Physical and virtual water transfers for regional water stress alleviation in China

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Water can be redistributed through, in physical terms, water transfer projects and virtually, embodied water for the production of traded products. Here, we explore whether such water redistributions can help mitigate water stress in China. This study, for the first time to our knowledge, both compiles a full inventory for physical water transfers at a provincial level and maps virtual water flows between Chinese provinces in 2007 and 2030. Our results show that, at the national level, physical water flows because of the major water transfer projects amounted to 4.5% of national water supply, whereas virtual water flows accounted for 35% (varies between 11% and 65% at the provincial level) in 2007. Furthermore, our analysis shows that both physical and virtual water flows do not play a major role in mitigating water stress in the water-receiving regions but exacerbate water stress for the water-exporting regions of China. Future water stress in the main water-exporting provinces is likely to increase further based on our analysis of the historical trajectory of the major governing socioeconomic and technical factors and the full implementation of policy initiatives relating to water use and economic development. Improving water use efficiency is key to mitigating water stress, but the efficiency gains will be largely offset by the water demand increase caused by continued economic development. We conclude that much greater attention needs to be paid to water demand management rather than the current focus on supply-oriented management.

water transfer | virtual water | regional water stress | multiregional input–output analysis

The geographical mismatch between freshwater demand and available freshwater resources is one of the largest threats to sustainable water supply in China (1) and throughout the world. It is well-known that China has a temperate south and an arid north (2). The North China Plain shows the greatest water scarcity, with per capita water availability under 150 m^3/y (3–5). At the same time, this area is home to 200 million people and provides more than one-half of China's wheat and one-third of its maize (6). Recognizing such a mismatch, China has been developing over 20 major physical water transfer projects with a total length of over 7,200 km (6), including the world's largest—the South–North Water Transfer Project (SNWTP) (7). Three routes are projected in the SNWTP, which will ultimately transfer 44.8 Gm^3 water from the Yangtze River Basin to the Huang-Huai-Hai River Basin annually, of which 14.8 Gm^3 is for the East Route, 13 Gm^3 is for the Middle Route, and 17 Gm^3 is for the West Route (7). After completion of the three routes, the transferred water is projected to amount to 30.5% of total water withdrawal in the Huang-Huai-Hai River Basin in 2012 (the latest available statistic) (8).

Apart from these major physical water transfer projects, there is another solution to remedy regional water scarcity—so-called virtual water (9–11). The virtual water concept, first introduced by Allan (12), is the water required for the production of goods and services along their supply chains (13). Based on this concept, water-scarce regions import water-intensive products instead of producing them locally, thus conserving local water resources (12, 14). Because the SNWTP has proved highly controversial in its potential impacts on both exporting and importing river ecosystems and its huge capital cost (~$60 US billion), scholars have suggested that the North China Plain should, instead, reduce the export of water-intensive products or even import virtual water from southern China (11, 13, 15–17). An important question is if such redistributions can be effective in mitigating regional water stress in China.

To answer this question, we report here on our quantification of China's physical and virtual water flows at the provincial level for the year 2007. We have used the most recent interregional trade data and evaluated the associated impacts on water stress. To calculate virtual water flows, we have calculated water use throughout the entire supply chain in China. The study focused on 30 provincial-level administrative regions (provinces, autonomous regions, and municipalities—for simplicity, they are referred to as provinces) (names are shown in *SI Appendix*, Fig. S1) in mainland China where data were available. The volume of physical water transfer for each province was acquired through the Water Resources Bulletin of the studied provinces (4). To study virtual water flows, we incorporated the direct water use of 30 economic sectors of each province into an environmental extended multiregion input–output (MRIO) model (18, 19) (*Methods*). An MRIO model distinguishes production structure, technology, and consumption for each study area and shows flows of goods and services between and within regions; thus, it is ideally suited for measuring interregional virtual water flows (20, 21). The virtual water trade generated by final consumption was evaluated using the emissions embodied in trade method (22). Water stress was evaluated using the water stress index (*WSI*) (10, 23, 24). Moderate, severe, and

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Significance

Freshwater resources are unevenly distributed in China. This situation drives a significant amount of water flow both physically and virtually across China. Here, we report on our quantification of China's physical and virtual water flows and associated water stress at the provincial level. In 2007, interprovincial physical water flows amounted to only a small part of China's total water supply, but virtual water flows amounted to over one-third of supply. We found that both physical and virtual water flows exacerbated water stress for the main water-exporting provinces. The results highlight the need for more emphasis to be placed on water demand management rather than the current focus on supply-oriented management.

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extreme water stresses occur when the ratio of the annual freshwater withdrawal to the renewable freshwater resource is 20–40%, 40–100%, and over 100%, respectively.

Results

***WSI*.** Our results show that 23 of 30 studied Chinese provinces had at least moderate water stress ($WSI > 0.2$), with 6 provinces showing extreme water stress ($WSI > 1$; i.e., they consumed more than the available annual renewable amount of freshwater). Fig. 1 shows that water is scarcer in northern China, whereas parts of southern China are also not spared water stress. Six provinces in southern China show levels of moderate water stress, and two provinces show extreme water stress.

Physical and Virtual Water Transfers. Fig. 1 shows the provinces relying on physical water transfers. In 2007, physical water flows by water transfer projects amounted to 26.3 Gm^3, accounting for 4.5% of national water supply in China. The magnitude of virtual water flows was much larger than the physical water transfers. The total volume of virtual water flows was 201 Gm^3 in 2007 (i.e., 35% of the national water supply was used for interprovincial virtual water trade). Fig. 2 shows the net virtual water balance and illustrates the major virtual water flows between eight economic regions. Virtual water flowed from the economically poor and less populated west to the more affluent and densely populated coastal areas of the east, where most of China's megacities are located. A small number of provinces was responsible for most of the net virtual water imports and exports. The top five importing provinces (Shandong, Shanghai, Guangdong, Zhejiang, and Tianjin, which are all coastal) accounted for 74% of net virtual water imports, whereas 78% of net virtual water exports were from five provinces (Xinjiang, Heilongjiang, Inner Mongolia, Guangxi, and Hunan).

Impacts on Water Stress Through Virtual and Physical Water Transfers. Water stress is calculated as the ratio of water withdrawal to renewable freshwater resources within a province. We have distinguished between actual water stress (*WSI*) and hypothetical water stress (WSI^*) (Eq. **2**), which refers to the hypothetical water stress on the local hydroecosystem if the importing province was not to have physical and virtual water inflows available to it (i.e., it would be required to withdraw all required water from local sources). Therefore, the difference between WSI^* and *WSI* represents the contribution of net virtual and physical water flows in terms of increasing or ameliorating water stress (Eq. **3**). Our results showed that 12 water-stressed provinces benefited from net virtual and physical water imports ($WSI^* > WSI$). The net water imports of these 12 provinces included 80 Gm^3 virtual water and 5 Gm^3 physical water. Although the water stress caused by final consumption (WSI^*) in these provinces was ameliorated, the water stress to local water resources (*WSI*) was still considerable (Fig. 3), with all 12 provinces remaining at the same category of water stress, despite virtual and physical water imports.

Meanwhile, for 11 already water-stressed provinces, the situation was further compounded through net virtual and physical water exports ($WSI^* < WSI$). Some 81 Gm^3 water was exported from these provinces. In Fig. 3, we see that net water exports pushed six water-exporting provinces (Heilongjiang, Inner Mongolia, Xinjiang, Guangxi, Hunan, and Jiangxi) over their respective water stress thresholds to the next more serious level (e.g., the first three provinces are listed from moderate to severe, and the latter three provinces and listed from no stress to moderate stress). This result implies that these provinces used a large share of local water to produce their exports, despite the water stress situation (*SI Appendix*, Fig. S4). Furthermore, these water-stressed provinces virtually exported more water (44% of water supply, on average, for virtual water export; ranging from 26% to 74%) compared with the provinces that showed no water stress (30% of water supply for virtual water export at the national level; ranging from 15% to 48% at the provincial level).

Future Water Stress Levels. Given the current water imbalance and the trend for increased water demand, water management will face even greater challenges in the future. Thus, we developed two simple scenarios to investigate the change of water stress and the possible ways of mitigating it.

A reference scenario was created based on the trajectory of a series of factors that play important roles in determining the

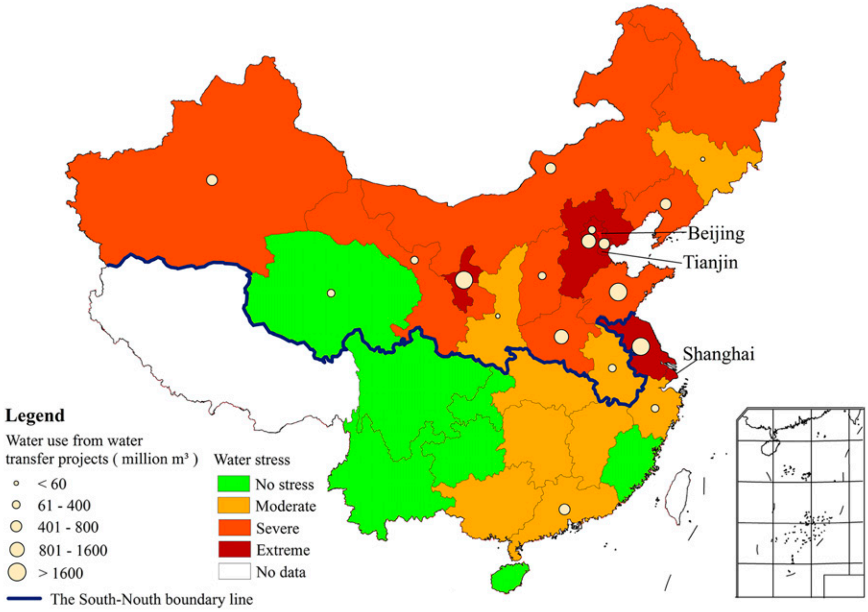

Fig. 1. Water stress evaluation of China's provinces (2007 baseline). The color coding of the regions distinguishes between moderate water stress, severe water stress, extreme water stress, and no water stress. The size of the dots reflects the amount of physical water transfer, and the color code reflects the extent of water stress. The south–north boundary line for provinces was drawn based on an acknowledged south–north dividing line (35).

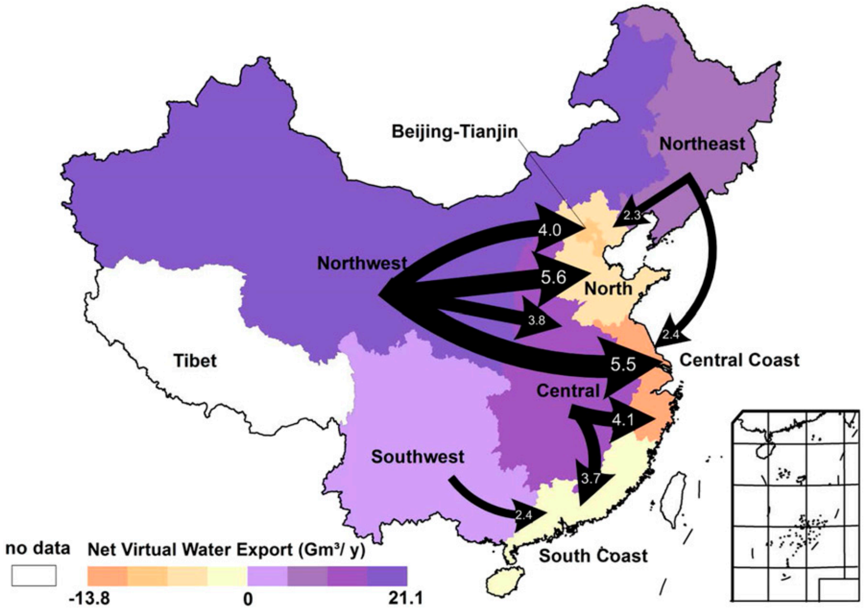

Fig. 2. Virtual water balance per economic region and the net direction of virtual water flows (2007 baseline). Only the largest net virtual water flows are shown (>2 Gm^3/y).

level of water stress. These factors included economic development, population growth, water use efficiency, and water transfer projects at the provincial level (*SI Appendix*). The production and consumption structure and trade flows for 2007 were updated to 2030 based on the projections of future population and changes to per capita income, consumption patterns, and technical and economic structure and in consideration to provincial economic disparities and future water use efficiencies (details in *SI Appendix*).

In the reference scenario, 21 provinces would continue to increase their *WSI*. However, the top five net virtual water-importing provinces in 2007 (Shandong, Shanghai, Guangdong, Zhejiang, and

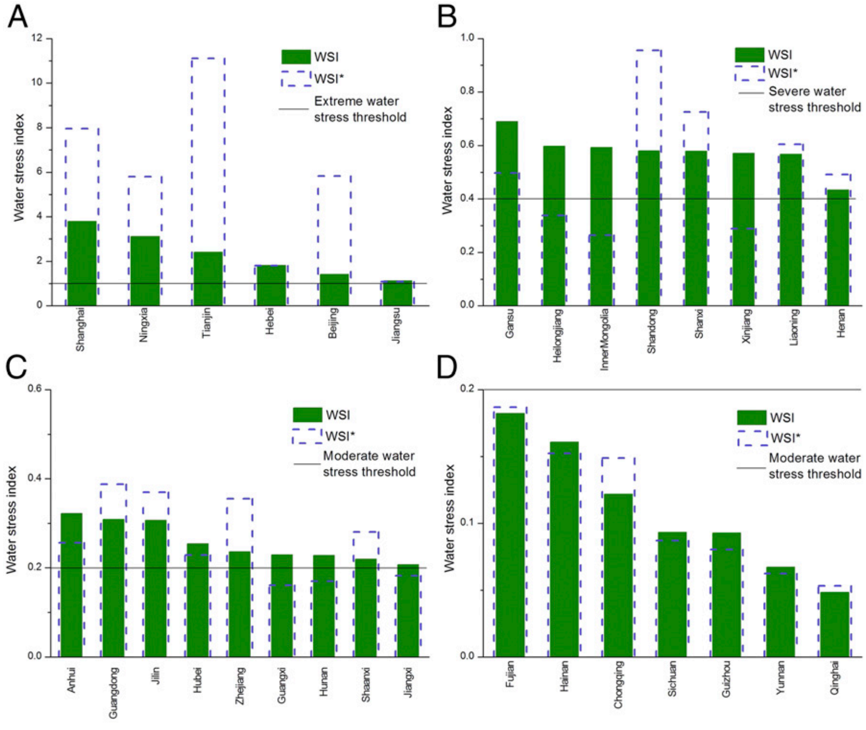

Fig. 3. Comparison of *WSI* and *WSI** of 30 Chinese provinces with different levels of water stress. The provinces are arranged in order of decreasing *WSI*: (*A*) provinces with extreme water stress, (*B*) provinces with severe water stress, (*C*) provinces with moderate water stress, and (*D*) provinces with no water stress. When *WSI** is higher than *WSI*, the province is a net virtual and physical water importer and has mitigated its water stress through net imports. When *WSI** is lower than *WSI*, the province is a net virtual and physical water exporter and has aggravated its water stress through net export.

Tianjin) would decrease their *WSI* in 2030, whereas the *WSI** of these five provinces would show an increase, reflecting an increasing dependence on external water import.

We further proposed a policy scenario to understand the effect of a restrictive water policy in mitigating water stress. This scenario was based on the most significant water-related policy in recent years adopted as the Central Document No. 1 in 2011 (1, 25, 26), which introduces water use caps (so-called water use redlines) for all Chinese provinces for 2030 (*SI Appendix*, Table S12).

According to the policy scenario, the total water use cap would be 700 Gm^3, 3.3% (24 Gm^3) lower than the water use projected in the reference scenario. However, at the provincial level, the *WSI* in 2030 would generally increase from the 2007 level, except in four provinces (Beijing, Tianjin, Guangdong, and Hebei), where the indicator would show only a minor drop (*SI Appendix*, Table S13). Compared with the reference scenario, the *WSI* values of 17 provinces in the policy scenario are even larger. The largest difference is seen for Zhejiang, where the *WSI* in the policy scenario (0.28) is 87% larger than in the reference scenario (0.15). This result implies that these provinces must be given more stringent water use redline caps to decrease their *WSI*. Meanwhile, the *WSI* of the remaining provinces would be smaller in the policy scenario than in the reference scenario, suggesting that these provinces have to introduce stricter water management strategies than in the past to decrease their water use to meet the water use caps in 2030 (*SI Appendix*, Table S13).

Discussion

Unsustainable Water Transfer. Huge physical water transfer projects and virtual water flows through trade activities within China significantly redistribute water among China's provinces. We have studied the extent of these water flows and the resulting impact on water stress.

In 2007, we found that several economically developed provinces (Beijing, Tianjin, Shandong, Shanghai, Zhejiang, and Guangdong) had imported large amounts of physical and virtual water to help ameliorate their water stress. In 2030, according to the reference scenario, the dependence on net virtual and physical water flows in terms of ameliorating water stress would be further intensified for these provinces, which was shown through a larger discrepancy between *WSI** and *WSI* (Eq. **3** and *SI Appendix*, Table S14). At the same time, both virtual and physical water transfers were shown to have exacerbated water stress for several water-exporting provinces in 2007, whereas in the future, the largest virtual and physical water-exporting provinces will continue to suffer from increasing water stress. In 2030, the top three virtual water-exporting provinces (Xinjiang, Heilongjiang, and Inner Mongolia) will have increased their *WSI* in both the reference and policy scenarios (*SI Appendix*, Table S13). The SNWTP will have a negative impact on the physical water-exporting provinces Hubei and Jiangsu; water transfer will contribute to a change for Hubei's *WSI* from moderate (0.25) to severe (0.4) by 2030 and a change for Jiangsu's *WSI* from 1.13 in 2007 to 1.21 in 2030.

The above analysis raises the question of the sustainability of supply-oriented water management strategies. Supply-side measures help to increase water supply but also, lead to the false perception of unrestricted water availability. Such a perception may encourage water-receiving provinces to further expand water-intensive consumption and production activities, thus exacerbating the water stress of water-exporting provinces (27, 28). To prevent such a situation, more emphasis should be placed on water demand rather than solely relying on supply-orientated management.

Mitigating Water Stress Through Efficiency Improvement. Given the general increasing trend of *WSI* among China's provinces by 2030, efficiency gains will be offset by water demand increases caused by economic development. The reference scenario was designed with a particular focus on the potential gains in water use efficiency in the agricultural and industrial sectors.

According to projections in the reference scenario, agricultural irrigation efficiency for the entire country will increase by 23% from 0.48 in 2007 to 0.59 in 2030. At the provincial level, the efficiency gains range between 11% and 59% (*SI Appendix*, Table S10). Such efficiency gains will help reduce irrigation water demand by 26% (122 Gm^3). To achieve this goal, significant investment needs to be made into more water-efficient irrigation infrastructures, turning ∼41% of efficiently irrigated land in 2007 (29) to 75% of efficiently irrigated land by 2030. Initial steps toward this goal have been made, because China's central government has committed investment of 4 trillion Chinese yuan (CNY, ∼\$600 US billion) to water infrastructures by 2020 (1, 7).

Industrial water use efficiency can be reflected in industrial water intensity, which is defined as the ratio of industrial water use to industrial output. According to the reference scenario, the industrial water intensity of the whole country is required to decrease by 81% from 2.54 m^3/1,000 CNY in 2007 to 0.48 m^3/1,000 CNY in 2030. Likewise, the efficiency gains in industry would help to reduce 80% of industrial water demand (949 Gm^3). Unlike the large fiscal transfer in promoting water-saving technologies in agricultural irrigation, most effort in reducing industrial water use is currently in pilot projects rather than widespread adaptation. Meanwhile, industrial concerns lack the necessary incentives to save water given the high cost and low returns (30). Incentive mechanisms are urgently required to promote water-saving technologies in industry, such as closing water cycles in industrial production processes (31).

In the policy scenario, 13 provinces, including the top 3 net virtual water exporter provinces in 2007 (Xinjiang, Heilongjiang, and Inner Mongolia), would need to further decrease their total water use by 26% from 449 Gm^3 in the reference scenario to 335 Gm^3 in the policy scenario (*SI Appendix*, Table S12). This result means additional investment in efficiency improvements with particular emphasis on the agricultural sector.

The recognition that affluent net virtual water-importing eastern provinces ameliorate their water stress by externalizing water stress to other regions can be used as a basis for designing new mechanisms to finance investments in efficiency improvements. Consumer responsibility (32) could be used as a basis for a compensation mechanism between the top net virtual water importers and exporters and fund such investments based on income from an earmarked water tariff designed to charge for the amount of water consumed throughout the entire production chain. Such compensation would need to be implemented with social considerations, such as distributional effects, in mind (33). Furthermore, institutions should be established to serve as clearinghouses in providing technical support for efficiency improvements as well as balancing the interests among different stakeholders.

Methods

***WSI*.** The *WSI* refers to the water stress arising from water withdrawal from local water sources (Q), which is expressed as

$$WSI = \frac{WW}{Q} = \frac{WU - PW_{net,im}}{Q}, \tag{1}$$

where WW refers to provincial water withdrawal, which equals water use (WU) minus net physical water import ($PW_{net,im}$). Water use is the quantity of water distributed to users, including water lost in transmission. Q is renewable freshwater availability. The categorization of *WSI* to evaluate water stress is listed in *SI Appendix*, Table S1.

Water used for final consumption of a province is the sum of WW plus the net virtual water import ($VW_{net,im}$) and physical water import ($PW_{net,im}$):

$$WSI^* = \frac{WU + VW_{net,im}}{Q} = \frac{WW + PW_{net,im} + VW_{net,im}}{Q}, \tag{2}$$

where WSI^* represents the water stress indicator that calculates the hypothetical water stress on the local hydroecosystem if the importing region would not have physical and virtual water inflows available and would withdraw the required water entirely from local sources. Thus, the hypothetical WSI^* increases through the (net) import of physical and virtual water flows.

According to Eqs. **1** and **2**, the difference between WSI^* and WSI represents the contribution of net virtual and physical water flows in terms of increasing or ameliorating water stress:

$$WSI^* - WSI = \frac{PW_{net,im} + VW_{net,im}}{Q}. \qquad [3]$$

Calculating Interprovincial Virtual Water Trade with the MRIO Model. The environmental input–output model used to calculate water use in region r can be written as follows:

$$w_r = d_r x_r = d_r (I - A_r)^{-1} y_r, \qquad [4]$$

where w_r is the vector of water use in each sector of region r, x_r is the vector of total economic output in region r, d_r is the vector of direct water use intensity, which means the direct water use per unit of output in each sector, y_r is the vector of final demand, A_r is the matrix of technical coefficients, and I is the unit matrix.

The variable x_r can be rewritten as

$$x_r = A_{rr} x_r + y_{rr} + \sum_{s \neq r} e_{rs}, \qquad [5]$$

where A_{rr} refers to domestic technical coefficients, and y_{rr} is domestically produced products to fulfill final demand. The export from region r to region s ($e_r = \sum_{s \neq r} e_{rs}$) is the total bilateral trade, regardless of how the exports are used (i.e., in final demand or interindustry demand) (34). Therefore, Eq. **4** becomes

$$w_r = d_r x_r = d_r (I - A_{rr})^{-1} \left(y_{rr} + \sum_{s \neq r} e_{rs} \right). \qquad [6]$$

Then, total water use in region r can be decomposed as

$$w_r = d_r x_r = d_r (I - A_{rr})^{-1} y_{rr} + d_r (I - A_{rr})^{-1} \sum_{s \neq r} e_{rs} = w_{rr} + vwe_{rs}, \qquad [7]$$

where w_{rr} is the water used to fulfill domestic final demand, and vwe_{rs} is the total virtual water export from region r to region s.

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