced in region k that is finally consumed in region s. Virtual water from region r exported abroad through international trade, denoted as vwe^r, is:

$$vwe^r = \sum_k \sum_i t_{ik}^r ex_{ik} \tag{3}$$

where ex_{ik} is the amount of product i from province k exported abroad. The consumption-based water footprint (or groundwater use/groundwater depletion) of region r, which indicates the amount of water (or groundwater/groundwater depletion) embodied in all the products finally consumed by inhabitants in region r, represented by wf^r, is calculated as the sum of the local water use wu^r and net virtual water flows:

$$wf^r = wu^r + \sum_{s \neq r} vw^{sr} - \sum_{s \neq r} vw^{rs} \tag{4}$$

where $\sum_{s \neq r} vw^{sr} - \sum_{s \neq r} vw^{rs}$ represents the net virtual water inflow of region r through interprovincial transfers. International virtual water import is not considered in this study, because China's MRIO table does not contain trading information with foreign countries and hence not allow international virtual water import accounting. We focus on tracing groundwater withdrawal and groundwater depletion that occur in production in China to final consumption by both domestic and international end consumers. Note that we do not consider international virtual water imports to China.

The consumption-based water withdrawal, groundwater withdrawal, and groundwater depletion of provinces are disaggregated at the grid scale based on grid-level population distribution, assuming that each person in one province consumes the same quantity of sectoral products.

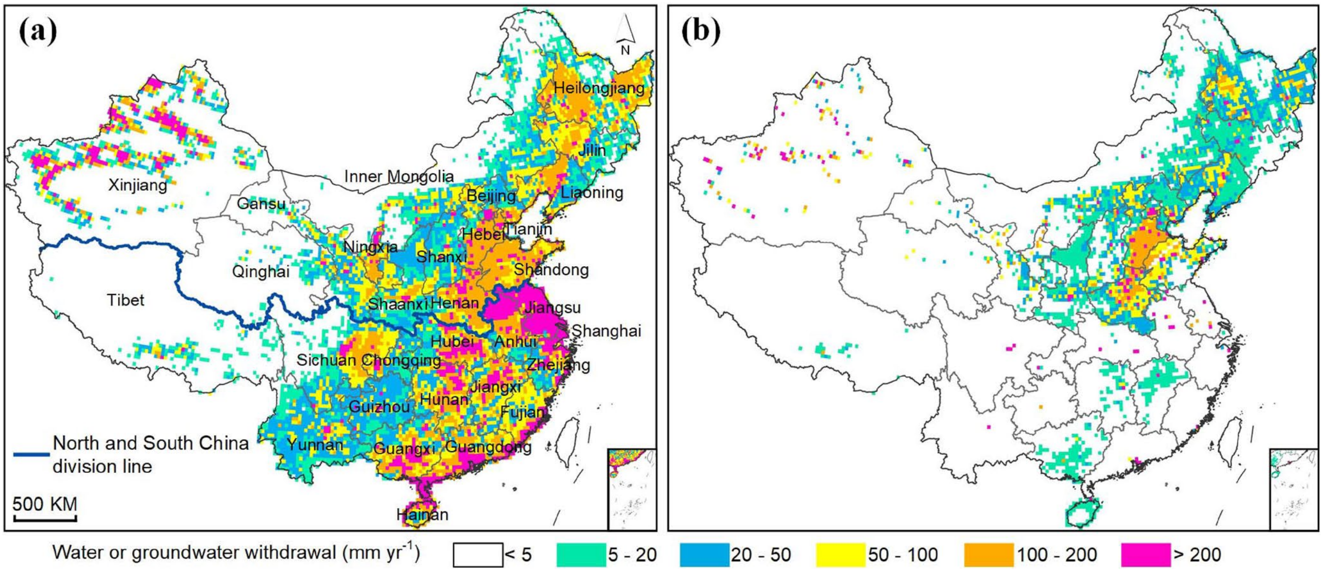

Figure 2. China's water withdrawal at the 0.25 × 0.25 arc-degree grid scale in 2012: (a) total water withdrawal and (b) groundwater withdrawal.

3. Results

3.1. Groundwater Depletion for Production and Consumption in China

The total annual water withdrawal in China was between 580 and 618 billion m^3 yr^{-1} in the past decade (2006–2015), and the total annual groundwater withdrawal was between 107 and 113 billion m^3 yr^{-1} from statistics (MWRC, 2006–2015). Based on the comparison between annual groundwater withdrawal and the natural recharge rate of groundwater at the grid level, we estimated groundwater depletion to be 59 ~ 64 billion m^3 yr^{-1} (±1 billion m^3 yr^{-1}, see Discussion section and Supporting Information S1 for detailed uncertainty analysis), comprising about 54%~58% of the total groundwater withdrawal.

Figure 2a shows China's water withdrawal in 2012 (the year when the latest MRIO table is available) at the 0.25 × 0.25 arc-degree scale, disaggregated based on provincial-level statistics based on multisourced information. Figure 2b shows grid-level groundwater withdrawal using the above-specified methodology that separates groundwater withdrawal from surface water withdrawal. Groundwater withdrawal was much more localized than the total water withdrawal, because groundwater is not required in locations where surface water supply is sufficient. Groundwater withdrawal is greater throughout much of the arid and semiarid North China, where the annual average precipitation is less than 500 mm. A few locations in South China also exhibit groundwater mining, but generally at a lower rate and for a smaller extent than in North China.

Groundwater depletion at the grid scale was calculated by subtracting natural groundwater recharge from withdrawals. Groundwater was abstracted at a higher rate than recharge mostly in North China (Figure 3a). This was primarily for irrigation in agriculture. Depleted groundwater was also withdrawn to provide urban water supplies in cities (mainly for industrial and domestic uses), including those in South China (e.g., Chengdu, Wuhan, and Shenzhen). Of all the 31 provinces, Hebei had the largest share of areas exposed to groundwater depletion (53.0% areas with groundwater depletion >5 mm yr^{-1}), followed by Henan (46.8%), Shandong (29.2%), Shanxi (26.1%), and Heilongjiang (21.6%), which are all located in North China. The top four provinces with the most intensive groundwater depletion (i.e., depletion per area) were Beijing, Henan, Hebei, and Anhui (groundwater depletion >20 mm on average). The top four provinces exploiting the largest groundwater depletion volumes were Xinjiang, Hebei, Henan, and Heilongjiang, which altogether depleted over a half of the national total. These results are consistent with reports of groundwater overexploitation in these regions (Fang et al., 2019; Tang et al., 2013).

Groundwater withdrawal and depletion in grids were disaggregated into agricultural, industrial, and domestic uses proportional to their grid-specific sectoral demands (Figures S1 and S2 in Supporting Information S1). Fractional groundwater depletion by sector of a province was different from that of total water withdrawal (Table

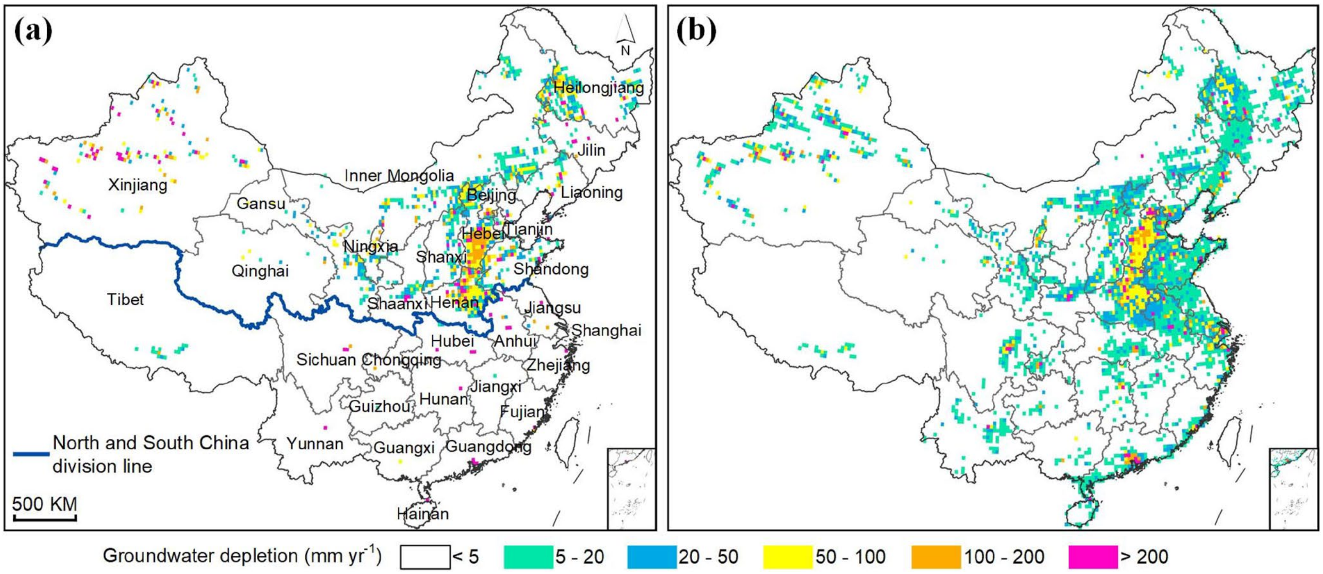

Figure 3. China's groundwater depletion at the 0.25 × 0.25 arc-degree grid scale in 2012: (a) groundwater depletion driven by local water uses; (b) groundwater depletion embedded in final consumption.

S2 in Supporting Information S1). At the national level, 52%, 33%, and 15% groundwater depletion can be attributed to agricultural, industrial, and domestic uses, respectively, in comparison to 63%, 23%, and 12% total water withdrawal for agricultural, industrial, and domestic sectors (2% for eco-environmental compensation use).

Water withdrawal, groundwater withdrawal, and groundwater depletion embedded in various products and services were calculated based on the MRIO table of China. We disaggregated the provincial-level groundwater depletion for final consumption of domestic consumers at the grid scale. While the groundwater depletion for production uses was relatively concentrated spatially (7% by area with groundwater depletion >5 mm yr^{-1}, Figure 3a), the groundwater depletion of end consumers was more spatially distributed (19% by area with groundwater depletion >5 mm yr^{-1}, Figure 3b). The groundwater depletion areas held 38% of the national population, but the final groundwater depletion consumption went to 1.174 billion people living on areas with consumption-based groundwater depletion >5 mm yr^{-1}, which is 87% of the national total. People across China relied on highly localized groundwater depletion through their consumption of products.

Nevertheless, intensive groundwater depletion by end consumers was concentrated in major cities. For example, Shanghai, which is not a major groundwater exploiting province in South China, had the highest consumption-based groundwater depletion rate, consuming on average 185 mm groundwater per year in which 54% was from depleted groundwater. This trend was followed by Beijing and Tianjin, consuming on average 83 and 60 mm groundwater depletion per year, respectively. The provinces with the largest consumption-based groundwater depletion included Guangdong, Sichuan, Jiangsu, and Zhejiang in South China, in addition to provinces in North China with heavy groundwater depletion (e.g., Hebei, Henan, Xinjiang, Heilongjiang, and Shandong; see Table S3 in Supporting Information S1). Xinjiang, Inner Mongolia, and Heilongjiang consumed the largest per capita groundwater depletion (over 110 m^3 per capita per year), which was consistent to their largest production-based per capita groundwater depletion (over 180 m^3 per capita per year, see Table S3 in Supporting Information S1).

3.2. Groundwater Depletion Embedded in China's Domestic Supply Chain

There was 38 billion m^3 yr^{-1} groundwater virtually transferred via interprovincial fluxes, including 21 billion m^3 yr^{-1} from depleted groundwater. The interprovincial transfer of groundwater depletion represented about 32% of the total groundwater depletion in China.

Chinese provinces exhibited markedly different patterns of groundwater and groundwater depletion uses (Figures 4a and 4b). In Xinjiang, Heilongjiang, Gansu, and Inner Mongolia in North China, more than 45%

10.1029/2021WR030695

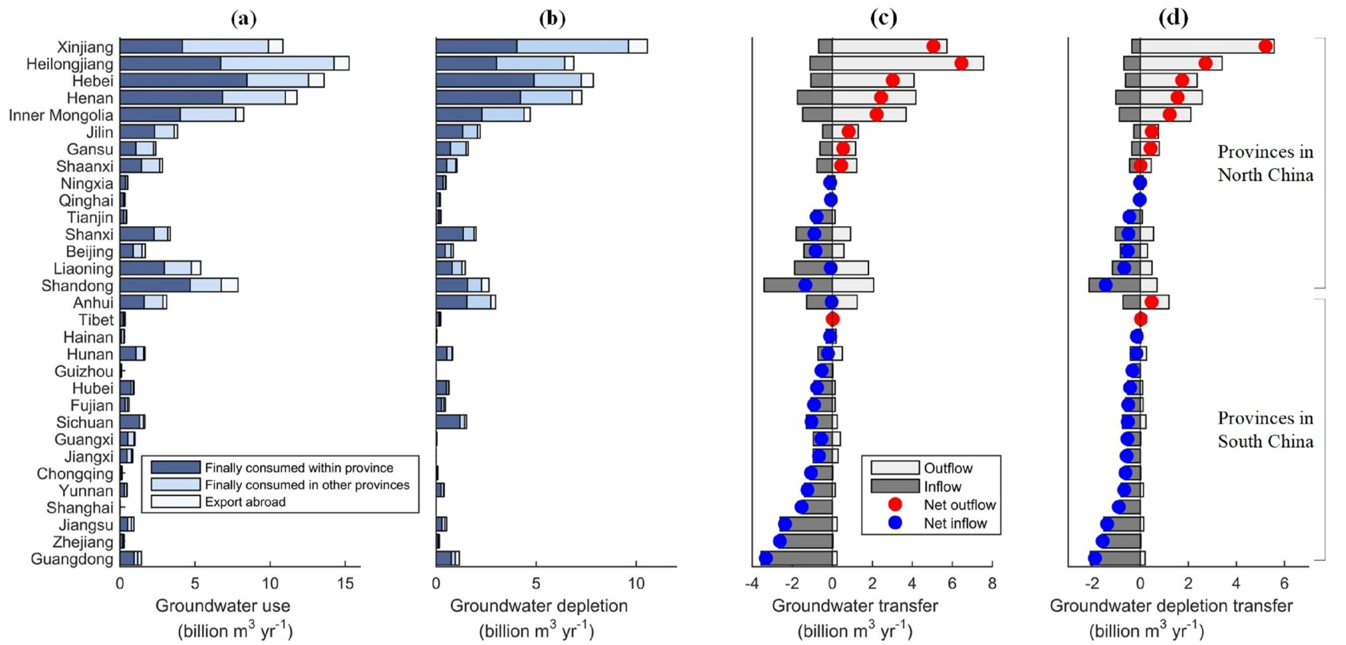

Figure 4. Groundwater flows of China in 2012: (a) Groundwater withdrawal of provinces; (b) groundwater depletion of provinces; (c) interprovincial groundwater transfer, and (d) interprovincial groundwater depletion transfer. A horizontal bar in panels (a and b) represents water withdrawal from one province that was finally consumed within the province and in other provinces or countries. Groundwater and groundwater depletion embedded in products for export are not considered in net outflow and inflow of panels (c and d).

groundwater and groundwater depletion can be traced to final consumption elsewhere in other provinces or abroad. In contrast, Hubei, Sichuan, Chongqing, and Hunan kept most of their groundwater and groundwater depletion for domestic use (over 75%). The major net outflows of groundwater depletion via interprovincial transfers occurred in Xinjiang, Heilongjiang, Hebei, Henan, Inner Mongolia, and Gansu, which are exclusively located in water scarce North China. The major net groundwater depletion recipients were Guangdong, Zhejiang, Jiangsu, and Shanghai, which are affluent and water-abundant provinces in South China that did not exploit much depleted groundwater. However, much depleted groundwater was incorporated indirectly in the supply chains of these net groundwater depletion receiving provinces for final consumption (Figures 4c and 4d). As a result, interprovincial groundwater transfers have reshaped the spatial distribution of groundwater use in China. It is important to note that net groundwater providers were not necessarily net water-delivering provinces (e.g., Hebei and Henan), and that net groundwater recipients were not necessarily net water-receiving provinces (e.g., Guangxi, Hunan, Jiangxi, and Jiangsu; see Figure S3 in Supporting Information S1) due to differences in the inflow and outflow structures of surface water and groundwater across provinces.

In the interprovincial virtual water transfer network, provinces received virtual water from other provinces across sectors (Figure S4 in Supporting Information S1). Table 1 shows groundwater depletion embedded in sectoral products for final consumption in different provinces. Agricultural products are often used as intermediate products in supply chains. This leads industrial and tertiary products to encompass a higher proportion of virtual depleted groundwater in products from a consumption perspective (55% and 15%, respectively, for domestic end consumers at the national level) than the production perspective (27% and 3%). “Food and tobacco processing” was the industrial sector with the most consumption-based groundwater depletion embedded in interprovincial transfers; “accommodation and catering” contained the most transferred groundwater depletion volume of all the tertiary sectors (Table S4 in Supporting Information S1). In Beijing, nearly two thirds of the consumption-based groundwater depletion was from other provinces, predominantly from the agricultural sector upstream the supply chains. However, the share of consumption-based groundwater depletion embedded in finally consumed agricultural products was only one fourth of its total consumption-based groundwater depletion. Due to specialization of production chains across sectors in different provinces, it is common that a province firstly transports sectoral products to an intermediate province where the goods are further processed and the downstream products are

10.1029/2021WR030695

Table 1
Provincial Groundwater Depletion Embedded in Sectoral Products for Final Consumption (Unit: Billion m³)

	Agricultural products		Industrial products		Tertiary products		All
Province	Volume	Percentage	Volume	Percentage	Volume	Percentage	Volume
Beijing	0.28	25%	0.46	40%	0.39	35%	1.14
Tianjin	0.16	25%	0.35	55%	0.12	20%	0.63
Hebei	2.66	49%	2.13	39%	0.63	12%	5.42
Shanxi	0.74	36%	1.14	54%	0.21	10%	2.09
Inner Mongolia	0.88	29%	1.71	57%	0.40	14%	3.00
Liaoning	0.46	26%	1.02	58%	0.28	16%	1.77
Jilin	0.19	11%	1.16	68%	0.35	21%	1.69
Heilongjiang	1.46	38%	1.81	46%	0.62	16%	3.90
Shanghai	0.26	33%	0.42	53%	0.12	14%	0.80
Jiangsu	0.25	15%	1.15	70%	0.24	15%	1.65
Zhejiang	0.46	31%	0.84	57%	0.18	12%	1.48
Anhui	0.18	7%	2.11	80%	0.33	13%	2.62
Fujian	0.12	14%	0.59	72%	0.12	14%	0.82
Jiangxi	0.17	31%	0.29	54%	0.08	15%	0.55
Shandong	0.82	25%	2.07	62%	0.45	13%	3.34
Henan	1.12	22%	3.23	63%	0.79	15%	5.14
Hubei	0.18	17%	0.79	73%	0.11	10%	1.08
Hunan	0.11	10%	0.76	75%	0.15	15%	1.02
Guangdong	0.61	26%	1.28	55%	0.43	19%	2.32
Guangxi	0.17	32%	0.31	58%	0.06	10%	0.54
Hainan	0.05	29%	0.10	57%	0.02	14%	0.17
Chongqing	0.17	25%	0.44	65%	0.07	10%	0.68
Sichuan	0.30	18%	1.07	63%	0.32	19%	1.70
Guizhou	0.12	39%	0.15	48%	0.04	13%	0.31
Yunnan	0.23	24%	0.59	64%	0.11	12%	0.93
Tibet	0.12	63%	0.05	28%	0.02	9%	0.19
Shaanxi	0.17	17%	0.67	65%	0.18	18%	1.02
Gansu	0.51	49%	0.38	37%	0.14	14%	1.04
Qinghai	0.08	34%	0.11	50%	0.04	16%	0.22
Ningxia	0.25	54%	0.18	37%	0.04	9%	0.47
Xinjiang	2.57	59%	1.33	30%	0.49	11%	4.39
China	15.86	30%	28.70	55%	7.54	15%	52.10

eventually delivered to and consumed in a different province. For instance, our results show that 184 million m^3 yr^{-1} groundwater depletion was transferred from Xinjiang to Beijing in which 12.6% passed through a third province. Approximately ∼70% groundwater depletion for production uses (excluding groundwater depletion export) was embodied in industrial and tertiary products for final consumption of domestic consumers. These findings highlight the importance of including intermediate, industrial, and tertiary virtual water to accurately represent the supply chain water use. Thus, our MRIO-based approach, coupled with spatially resolved groundwater use modeling, is an advancement upon previous virtual groundwater studies that only include agricultural commodities (Dalin et al., 2017, 2019; Marston et al., 2015). It should be noted that there are multiple uncertainty sources, and uncertainty in this groundwater depletion along the supply chain should not be neglected (see Discussion and Supporting Information S1 for detailed analysis).

3.3. Groundwater Depletion Embedded in China's Exports

China plays a crucial role in the global economy. Export, which made up ~21% of China's GDP, has led to ~56 billion $m^3\ yr^{-1}$ virtual water export, containing ~8.6 billion $m^3\ yr^{-1}$ groundwater and ~4.8 billion $m^3\ yr^{-1}$ groundwater depletion in 2012. The groundwater depletion export via international trade comprised ~7% of China's total groundwater depletion. The groundwater depletion embedded in the international export represented ~9% China's exported virtual water. According to global assessments, about two-fifths of global blue virtual water trade in agricultural products are from unsustainable water sources (often groundwater depletion, Dalin et al., 2017). China's exported virtual water relied less on groundwater depletion. However, in the most heavily overexploited regions, the proportion of virtual water export attributed to groundwater depletion reached one third (i.e., Hebei, Shanxi, Henan, and Beijing). Groundwater export from China contributed to intensifying the trade-associated groundwater depletion at the global scale.

Groundwater depletion was exported primarily in the form of the industrial and tertiary products, which comprised respective shares of ~84% and ~11% of the total groundwater depletion export (Table S4 in Supporting Information S1). Most of the depleted groundwater stemmed from agricultural water use (~53%, Figure 5a), which was then incorporated into the production chains of processed food and other commodities. The inclusion of intermediate and nonagricultural groundwater use made our estimate of China's groundwater depletion export (4.8 billion $m^3\ yr^{-1}$) much higher than a previous estimate (0.3 billion $m^3\ yr^{-1}$, Dalin et al., 2017). "Garments, leather, furs, down and related products," "Textile industry," and "food and tobacco processing" were the three detailed industrial sectors containing the most consumption-based groundwater depletion embedded in exported products with each sector alone contributing to more groundwater depletion export than agricultural products. International importers mainly received China's groundwater in the trade of industrial products, highlighting the importance of analyzing groundwater depletion along the full supply chain. In addition, as a result of disaggregated production chains among different provinces in China, while the groundwater depletion embedded in export was originally from groundwater depleted in North China (i.e., Xinjiang, Hebei, Henan, and Heilongjiang, Figure 5a), the products embodying groundwater depletion were mostly exported from the international harbors along the coastlines (i.e., Guangdong, Shandong, Jiangsu, and Zhejiang, Figure 5b).

4. Discussion

Our study simulates groundwater depletion embedded in the supply chain through quantifying both the physical and virtual water cycles. Our estimate of China's national groundwater withdrawal based on physical water cycle simulation is close to previous estimates. For instance, Döll et al. (2014) estimated China's total groundwater use to be ~90 billion $m^3\ yr^{-1}$ between 2000 and 2009, whereas our estimate is 107 ~113 billion $m^3\ yr^{-1}$ between 2006 and 2015. Importantly, our approach additionally ensures that provincial-level estimates are consistent with the provincial statistics provided by China Water Resources Bulletin, which other national-scale studies do not. Specifically, we ensure that pixels contained within each province sum to the water use information of that province. We quantify virtual blue water embedded in the interprovincial trade and export (about 182 and 56 billion m^3, respectively, see Figure S3 in Supporting Information S1), which is generally consistent with estimates in previous studies (Sun et al., 2017; C. Zhang & Anadon, 2014; Zhao et al., 2015).

We use the best of available information to conduct this national groundwater analysis, which aims at characterizing the general spatial pattern of groundwater withdrawal and depletion from both the production and consumption perspectives. We recognize uncertainty in our simulation results due to the existence of various uncertainty sources, given the large scale of the analysis and high-resolution sectoral and spatial data required in this study.

Grid-level water availability and withdrawal are disaggregated based on provincial statistics and multiple-sourced information, following Ma et al. (2020). Uncertainty in these two high-resolution data sets has to be recognized because of uncertainty in the multisourced data. Compared to water availability and withdrawal estimations in the global hydrological model-based simulations using the FAO AQUASTAT country-specific data (Huang et al., 2018; Schewe et al., 2014; Veldkamp et al., 2015; Wada et al., 2014), the uses of subnational statistics (e.g., provincial-level data) and validation with more gauging measurements (including both climatic forcing and streamflow data) in China (X. Zhang et al., 2014) allow more accurate high-resolution water availability and

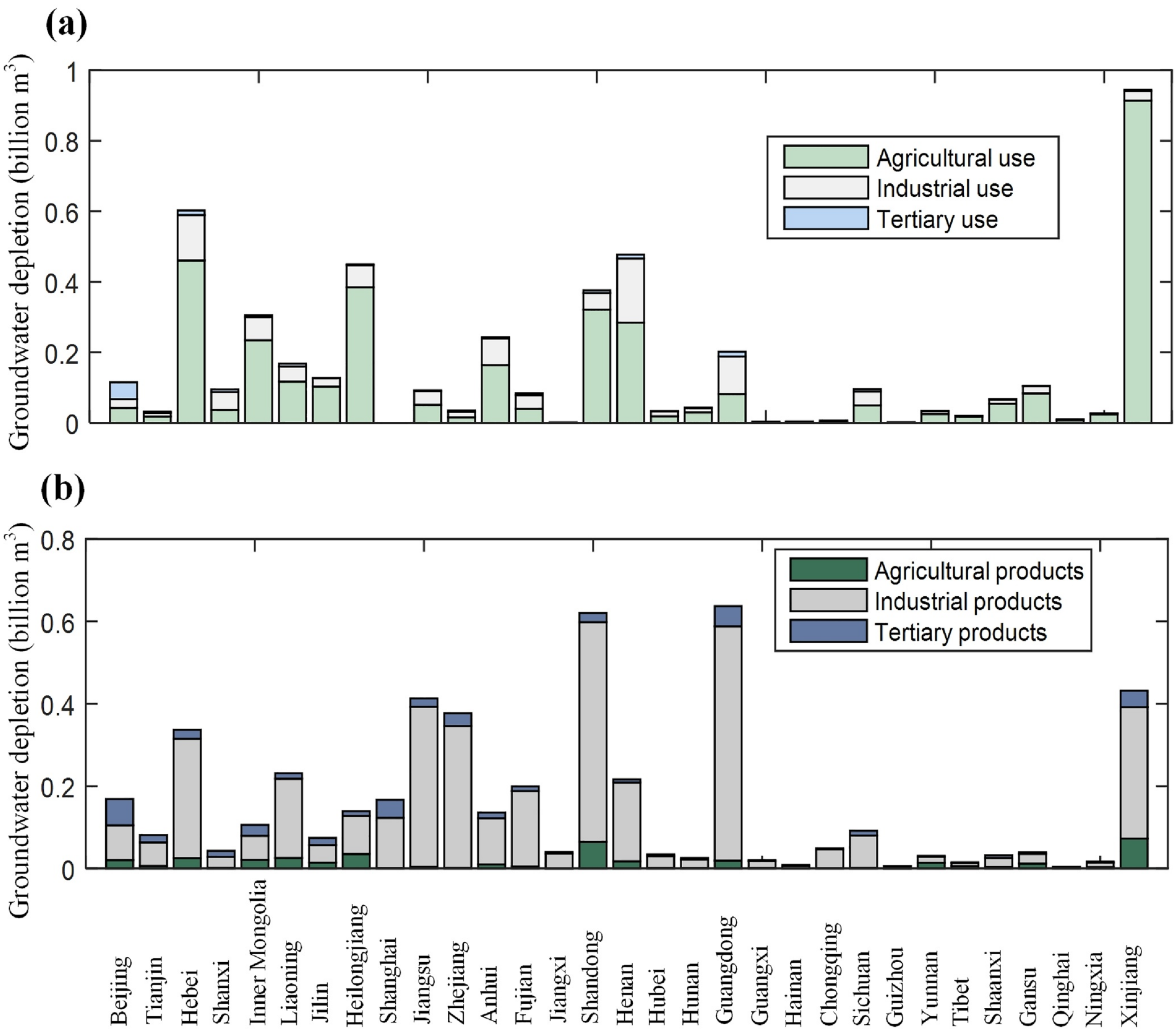

Figure 5. China's groundwater depletion embedded in sectoral products for international trade (4.8 billion m^3 yr^{-1}): (a) Sectors and locations where groundwater depletion firstly entered the Chinese supply chain and (b) provinces from which the sectoral products were exported.

withdrawal downscaling (Ma et al., 2020). Albeit uncertainty, the general spatial pattern of water availability and withdrawal can be well captured.

Basin-scale analyses have often been criticized for not being able to capture spatial variation of water availability and demand within basins (Mekonnen & Hoekstra, 2016). To address this issue, we account for upstream-downstream hydrographic information between pixels, which represents the state of the art for representing subbasin water availability and demand (Mekonnen & Hoekstra, 2016). The grid cell is 0.25 arc-degree (~25 km), so the inter-grid water transfer is subject to corresponding costs. Interbasin water transfer amounted to ~4.5% of national water supply by 2012 (Sun et al., 2021; Zhao et al., 2015). Unfortunately, there are not sufficient data on fine-scale water transfers to explicitly incorporate them into this grid-based study. Water supply from interbasin water transfer is included in the surface water supply in provincial-level statistics. Our rescaling procedure forced the groundwater withdrawal simulation results to conform with provincial statistics, which means that this lack of spatially explicit fine-scale physical transfers information should not significantly impact the results, although information on fine-scale surface water transfers would improve the accuracy of our grid-level estimates. Despite the lack of information on lateral groundwater flow between grids, a shortcoming shared by most groundwater use models at large spatial scales (Aeschbach-Hertig & Gleeson, 2012), the model generally simulates the rate of change in groundwater storage fairly well at the global scale (Pokhrel et al., 2016) and in China (Tang et al., 2013). We recognize uncertainty in the grid-level groundwater withdrawal simulation by not accounting for water transfer and dynamic responses of water systems to human water withdrawal.

When simulating grid-level surface and groundwater withdrawals, 80% of the surface water availability at a grid is appropriated for environmental flow requirement, which is a rather subjective assumption. The surface water and groundwater withdrawals at the grid scale in one province are then rescaled to force the grid-level simulations to be equal to provincial statistics. The sensitivity analysis shows that the simulated provincial-level groundwater depletion volume is not sensitive to the assumed share of surface water availability for human water use appropriation because the rescaling step is applied to make provincial-level groundwater withdrawal equal to corresponding statistics (Text S1 and Figure S5 in Supporting Information S1).

When disaggregating provincial-level industrial and domestic groundwater withdrawal (or depletion) into subsectoral values, it is assumed that subsectoral groundwater withdrawal (or depletion) is proportional to provincial subsectoral water demands. This assumption does not take into account the spatial difference of subsectoral groundwater withdrawal (or depletion) and may lead to biased assessment of groundwater withdrawal (or depletion) embedded in sectoral products. We use a Monte Carlo-based approach to analyze uncertainty in the estimates of groundwater depletion embedded in the interprovincial transfer and export. The results show that uncertainty due to disaggregation of subsectoral water depletion is relatively small, given the aggregated industrial and tertiary groundwater depletion (see Text S1 and Figure S6 in Supporting Information S1).

In the MRIO analysis, one uncertainty comes from the effect of sector aggregation (Lenzen, 2011; Oita et al., 2016). Water withdrawals for various crops and livestock production are considered as one aggregated agricultural water use, the water use intensities of which are assumed the same in the MRIO analysis, possibly leading to uncertainty in the assessment of virtual water transfers and consumption-based water footprints/depletion. This uncertainty can be attributed to the sector deviation in China's MRIO table, which is commonly shared by all the MRIO-based environmental footprint studies in China (Sun & Fang, 2019; Zhao et al., 2015). Ideally, this uncertainty can be reduced by utilizing MRIO data with high-resolution sectors.

Groundwater protection is high on the policy agenda in China. Existing policies have mostly focused on restricting direct groundwater depletion and preventing groundwater pollution. Since 2014, the South-to-North Water Diversion Project has delivered water via vast infrastructure to alleviate groundwater overexploitation (at high economic and environmental costs). In addition to interbasin water transfer that supplements local water supply in groundwater depletion hot spots, water demand management (e.g., improving water use efficiency and producing less water intensive products) benefits sustainable groundwater use. Sectoral water use intensities of different provinces distributing in a wide range (Table S5 in Supporting Information S1) suggest the potential for water conservation in provinces with high water use intensities (Qin et al., 2019). This is particularly important for a few water scarce provinces with groundwater depletion problem (e.g., Xinjiang, Ningxia, and Qinghai) though many other provinces in water scarce North China have lower sectoral water use intensities than national average (e.g., Beijing, Tianjin, Shandong, Liaoning, and Shanxi). There is a positive rank correlation coefficient between general water use and groundwater depletion intensities in provinces (0.35, p-value = 0.05, Figure S7 in Supporting Information S1), indicating that groundwater depletion in some provinces can be alleviated by improving water use efficiency and upgrading water use structure toward less-water-intensive production. Regulation of groundwater depletion (for instance, the recent action plan for groundwater protection in North China Plain) should limit the development of water intensive industries in water scarce areas.

Groundwater is a common pool resource whose sustainable use is a collective action problem. Our analysis quantifies groundwater incorporated in the supply chain of sectoral products from production to consumption, providing a new perspective for demand-side policies and supply chain risk management. Producers and groundwater managers could signal the value of groundwater through increased prices and markets for this critical input. If groundwater was properly market-priced, then that would likely increase the price of groundwater-intensive goods, potentially leading consumers to demand less of that product and reduce groundwater pumping.

5. Concluding Remarks

This study advances our understanding of groundwater use throughout the full supply chain (primary, secondary, and tertiary products) of China using the MRIO technique combined with a model for simulating spatially explicit groundwater use and depletion. It is important to resolve the locations of groundwater withdrawal in production, because groundwater depletion leads to declines in groundwater levels, reductions in river flow discharges, land subsidence, increasing pumping costs, and eco-environmental degradation. Consumers that receive groundwater-intensive goods in their supply chain, such as those in South China, should be aware of risk from groundwater depletion upstream in their supply chain. A number of provinces in North China including Beijing, Hebei, Inner Mongolia, Henan, and Heilongjiang, are particularly exposed to the risks from groundwater depletion because they both produce and receive products made of depleted groundwater. International consumers have been particularly reliant upon China's groundwater in their import of industrial products. This knowledge could be used to inform sustainable production and consumption policies. Groundwater managers, producers, and end consumers can all have a role in the supply chain to alleviate groundwater depletion.

Our results quantify how groundwater is incorporated in the full supply chain from production to consumption, which provides a new perspective for demand-side policies and supply chain risk management. Groundwater depletion is a long-term risk to supply chains. Yet, groundwater is a common pool resource whose sustainable use is a collective action problem. This requires broad policy and management objectives to bring the use within sustainable limits to secure future supply chains. Our results have policy implications for sustainable groundwater and supply chain management. Sectoral water use intensities of different provinces distributing in a wide range suggest the potential for water conservation in a few provinces with water depletion issues.

Groundwater depletion is a global problem threatening production in many regions of the world and consumers through their reliance on global supply chains. The methodology presented in this study can be applied to trace groundwater depletion in other countries to global consumers through domestic and international supply chains. Our study focuses on analyzing spatial patterns in China's groundwater and supply chains. Data limitations often introduce uncertainties into the assessment of groundwater use and its incorporation into supply chains. Future efforts are needed to monitor high-resolution spatial and sectoral groundwater use and assess water-related risks along supply chains. Performing the time-trend analysis of groundwater depletion incorporated in China's supply chain and assessing the policies and measures for mitigation of groundwater depletion are also important areas for future research.

Data Availability Statement

Provincial-level water availability data, water withdrawal data for agricultural, industrial, domestic, and eco-environmental compensation sectors, and water withdrawal from surface water and groundwater are available from China Water Resources Bulletin at http://www.mwr.gov.cn/sj/tjgb/szygb. Water resources availability simulation data by the VIC hydrologic model are referenced from X. Zhang and Tang (2014) and can be downloaded at http://hydro.igsnrr.ac.cn. Grid-level sectoral water withdrawal data are referenced from Ma et al. (2020). Hydrography information is referenced from Wu et al. (2011), and the Global Dominant River Tracing-based hydrography data sets are freely available at ftp://ftp.ntsg.umt.edu/pub/data/DRT/. The MRIO data are referenced from Liu et al. (2018). Provincial groundwater withdrawal and groundwater depletion for agricultural, industrial, and domestic uses as well as sectoral-level groundwater depletion embedded in virtual water transfer and international export are provided in Supporting Information S1 of this paper.

Acknowledgments
This study was supported by the Second Tibetan Plateau Scientific Expedition and Research Program (2019QZKK1005), National Natural Science Foundation of China (42071272), and the Program for "Kezhen Bingwei" Excellent Talents in Institute of Geographic Sciences and natural Resources Research.

References

Aeschbach-Hertig, W., & Gleeson, T. (2012). Regional strategies for the accelerating global problem of groundwater depletion. *Nature Geoscience*, *5*(12), 853–861. https://doi.org/10.1038/ngeo1617
Allan, J. A. (1998). Virtual water: A strategic resource. Global solutions to regional deficits. *Groundwater*, *36*(4), 545–546. https://doi.org/10.1111/j.1745-6584.1998.tb02825.x
Cai, X. (2008). Water stress, water transfer and social equity in Northern China implications for policy reforms. *Journal of Environmental Management*, *87*(1), 14–25. https://doi.org/10.1016/j.jenvman.2006.12.046
Castle, S., Thomas, B., Reager, J., Rodell, M., Swenson, S., & Famiglietti, J. (2014). Groundwater depletion during drought threatens future water security of the Colorado River Basin. *Geophysical Research Letters*, *41*(16), 5904–5911. https://doi.org/10.1002/2014gl061055

Dalin, C., Hanasaki, N., Qiu, H., Mauzerall, D. L., & Rodriguez-Iturbe, I. (2014). Water resources transfers through Chinese interprovincial and foreign food trade. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(27), 9774–9779. https://doi.org/10.1073/pnas.1404749111

Dalin, C., Taniguchi, M., & Green, T. R. (2019). Unsustainable groundwater use for global food production and related international trade. *Global Sustain*, *2*, e12. 1–11. https://doi.org/10.1017/S2059479819000073

Dalin, C., Wada, Y., Kastner, T., & Puma, M. J. (2017). Groundwater depletion embedded in international food trade. *Nature*, *553*(7688), 366. https://doi.org/10.1038/nature24664

Döll, P., Hoffmann-Dobrev, H., Portmann, F. T., Siebert, S., Eicker, A., Rodell, M., et al. (2012). Impact of water withdrawals from groundwater and surface water on continental water storage variations. *Journal of Geodynamics*, *59*, 143–156. https://doi.org/10.1016/j.jog.2011.05.001

Döll, P., Müller, S. H., Schuh, C., Portmann, F. T., & Eicker, A. (2014). Global-scale assessment of groundwater depletion and related groundwater abstractions: Combining hydrological modeling with information from well observations and GRACE satellites. *Water Resourources Research*, *50*(7), 5698–5720. https://doi.org/10.1002/2014wr015595

Famiglietti, J. (2014). The global groundwater crisis. *Nature Climate Change*, *4*(11), 945–948. https://doi.org/10.1038/nclimate2425

Fang, C., Sun, S., Jia, S., & Li, Y. (2019). Groundwater level analysis using regional Kendall test for trend with spatial autocorrelation. *Groundwater*, *57*(2), 320–328. https://doi.org/10.1111/gwat.12800

Garcia, S., Gomez, M., Rushforth, R., Ruddell, B. L., & Mejia, A. (2021). Multilayer network clarifies prevailing water consumption telecouplings in the United States. *Water Resources Research*, *57*(7), e2020WR029141. https://doi.org/10.1029/2020wr029141

Garcia, S., Rushforth, R., Ruddell, B., & Mejia, A. (2020). Full domestic supply chains of blue virtual water flows estimated for major U.S. Cities. *Water Resources Research*, *56*(4), e2019WR026190. https://doi.org/10.1029/2019wr026190

Gleeson, T., Guthbert, M., Ferguson, G., & Perrone, D. (2020). Global groundwater sustainability, resources, and systems in the Anthropocene. *Annual Review of Earth and Planetary Sciences*, *48*(17), 1–17. https://doi.org/10.1146/annurev-earth-071719-055251

Gleeson, T., Wada, Y., Bierkens, M. F. P., & van Beek, L. P. H. (2012). Water balance of global aquifers revealed by groundwater footprint. *Nature*, *488*(7410), 197–200. https://doi.org/10.1038/nature11295

Gumidyala, S., Ruess, P. J., Konar, M., Marston, L., Dalin, C., & Wada, Y. (2020). Groundwater depletion embedded in transfers and exports of the United States. *Water Resources Research*, *56*(2), e2019WR024986. https://doi.org/10.1029/2019wr024986

Hoekstra, A., Chapagain, A., Aldaya, M., & Mekonnen, M. (2011). *The water footprint assessment manual*. Earthscan.

Huang, Z., Hejazi, M., Li, X., Tang, Q., Leng, G., Liu, Y., et al. (2018). Reconstruction of global gridded monthly sectoral water withdrawals for 1971-2010 and analysis of their spatiotemporal patterns. *Hydrology and Earth System Sciences*, *22*(4), 1–30. https://doi.org/10.5194/hess-22-2117-2018

Lenzen, M. (2011). Aggregation versus disaggregation in input-output analysis of the environment. *Economic Systems Research*, *12*(1), 73–89. https://doi.org/10.1080/09535314.2010.548793

Lin, J., Tang, D., Davis, S., Ni, R., Tan, X., Pan, D., et al. (2016). Global climate forcing of aerosols embodied in international trade. *Nature Geoscience*, *9*(10), 790–794. https://doi.org/10.1038/ngeo2798

Liu, W., Tang, Z., & Han, M. (2018). *The 2012 China multi-regional input-output table of 31 provincial units*. China Statistics Press.

Ma, T., Sun, S., Fu, G., Hall, J. W., Ni, Y., He, L., et al. (2020). Pollution exacerbates China's water scarcity and its regional inequality. *Nature Communications*, *11*(1), 650. https://doi.org/10.1038/s41467-020-14532-5

Marston, L., Ao, Y., Konar, M., Mekonnen, M. M., & Hoekstra, A. Y. (2018). High-resolution water footprints of production of the United States. *Water Resources Research*, *54*(3), 2288–2316. https://doi.org/10.1002/2017wr021923

Marston, L., & Konar, M. (2017). Drought impacts to water footprints and virtual water transfers of the Central Valley of California. *Water Resources Research*, *53*(7), 5756–5773. https://doi.org/10.1002/2016wr020251

Marston, L., Konar, M., Cai, X., & Troy, T. (2015). Virtual groundwater transfers from overexploited aquifers in the United States. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(28), 8561–8566. https://doi.org/10.1073/pnas.1500457112

Martina, F., Schneider, C., & McDonald, R. (2018). Water competition between cities and agriculture driven by climate change and urban growth. *Nature Sustainability*, *1*, 51–58. https://doi.org/10.1038/s41893-017-0006-8

Mekonnen, M., & Hoekstra, A. (2016). Four billion people facing severe water scarcity. *Science Advances*, *2*, e1500323. https://doi.org/10.1126/sciadv.1500323

Morris, B. L., Lawrence, A. R. L., Chilton, P. J. C., Adams, B., Calow, R. C., & Klinck, B. A. (2003). *Groundwater and its susceptibility to degradation: A global assessment of the problem and options for management*. UNEP.

Munia, H., Guillaume, J. N., MirumachiPorkka, M., Wada, Y., & Kummu, M. (2016). Water stress in global transboundary river basins: Significance of upstream water use on downstream stress. *Environmental Research Letters*, *11*(1), 014002. https://doi.org/10.1088/1748-9326/11/1/014002

MWRC. (2006–2015). *Ministry of water resources of the people's Republic of China) China water resources bulletin 2006-2015*. China water & Power Press.

Oita, A., Malik, A., Kanemoto, K., Geschke, A., Nishijima, S., & Lenzen, M. (2016). Substantial nitrogen pollution embedded in international trade. *Nature Geoscience*, *9*(2), 111–115. https://doi.org/10.1038/ngeo2635

Pokhrel, Y., Hanasaki, N., Wada, Y., & Kim, H. (2016). Recent progresses in incorporating human land–water management into global land surface models toward their integration into Earth system models. *WIREs Water*, *3*(4), 548–574. https://doi.org/10.1002/wat2.1150

PWRB (Provincial Water Resources Bureau). (2012). *Provincial water resource bulletin 2012*. (in Chinese).

Qin, Y., Mueller, N., Siebert, S., Jackson, R., Aghakouchak, A., Zimmerman, J., et al. (2019). Flexibility and intensity of global water use. *Nature Sustainability*, *2*(6), 515–523. https://doi.org/10.1038/s41893-019-0294-2

Richter, B. D., Bartak, D., Caldwell, P. V., Davis, K. F., Debaere, P., Hoekstra, A. Y., et al. (2020). Water scarcity and fish imperilment driven by beef production. *Nature Sustainability*, *3*(4), 319–328. https://doi.org/10.1038/s41893-020-0483-z

Scanlon, B. R., Faunt, C. C., Louguevergne, L., Reedy, R. C., Alley, W. M., McGuire, V. L., & McMahon, P. B. (2012). Groundwater depletion and sustainability of irrigation in the US high plains and central valley. *Proceedings of the National Academy of Sciences of the United States of America*, *109*(24), 9320–9325. https://doi.org/10.1073/pnas.1200311109

Schewe, J., Heinke, J., Gerten, D., Haddeland, I., Arnell, N. W., Clark, D. B., et al. (2014). Multimodel assessment of water scarcity under climate change. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(9), 3245–3250. https://doi.org/10.1073/pnas.1222460110

SCLGOSCEC (the State Council Leading Group Office of Second China Economic Census). (2008). *Chinese economic Census Yearbook 2008*. China Statistics Press.

Siebert, S., Burke, J., Faures, J. M., Frenken, K., Hoogeveen, J., Doll, P., & Portmann, F. T. (2010). Groundwater use for irrigation—A global inventory. *Hydrology and Earth System Sciences*, *14*(10), 1863–80. https://doi.org/10.5194/hess-14-1863-2010

Steward, D., Bruss, P., Yang, X., Staggenborg, S., Welch, S., & Apley, M. (2013). Tapping unsustainable groundwater stores for agricultural production in the High Plains Aquifer of Kansas, projections to 2110. *Proceedings of the National Academy of Sciences of the United States of America*, E3477–E3486. https://doi.org/10.1073/pnas.1220351110

Sun, S., Bao, C., & Tang, Z. (2019). Tele-connecting water consumption in Tibet: Patterns and socioeconomic driving factors for virtual water trades. *Jounal of Cleaner Production*, *233*, 1250–1258. https://doi.org/10.1016/j.jclepro.2019.06.141

Sun, S., & Fang, C. (2019). Factors governing variations of provincial consumption-based water footprints in China: An analysis based on comparison with national average. *The Science of the Total Environment*, *654*, 914–923. https://doi.org/10.1016/j.scitotenv.2018.11.114

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. *Journal of Hydrology*, *553*, 398–407. https://doi.org/10.1016/j.jhydrol.2017.08.020

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 Research*, *194*, 116931. https://doi.org/10.1016/j.watres.2021.116931

Tang, Q., Zhang, X., & Tang, Y. (2013). Anthropogenic impacts on mass change in North China. *Geophysical Research Letters*, *40*(15), 3924–3928. https://doi.org/10.1002/grl.50790

UNDP (United Nations Development Programme) (2006). *Human Development Report 2006 beyond scarcity: Power, poverty and the global water crisis*. Palgrave Macmillan.

Vanham, D., Comero, S., Gawlik, B., & Bidoglio, G. (2018). The water footprint of different diets within European sub-national geographical entities. *Nature Sustainability*, *1*(9), 518–525. https://doi.org/10.1038/s41893-018-0133-x

Veldkamp, T., Wada, Y., de Moel, H., Kummu, M., Eisner, S., Aerts, J., & Ward, P. J. (2015). Changing mechanism of global water scarcity events: Impacts of socioeconomic changes and inter-annual hydro-climatic variability. *Global Envivonmental Change*, *32*, 18–29. https://doi.org/10.1016/j.gloenvcha.2015.02.011

Wada, Y., van Beek, L., & Bierkens, M. (2012). Nonsustainable groundwater sustaining irrigation: A global assessment. *Water Resources Research*, *48*(6), W00L06. https://doi.org/10.1029/2011wr010562

Wada, Y., van Beek, L., Kempen, C., Reckman, J., Vasak, S., & Bierkens, M. (2010). Global depletion of groundwater resources. *Geophysical Research Letters*, *37*(20), L20402. https://doi.org/10.1029/2010gl044571

Wada, Y., van Beek, L., Weiland, S., Chao, B. F., Wu, Y.-H., & Bierkens, M. (2012). Past and future contribution of global groundwater depletion to sea-level rise. *Geophysical Research Letters*, *39*(9), L09402. https://doi.org/10.1029/2012gl051230

Wada, Y., Wisser, D., & Bierkens, M. (2014). Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources. *Earth System Dynamics*, *5*(1), 15–40. https://doi.org/10.5194/esd-5-15-2014

Wiedmann, T., & Lenzen, M. (2018). Environmental and social footprints of international trade. *Nature Geoscience*, *11*(5), 314–321. https://doi.org/10.1038/s41561-018-0113-9

Wiedmann, T. O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., & Kanemoto, K. (2015). The material footprint of nations. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(20), 6271–6276. https://doi.org/10.1073/pnas.1220362110

Wu, H., Kimball, J. S., Mantua, N., & Stanford, J. (2011). Automated upscaling of river networks for macroscale hydrological modeling. *Water Resources Research*, *47*(3), W03517. https://doi.org/10.1029/2009WR008871

Xu, Z., Li, Y., Chau, S. N., Dietz, T., Li, C., Wan, L., et al. (2020). Impacts of international trade on global sustainable development. *Nature Sustainability*, *3*(11), 964–971. https://doi.org/10.1038/s41893-020-0572-z

Zhang, C., & Anadon, L. D. (2014). A multi-regional input-output analysis of domestic virtual water trade and provincial water footprint in China. *Ecological Economics*, *100*(2), 159–172. https://doi.org/10.1016/j.ecolecon.2014.02.006

Zhang, X., & Tang, Q. (2014). A long-term land surface hydrologic fluxes and states dataset for China. *Journal of Hydrometeorology*, *15*, 2067–2084.

Zhang, X., Tang, Q., Pan, M., & Tang, Y. (2014). A long-term land surface hydrologic fluxes and states dataset for China. *Journal of Hydrometeorology*, *15*(5), 2067–2084. https://doi.org/10.1175/jhm-d-13-0170.1

Zhang, Z., Shi, M., & Yang, H. (2012). Understanding Beijing's water challenge: A decomposition analysis of changes in Beijing's water foot print between 1997 and 2007. *Environmental Science & Technology*, *46*(22), 12373–2380. https://doi.org/10.1021/es302576u

Zhao, X., Liu, J., Liu, Q., Tillotson, M. R., Guan, D., & Hubacke, K. (2015). Physical and virtual water transfers for regional water stress alleviation in China. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(4), 1031–1035. https://doi.org/10.1073/pnas.1404130112