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The pattern of virtual water transfer in China: From the perspective of the virtual water hypothesis

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ABSTRACT

Limited and uneven distributed water resources have become one of the main obstacles to China's sustainable development, and the "virtual water hypothesis" (VWH) is expected to help mitigate water stress. This study discusses the virtual water transfer pattern and water resources stress in China from the VWH perspective. Economic sectors in China are divided into land-dependent sectors and non-land-dependent sectors according to their dependence on specific local land types. Furthermore, the water resources withdrawal and utilization corresponding to these sectors are divided into land-dependent water resources (LDW) and non-land-dependent water resources (NLDW). Results show that the virtual LDW flows from economically poor to relatively developed regions, while the virtual NLDW flows in the opposite direction. LDW dominates Chinese water stress (78.2%) and virtual water flow (74.5%). Furthermore, the virtual water dominated by LDW ameliorates national water stress (the population under unsustainable water stress declined by 0.21 billion) but aggravates the imbalance of water resources between North and South. The transfer of virtual NLDW alleviates this imbalance slightly. Suitable land conditions play a decisive role in LDW withdrawal, which then cannot be replenished by virtual water. However, the withdrawal and transfer of NLDW are flexible, which should be a focus. The results point out that the possibility of water-rich regions as virtual water exporters is the key to alleviating the North–South water resource imbalance in China with VWH theory. Improvement of land productivity and water efficiency can be helpful to alleviate water stress. These findings may provide new insight into China's virtual water transfer pattern from the VWH perspective.

1. Introduction

China is one of the most water-scarce countries in the world, and nearly 0.92 billion people suffer water stress annually (Mekonnen and Hoekstra, 2016). More seriously, China's limited water resources are mostly distributed in the south of China (NBSC, 2012). North and Northwest China are the most water-deficient regions in China (NBSC, 2012; Aeschbach-Hertig and Gleeson, 2012). Limited and uneven distributed water resources have become one of the main obstacles to China's sustainable development (Yu, 2011, Lu et al., 2019). The "virtual water hypothesis" (VWH) (Allan, 1993; Hoekstra and Hung, 2005; Liu and Savenije, 2008) is highly expected to alleviate unevenly distributed water resources. According to VWH, water stress in water-short regions can be alleviated with minimal environmental impact by importing water-intensive goods and services from water-abundant regions (Allan, 1993; Dalin et al., 2012). However,

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observed virtual water transfer patterns usually do not support this hypothesis (Ramirez and Rogers, 2004). Thus, exploring the causes of the virtual water transfer pattern is important for the application of VWH theory.

In the past decades, many studies reported the transfer pattern of virtual water in China (Guan and Hubacek; 2007; Zhang and Anadon, 2014; Cai et al., 2019). They found that China's virtual water mainly flowed from the water-short north to the water-rich south. Scholars have also investigated the formation mechanism of virtual water transfer patterns and made many discoveries (Zhao et al., 2015; Liu et al., 2019; Tian et al., 2019). For example, Zhuo et al. (2016a, 2016b) showed that virtual water flows in related crops were from North to South. The water-abundant South began to depend on food supply from the water-short North in 2000. They suggested that economic and government policies were the main dominators in domestic virtual water flows rather than regional water resource endowments. Zhao et al. (2019) explained virtual water flow patterns in China based on the comparative advantage theory. They pointed out that regional differences in land productivity between agricultural and non-agricultural sectors were the main forces determining the pattern of virtual water flows across major regions. Cai et al. (2020) investigated the tele-connections of agricultural land and water use in China. They found that the availability of land, rather than water resources, played a decisive role in the agricultural virtual water use by importers and exporters.

Scholars believed that China's virtual water transfer pattern aggravates water stress. The cause of the virtual water transfer pattern mainly depends on economic, land, and policy elements, rather than water resources. However, some concerns remain to be further explored. First, existing studies all point out the importance of land in virtual water transfer. However, they are more limited to the study of virtual water transfer of the agricultural sector. Although the agricultural sector is the main water use sector, a more comprehensive analytical framework involving all economic sectors can be helpful to understand the role of land in virtual water transfer. Second, some studies believe in the potential choice of land use due to productivity differences, and this choice leads to the virtual water pattern. However, the competition over land among economic sectors and the possibility of land use transformation is rarely discussed. Third, virtual water transfer studies combined with the traditional water stress index (WSI) usually show that the virtual water transfer aggravates China's water stress. However, the classification of the traditional water stress level lacks standards with practical implication. Thus, the application of the VWH concept needs to clarify the actual impact of virtual water transfer on China's water stress based on a more effective index.

In response to these concerns, economic sectors in China are divided into land-dependent sectors (LDS) and non-land-dependent sectors (NLDS) according to their dependence on specific local land types. Furthermore, the water resources withdrawal and utilization corresponding to these sectors are divided into land-dependent water resources (LDW) and non-land-dependent water resources (NLDW) (further details are provided in Methods). Based on this classification, the present study quantifies China's virtual water transfer at the provincial level with the multi-regional input–output (MRIO) model. An improved WSI based on physical interpretation is selected to evaluate water stress. In this study, 2012 is selected as the study point based on the availability and representativeness of data. Outputs of this study are expected to enhance the understanding of the causes of China's virtual water transfer pattern.

2. Methods

2.1. MRIO model for virtual water transfer with inter-provincial trade

The environmental extended MRIO model is applied to calculate the transfer of virtual water (Miller and Blair; 2009; Feng et al., 2011). The environmental extended MRIO model can be expressed as (Wiedmann et al., 2011; Feng et al., 2014):

$$X^{*} = Z^{*} + Y^{*}$$

where X^{*}, Z^{*}, and Y^{*} is the total output, intermediate use, and final consumption matrixes, respectively. Owing to the competitive-IO table being adapted in this study, the direct consumption coefficient can be calculated as

$$A^{*} = [A^{rs}]$$

$$A^{rs} = \left[\frac{z_{ij}^{rs}}{X_j^{s}}\right]$$

where A^{*} is the intermediate use coefficient matrix, z_{ij}^{rs} is the intermediate use from sector i in region r to sector j in region s, X_j^{s} is the output of sector j in region s. Then, the input–output model can be written as

$$X^{*} = A^{*}X^{*} + Y^{*}$$

which can be transformed further into

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

Then, the direct water consumption coefficient (e_j^{r}) is the water consumption of unit product produced, which can be calculated as

$$e_j^{r} = \left[\frac{w_j^{r}}{x_j^{r}}\right]$$

$$E^{r} = \left[e_j^{r}\right]$$

where E^{r} is direct water consumption coefficient vector in region r, w_j^{r} is the direct water consumption from sector j in region r, and x_j^{r} is the total output of sector j in region r.

Then, the direct water consumption matrix (E^{*}) can be written as

$$E^{*} = \begin{bmatrix} E^{1} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & E^{n} \end{bmatrix}$$

where n is number of provinces for China.

The virtual water transfer among provinces can be written as

$$W^{*} = E^{*}X^{*}$$

which also can be written as

$$W^{*} = E^{*}(I - A^{*})^{-1}Y^{*}$$

where W^{*} is virtual water transfer matrix. The element $W^{rs} = E^{r}X^{rs}$ represents the virtual water flows from region r to region s.

Finally, the virtual water exchange of region r can be calculated as

$$W_{export}^{r} = \sum_{r=1, r \neq s}^{n} W^{rs}$$

$$W_{import}^{r} = \sum_{r=1, r \neq s}^{n} W^{sr}$$

where W_{export}^{r} is the virtual water export for region r, W_{import}^{r} r is the virtual water import for region r.

2.2. Improved WSI

WSI is typically defined as the relationship between total water use and water availability. The closer water use is to the water supply, the more likely stress will occur in natural and human systems. This indicator was developed by Pfister et al. (2009). The original WSI refers to water stress arising from water withdrawal from local water sources and is expressed as

$$WSI = \frac{WW}{Q}$$

where WW is the local water withdrawal. Q is the freshwater renewal amount. The WSI to evaluate stress levels is divided into many categories. Moderate and severe water stress occur above a threshold of 20% and 40%, respectively. The standard is that expert judgments and thresholds for severe water stress might vary from 20% to 60%. These categorizations are first suggested by Raskin et al. (1997). They indicate that a country is severely water-scarce if the ratio of annual withdrawal to annual renewable water resources exceeds 40%, water scarce in the range 20%–40%, moderate water scarce in the range 10%–20%, and low water scarce below 10%. These standards were adopted by the UN report "Comprehensive Assessment of the Freshwater Resources of the World" and consequently widely used in the literature (UN, 1997). However, for a specific area, the standard for the classification of the water stress level is fuzzy. The water resource background differences of countries and regions also limit the application of these categorizations (Vanham et al., 2018). Thus, an improved WSI is used in this study. The improved WSI refers to water stress arising from water withdrawal from available local water sources. The available freshwater resource is the maximum water that can be supplied by the basin under present and foreseeable future technical conditions and environmental capacity. In China, only 16.9%–64.1% of renewable freshwater resources are available in different basins (MWR, 2011). A high proportion of water resources are unusable water resources. Thus, WSI^*, including available local water resources, can represent the real water resource stress better, which can be expressed as:

$$WSI^* = \frac{WW}{Q^*}$$

where WW is the local water withdrawal. Q^* is the available local water resources. Sustainable and unsustainable water stresses occur when the ratio of the annual freshwater withdrawal to the available freshwater resource is less than 100% and over 100%, respectively. The LDW-WSI*, NLDW-WSI*, and Final-WSI* is WSI* caused by LDW, NLDW, and total water withdrawal.

Knowing the water stress from the virtual water transfer is also important. It can be calculated as (Zhao et al., 2015)

$$WSI_{scenario} = \frac{WW + VW_{net}}{Q^*}$$

where VW_{net} is the net virtual water transfer. $WSI_{scenario}$ represents the water stress indicator that calculates the hypothetical water stress on the local hydro-ecosystem if the importing region would not have LDW and NLDW virtual inflows available and would withdraw the required water entirely from local sources. Four scenarios, comprising one basic scenario and three hypothetical scenarios, are set in this study. S1 represents the basic scenario which is actual water stress. S2 represents the hypothetical water stress, which has no virtual NLDW flows. S3 represents the hypothetical water stress, which has no virtual LDW flows. S4 represents the hypothetical water stress, which has no virtual water flows. The difference between the four WSI scenarios represents the contribution of net virtual LDW and NLDW flows in terms of increasing or mitigating water stress.

2.3. Classification of LDW and NLDW

Water scarcity usually refers to locally available water resources that cannot meet the local water resources withdrawal demand. Thus, VWH is proposed and expected to alleviate water scarcity. This theory holds that regions with water scarcity can import commodities that consume considerable water resources to relieve the water stress. However, many production sectors depend on local specific land and resources endowments. For example, coal mining consumes a vast quantity of water resources, but the water scarcity regions cannot import coal from regions lacking coal mines, even if they are rich in water resources. Whether mines are present is a prerequisite for mining and export of mineral products. However, some production activities can be done anywhere theoretically. Therefore, economic sectors are divided into LDS and NLDS according to their dependence on specific local land types. Furthermore, the water resources withdrawal and utilization corresponding to these sectors are divided into LDW and NLDW. In LDW, the water resources are withdrawn by LDS, e.g., agriculture and mining. By contrast, in NLDW, that water resources are extracted and consumed by NLDS, e.g., the manufacturing industry. NLDS is usually more flexible than LDS in the framework of virtual water transfer. Reshaping the flow patterns of virtual NLDW by transferring NLDS is feasible. Nevertheless, LDS is "heavier" from the perspective of virtual water transfer. Detailed classifications of economic sectors according to their dependence on land are presented in Table S2.

2.4. Data sources

Virtual water transfer is calculated among provinces with the environmental extended MRIO model. The MRIO table and water resources utilization data are key to this model. The MRIO table reflects the flow of goods and services in various sectors, providing a platform to discuss virtual water transfer. In this study, the MRIO table of 2012 includes 42 sectors across 31 provinces (excluding Hong Kong, Macao, and Taiwan). This table is the most recent MRIO table that was published by the National Bureau of Statistics in 2018 (Liu et al., 2018) and has been applied in many studies (Zhang et al., 2018; Guo et al., 2019). Water extracted volumes for agricultural, industrial, and household sectors with provinces scale are collected from the China Statistical Yearbook (NBSC, 2012). Then, more specific water usage ratios by secondary industrial and household sectors are available from the Chinese Economic Census Yearbook (SCSNEC, 2008; Tian et al., 2022). Last, the water usage ratios of secondary industrial and household sectors in 2008 are applied to estimate those in 2012 (Zhang et al., 2014; Liu et al., 2019). All data used in this study can be freely accessed in published literature and databases.

3. Results

3.1. Withdrawal and consumption of LDW and NLDW

The results show that the annual withdrawal and consumption of LDW reaches 470 billion tons, which accounts for 78% of the total. That of NLDW only accounts for 22% (Fig. 1). The LDW dominates the withdrawal and consumption of China's water resources. Xinjiang is the largest LDW withdrawal province (57.4 billion tons), and Guangdong consumes the most LDW (37.6 billion tons). Jiangsu plays a major role in NLDW withdrawal (18.2 billion tons) and consumption (9.5 billion tons). In terms of the proportion of LDW and NLDW in each province (Table S3), significant differences occur in the withdrawal and consumption of LDW and NLDW among China's provinces. Provinces with higher LDW proportion (involving withdrawal and consumption) are mainly underdeveloped western provinces (Xinjiang, Xizang, Ningxia). However, provinces with higher NLDW proportion are mainly located in relatively developed regions in the east (Shanghai, Jiangsu) (Table S3).

3.2. Improved WSI

Fig. 2 shows the improved WSI (WSI*, hereinafter referred to as WSI). In 2012, the WSI is sustainable for the whole of China, and LDW-related WSI dominates the WSI in China. For provinces, 20 of 31 China's provinces have sustainable water stress (WSI $<$ 1), while the other 11

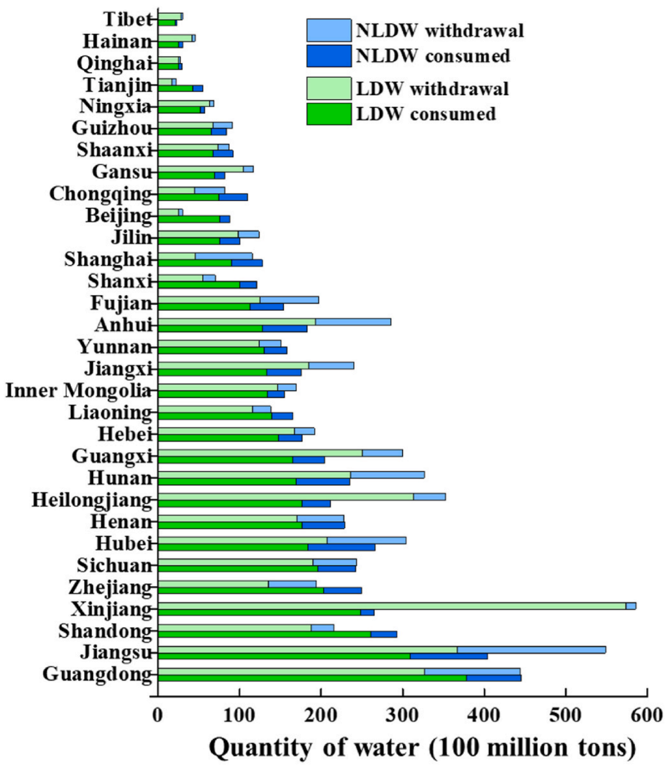

Fig. 1. Withdrawals and consumptions of NLDW and LDW for 31 Chinese provinces. Note that provinces are presented by increasing order of consumption of LDW.

provinces show unsustainable water stress (WSI > 1). Almost all LDW-related WSI is higher than 1 in unsustainable water stress provinces (expect Heilongjiang with LDW-related WSI 0.96). The withdrawal of LDW causes unsustainable WSI in these provinces. Only final WSI in some developed provinces (i.e., Jiangsu, Shanghai, and Tianjin) are considerably affected by the withdrawal of NLDW. The spatial map of WSI (Fig. S1) shows that water is relatively unsustainable in the north of China (i.e., 9 of 11 unsustainable provinces are located in the North), whereas the situations are much better in the southern provinces. Thus, improving the uneven distribution of water resources in China is very important to China's sustainable utilization of water resources.

3.3. Virtual LDW and NLDW transfers

Fig. 3 shows the virtual water balance and major virtual LDW and NLDW transfers between eight economic regions. The total volume of provincial virtual water flows is 263 Gm^3 in 2012 (i.e., 43.7% of the national annual water supply). Among them, the transfer of virtual LDW (black arrows in Fig. 3) is 196 Gm^3, which accounts for 74.5% of total provincial virtual water flows). The transfer of virtual NLDW (red arrows in Fig. 3) is 67 Gm^3 with a 25.5% proportion. The virtual LDW flows from economically poor (western and northern China) to relatively developed regions (eastern and southern China) (Fig. S2), while the virtual NLDW flows in the opposite direction (i.e., from eastern and central China to the whole country). At the province-scale, Xinjiang is the largest LDW exporter, and Jiangsu exports major NLDW (Figs. S3 and S4). From the national scale, the West and North provide LDW-related virtual water, while the East and South supply NLDW-related virtual water. The reason for this finding is that the magnitude of transfers of virtual LDW is much larger than that of transfers of virtual NLDW. The virtual water transfer pattern of China mainly presents the transfer pattern of LDW. The agricultural sector contributes the most to the virtual LDW transfer (74.9%). The electric sector contributes the most to the virtual NLDW transfer (37.2%) (Fig. S5).

3.4. Impacts on water stress through virtual LDW and NLDW transfers

The results show that 6 of 31 provinces are sensitive to virtual water transfers (i.e., the water stress conditions of these provinces are changed after virtual water transfers) (Figs. S6 and S7). Fig. 4 presents the four different WSI scenarios of six WSI-sensitive provinces. S1 is actual water stress. S2–S4 are the hypothetical water stress (i.e., if the local system does not have virtual water flows, it would be required to withdraw all required water from local sources). The difference between the four WSI scenarios represents the contribution of net virtual LDW and NLDW flows in terms of increasing or mitigating water stress. That is, when S2 is less than S4, the net virtual LDW has relieved the province's water stress through virtual LDW flows. When S2 is higher than S4, the province is a net virtual LDW exporter and has aggravated its water stress through LDW export. The hypothetical water stress concept comes from Zhao et al. (2015). The difference between the four WSI scenarios represents the contribution of net virtual LDW and NLDW flows in terms of aggravating or mitigating water stress. Four provinces (Shanxi, Henan, Guangdong, and Zhejiang) benefit from net virtual water transfer (S1 < S4). The water stress in these provinces is relieved from unsustainable levels to sustainable conditions after virtual water flows. However, the water stress in Xinjiang and Heilongjiang are aggravated by virtual water transfer (S1 > S4). Although the water stress is ameliorated by virtual water transfer from the national level (Table S4), the virtual water transfer aggravates the water stress of some people. That is, the number of provinces with unsustainable water stress from 13 to 11 and populations with unsustainable water stress decreases from 0.64 billion to 0.43 billion, but more people receive sustainable water stress at the cost of the unsustainable water conditions of Xinjiang and Heilongjiang. The difference between S2 and S4 is much larger than that between S3 and S4. Therefore, the LDW-related virtual water plays a major role in the water stress conditions changed of six WSI sensitive provinces compared with NLDW-related virtual water.

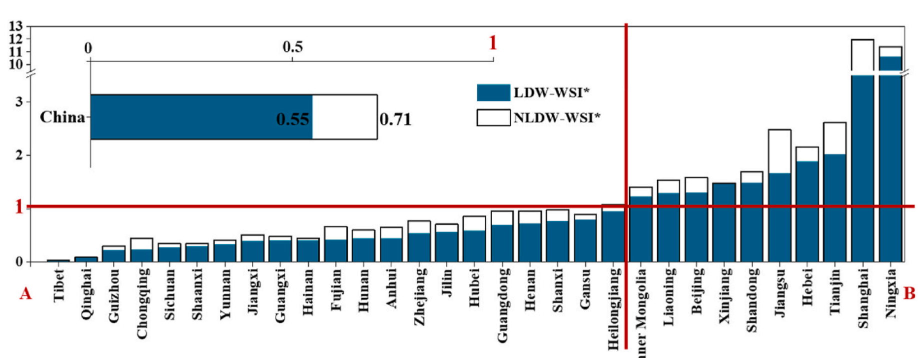

Fig. 2. WSI* of 31 Chinese provinces. Note that provinces are presented by increasing order of LDW-WSI*.

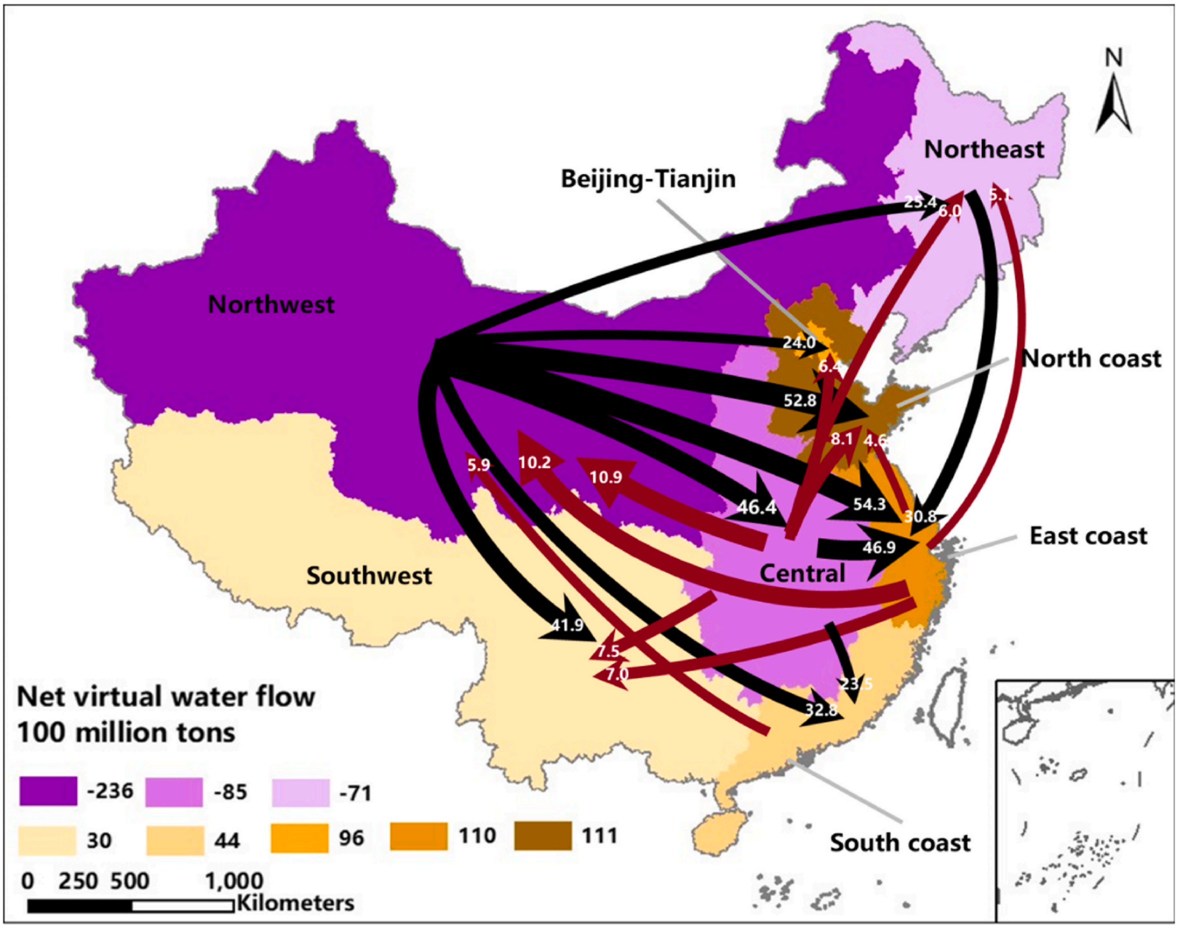

Fig. 3. Virtual water balance and the net virtual water flows in eight Chinese economic regions in 2012. Note that only the ten largest nets virtual LDW and NLDW flows are shown. The flows of net virtual LDW are four times larger than net virtual NLDW for the same width of flows.

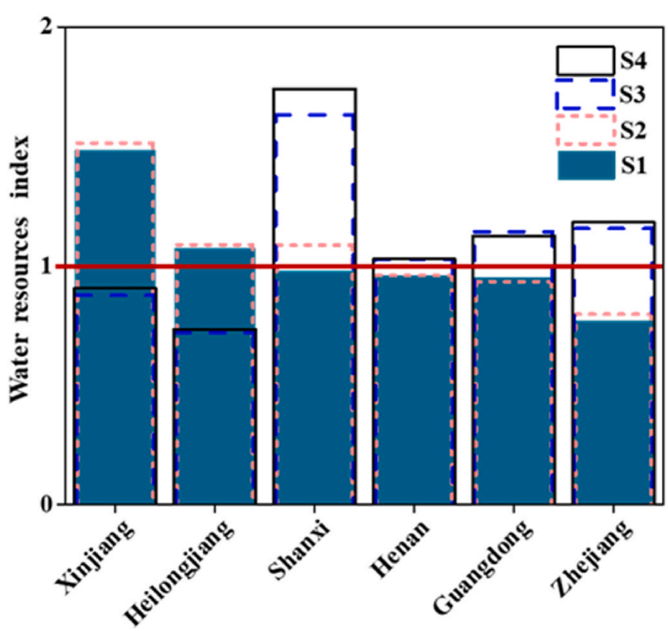

Fig. 4. Four WSI* scenarios of six provinces which are sensitive to virtual water transfer.

4. Discussion

4.1. Virtual water transfer pattern in China

This study explores the virtual water flow pattern in China based on the divisions of economic sectors and water resource use. The pattern of virtual water flows in China is driven by demand for products and services of LDS (i.e., LDW withdrawal has a proportion of 78.18% and its virtual transfer accounts for 74.5% of the total). The eastern and southern provinces import large amounts of LDW related virtual water from western and northern provinces to meet their consumption demands. The eastern and southern provinces also export NLDW related virtual water. The differences in the magnitude between virtual LDW and NLDW obscure this pattern. The virtual water flow pattern of China is mainly presented as the flow pattern of virtual LDW (i.e., from western and northern China to eastern and southern China). Along with LDW withdrawal in western and northern China, these products and services are produced by provinces with appropriate land conditions and are then transferred to all the country. Land conditions determine virtual water flow patterns. This analysis raises the question of the limitation of VWH (Wichelns, 2010; Zhao et al., 2019). In the LDW-related virtual water transfers, suitable land conditions are the prerequisite for the production of these LDW-related sectors under the existing technological level (i.e., provinces without available land production cannot be an exporter in LDW related virtual water transfers). Thus, the utilization of LDW is subject to land conditions, whereas that of NLDW is flexible. For VWH, additional emphasis should be placed on the possibility of water-rich provinces as virtual LDW exporters (Guan and Hubacek, 2007; Duchin et al., 2012).

Thus, can the pattern of virtual water flow in China be changed through the transformation of land use? This process is considered difficult for two reasons. On the one hand, China's land use transformation (especially the transformation of farmland) is limited by some policies, e.g., the "1.8 billion mu" red line of farmland. The area of farmland held in the northern water shortage provinces in this policy is much larger than that in the southern water-rich provinces, i.e., the farmland in the North is 78% more than that in the South, while the population in the South is 30% more than that in the North (NSBC, 2013). Owing to the land productivity of the agricultural sector being lower than that of other sectors, motivation to reclaim farmland is nonexistent in the water-rich southern provinces. Thus, the agriculture-related virtual LDW is exported to the South with grains transfer from northern provinces with larger farmland. On the other hand, some types of land use changes are unrealistic. For example, other types of land cannot be transformed into mines driven by the comparative advantage of output, unless mines are present here. In general, China's virtual water flow pattern is estimated to continue to be presented as North to South for the foreseeable future.

4.2. Implications of water resources stress mitigation

Trades connect production, consumption of water, and impacts on water stress. Huge virtual water transfers within China reshape provincial water stress. This study found that although the virtual water transfer has relieved the water stress of several provinces with more people, it further aggravated the imbalance of water stress between North and South. This finding is different from those of previous studies (Zhao et al., 2015; Zhuo et al., 2016a, 2016b). That's due to the application of improved WSI contributes to this difference. The measurement of water stress has a considerable effect on the understanding of the consequences of virtual water transfer. Thus, a WSI with not only statistical significance, but also physical significance is very important to accurately measure the stress of water resources. The traditional WSI is introduced to report the effect of virtual water transfer on local water resources stress in many studies. However, this index is not always in line with reality. Because a considerable proportion of total water resources cannot be used by human beings without destroying the ecology. The proportion of available water resources varies greatly in different basins. Thus, incorporating the improved WSI including available water resources can report the actual water resource stress better. This improved index is also helpful to better understand the role of virtual water transfer. Some regions must undertake the water stress of LDW withdrawal to meet the demands in a non-import-dependent economy. These regions exist as virtual LDW providers, and the water stress therefore cannot be alleviated by virtual water import. Although the NLDW withdrawal is agile in the VWH, it has limited ability to relieve water stress due to its small proportion. Furthermore, the supply of virtual NLDW is already mainly in the South with abundant water resources. However, the LDW withdrawal occurring in water-rich regions would be profitable for the whole country's water stress. Thus, the feasibility of the South as a virtual LDW supplier is the core to applying VWH theory to mitigate the imbalance of water stress in China. Notably, the discussions about China's water stress are based on the situation of the stable technical level, land production efficiency, and water resource utilization efficiency. Improvement of land productivity and water efficiency is crucial to alleviating water stress (Hoekstra and Mekonnen, 2012; Zhao et al., 2015, 2019).

VWH is proposed and expected to alleviate water scarcity. Water stress regions could import products from water-abundant regions to alleviate water scarcity. However, many trades run contrary to this hypothesis. This study explores virtual water flow patterns in China. On the one hand, suitable land conditions play a decisive role in LDW withdrawal and it then cannot be replenished with virtual water. Thus, planning water resources management according to local conditions is very important. On the other hand, NLDW withdrawal usually does not depend on land conditions. Therefore, NLDW-related sectors should be put into water-abundant regions, a practice already being done in China.

5. Conclusions

This study discusses the virtual water transfer pattern and water resource stress in China from the concept of VWH. Economic sectors in China are divided into LDS and NLDS according to their dependence on specific local land types. Furthermore, the water resources withdrawal and utilization corresponding to these sectors are divided into LDW and NLDW. The results show that the virtual LDW flows from economically poor to relatively developed regions, while the virtual NLDW flows in the opposite direction. LDW dominates Chinese water stress (78.2%) and virtual water flow (74.5%). Furthermore, the virtual water dominated by LDW ameliorates national water stress (the population under unsustainable water stress declined by 0.21 billion) but aggravates the imbalance of water resources between North and South. The transfer of virtual NLDW alleviates this imbalance slightly. Suitable land conditions play a decisive role in LDW withdrawal and it then cannot be replenished by virtual water. However, the withdrawal and transfer of NLDW are flexible, which should be a focus. The results point out that the possibility of water-rich regions as virtual water exporters is the key to alleviating the North–South water resource imbalance in China with VWH theory. Improvement of land productivity and water efficiency can be helpful to alleviate water stress. Outputs are expected to promote the understanding of virtual water and help alleviate the imbalance of water resources between North and South in China.

Future studies should further be investigated in two aspects. First, the agriculture and electric power sectors are the core sectors of water resource withdrawal and virtual water transfer. A more comprehensive framework with a mechanism model is expected to be established to improve the understanding of agriculture and electric power sectors' virtual water transfer. Second, the division of LDW and NLDW is from the perspective of economic sectors. More universal and effective methods should be applied to explore the decisive role of land in virtual water transfer.

CRediT authorship contribution statement

Peipei Tian: Conceptualization, Methodology, Writing – original draft. **Hongwei Lu:** Validation, Supervision. **Junguo Liu:** Validation, Supervision. **Kuishuang Feng:** Methodology, Investigation, Supervision. **Reinout Heijungs:** Methodology, Investigation, Supervision. **Dan Li:** Visualization, Data curation, Software. **Xing Fan:** Validation, Supervision.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.131232.

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