Virtual water scarcity risk to global trade under climate change

Haoran Zhao a, b, Shen Qu b, *, Sen Guo a, Huiru Zhao a, Sai Liang c, Ming Xu b, d

a School of Economics and Management, North China Electric Power University, Beijing, 102206, China
b School for Environment and Sustainability, University of Michigan, Ann Arbor, MI, 48109-1041, United States
c State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing, 100875, China
d Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI, 48109-2125, United States

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ABSTRACT

The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) has concluded that climate change will have significant impacts on global water resources. The risk of production loss due to water scarcity can be transmitted through international trade to distant economies downstream the supply chain. In this research, how climate change may affect the global economy via reducing available water resources in some regions is investigated based on a multi-regional input output (MRIO) model that provides information on the current global economic structure. Key nation-sectors with the greatest virtual water scarcity risk (VWSR) exports are identified under two climate change scenarios, including the Agriculture sectors in Syria, Pakistan, Kazakhstan, India, Uzbekistan, Iran, and China. Improving water efficiency in these sectors is essential for increasing the resilience of the global economy against climate change-induced water scarcity. Nation-sectors with the largest VWSR imports are also identified under the two climate change scenarios, including Food & Beverages sectors, Textiles and Wearing Apparel sectors, and Petroleum, Chemical and Non-Metallic Mineral Products sectors in Saudi Arabia, the United States of America, Russia, Germany, Italy, and China. These are the most vulnerable nation-sectors facing the reduction in foreign water resources due to climate change. Additionally, through comparing the change of rankings of VWSR imports, VWSR exports, and LWSRs at country and sector level, the rankings of VWSR exports are relatively close to LWSRs, while the rankings of VWSR imports are quite different from LWSRs. The evaluation demonstrates that nations should cooperatively manage water resources and be aware of the transmission of virtual water scarcity risk through international trade under climate change. Moreover, nation-sectors with high VWSR imports may reduce the reliance on water-intensive products and diversify importing sources, and national governments can encourage residents to change consumption patterns.

Abbreviation List with Definition

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Name</th>
<th>Definition in the Main Text</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAU</td>
<td>Business as Usual</td>
<td>A scenario in which greenhouse gas emissions keep rising in the 21st century.</td>
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<td>LWSR</td>
<td>Local Water Scarcity Risk</td>
<td>Production loss due to domestic water scarcity.</td>
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<td>MRIO</td>
<td>Multi-Regional Input-Output</td>
<td>A widely-used approach to analyze the economic interdependence between regions and sectors.</td>
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<td>RCP</td>
<td>Representative Concentration Pathways</td>
<td>Greenhouse gas concentration trajectories envisioned by the IPCC.</td>
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<td>VWSR</td>
<td>Virtual Water Scarcity Risk</td>
<td>Production loss due to foreign water scarcity, transmitted through global supply chains.</td>
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<td>WD</td>
<td>Water Dependency</td>
<td>The proportion of a sector's output loss due to 1% less water consumption.</td>
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<td>WDR</td>
<td>Water Deprivation Risk</td>
<td>The potential reduction of water use of a region due to water scarcity.</td>
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<td>WI</td>
<td>Water Intensity</td>
<td>The ratio of a sector’s water consumption to its unitary economic output</td>
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<td>WSI</td>
<td>Water Stress Index</td>
<td>An index to measure regional water scarcity, defined as the ratio of water use to water availability in a period.</td>
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<tr>
<td>WSR</td>
<td>Water Scarcity Risk</td>
<td>Production loss due to water scarcity.</td>
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* Corresponding author.
E-mail address: shenquin@umich.edu (S. Qu).

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1. Introduction

Climate change is projected to have significant influences on the availability of water resources worldwide. The AR5 of IPCC has concluded that climate change will ‘reduce renewable surface water and groundwater resources significantly in most dry subtropical regions (robust evidence, high agreement)’ and in contrast, water resources will increase at high latitudes. Other studies building on ensembles of Coupled Model Inter-comparison Project Phase 5 (CMIP5) multi-models and hydrological models also point to the uneven impacts of climate change on global water resources (Gosling and Arnell, 2016; Schewe et al., 2014). While an immediate concern is water security of the population living in areas getting drier, an equally important concern is the risk to the global economic system, i.e., the production in various nation-sectors globally and the availability of the products, as over 90% of water consumption is embodied in the life cycle of products in the ever increasingly interconnected global supply network (Ridoutt and Pfister, 2010).

Water management has mainly been local, but the nature of water-related issues can be global (Hess et al., 2015). Previous studies have studied virtual transfers of water resources through trade (Brindha, 2017; Hoekstra and Mekonnen, 2016). They demonstrated that economic activities of one country can have significant impacts on water consumption in distant economies. Although virtual water trade contributed to the alleviation of water stress globally, it also exacerbated water scarcity in many regions of the world (Feng et al., 2014; Wang and Zimmerman, 2016). Therefore, if water availability becomes lower in already water-stressed regions under climate change, production losses in water-using sectors such as agriculture, energy and chemicals are likely. Due to the interconnected of the global economy, this may consequently lead to indirect impacts to production in countries not directly experiencing physical water scarcity. In fact, water scarcity risk (WSR) has already been regarded as a supply chain threat (Hoekstra and Change, 2014). Business decision and water management policy need not only to consider the potential production loss due to domestic water scarcity, i.e., local water scarcity risk (LWSR), but also the threat of water scarcity coming from global supply chains (WWAP, 2012).

This study investigates how climate change may affect the global trade system through decreasing water supply in some parts of the world. First, we quantify LWSR for each sector in each nation, using the projection of global water resource changes under business as usual (BAU) and optimistic climate change scenarios, information on economic output and current water consumption of each nation-sector, and global distribution of current water stress. Second, we evaluate the indirect influences of LWSR delivered to downstream sectors via reducing input supply, employing a latest MRO database with 189 regions under two climate change scenarios. Third, WSR "exporters" and "importers" at both national and sectoral levels are analyzed, which can help decision makers better understand the impact of changing water resources under climate change on human societies. Economic production may not only be affected in water-intensive sectors such as energy and agriculture, but in various other sectors using inputs embedding virtual water use. Societies will be threatened not only in regions that are projected to get drier, but in the many other regions importing products whose life cycle depends on the use of scarce water resources which will become even more scarce under the change climate.

The remainder of this paper are organized as below. The methods for assessing LWSR and VWSR exports and imports are elaborated in Section 2. Data resources are introduced in Section 3. Results for the influences of changing water resources under climate change on the global trade are analyzed in Section 4. Section 5 discusses the results of this study and proposes several recommendations.

2. Methods

In this study, WSR means potential production loss due to (1) water scarcity in the domestic country (i.e., LWSR) and (2) water scarcity in foreign countries transmitted through international trade (i.e., VWSR). This section describes the methods to evaluate LWSR and VWSR under climate change scenarios, based on structure of the current global economy. The methodology is an extension to a previous framework (Qu et al., 2017), considering changing water resources included by climate change.

2.1. Quantifying LWSR

There are a variety of indictors to evaluate water scarcity, including basic human water requirements (Gleick, 1996), water vulnerability index (Raskin, 1997), water poverty index (Sullivan et al., 2003), social water stress indicator (Ohlsson, 2000), the Falkenmark index (Falkenmark, 1989), and water stress index (Hoekstra et al., 2012; Wang and Zimmerman, 2016). This research evaluates water scarcity using the water stress index, defined as the ratio of annual water withdrawal to renewable water resource in a region. LWSR of a nation-sector is evaluated as the potential loss of output resulting from water shortage, considering water withdrawal, water availability, and output of each sector. For example, if a sector is affiliated to a water-scarce nation, withdraws more water for unitary output, and provides more output, its LWSR will be higher. The LWSR of an economic sector is evaluated in relative values instead of absolute values, so that the vulnerability of various sectors can be compared without relying on accurate monetary evaluations.

In water-scarce nations, water-consuming sectors are exposed to the risk of being supplied inadequate water which cannot meet the production requirements. Under such circumstances, the output may decrease, and the amount of the reduced output relies on the degree of dependence on production on water resources. Based on this logic, we can presume a relationship connecting water scarcity to possible output decrease for each nation-sector using the following equation:

\[ \text{LWSR}_{k,c} = \text{WDR}_c \times \text{WD}_{k} \times x_{k,c} \]  

where \( \text{LWSR}_{k,c} \) is the direct output decrease of sector \( k \) in nation \( c \) owing to water scarcity; \( \text{WDR}_c \) represents the water deprivation risk in nation \( c \), assessing the possible decrease fraction of water consumption resulting from water scarcity; \( \text{WD}_k \) indicates the degree of water dependency of sector \( k \), estimated by the proportion of output loss brought about by 1% water deprivation; \( x_{k,c} \) represents the reference output of economic sector without being deprived of water resources.

Since there are no comprehensive statistical results on WDR and WD at the global level, we need to deduce them via related
variables. We will evaluate WDR and WD in relative terms, focusing on the rankings of sectors and countries. The calculation process of WDR and WD concerns choosing parameters and therefore we will carry out sensitivity analysis and test the robustness.

The evaluation of WDR and WD are introduced in the following two sections.

2.1. Water deprivation risk

Since the reduction of water availability of the country caused by climate change may affect water consumption, the variable WDR, ranging in the range [0, 1], evaluates the potential reduction of water consumption in a country due to water scarcity under climate change.

For countries where water availability will decrease under climate change, considering the adaptive capacity of the country's water supply system to satisfy the current water demand, WDR can be measured as:

\[ WDR_c = \sigma \times (\text{Fraction of Reduced Water Resources})_c \quad (0 < \sigma \leq 1) \]  

(2)

where \( \text{Fraction of Reduced Water Resources} = \frac{\text{Current water availability} - \text{Future water availability}}{\text{Current water availability}} \)

Under climate change, the fraction of water withdrawal reduction in country \( c \) is assumed to be the fraction of water availability resources reduction multiplied by the parameter \( \sigma \) \((0 < \sigma \leq 1)\). The parameter \( \sigma \) is related to the adaptive capacity of the country's water supply system, and smaller \( \sigma \) indicates the country can better adapt to water availability change. The parameter \( \sigma \) is defined as:

\[ \sigma = \begin{cases} 
WSI^p & \text{if } WSI < 1 \\
1 & \text{if } WSI \geq 1 
\end{cases} \quad (0 < \sigma < \infty) \]  

(3)

The water stress index (WSI), defined as the ratio of water withdrawal to current renewable water resource (i.e., water availability) of a country, is widely used to evaluate water scarcity. High WSI does not necessarily lead to economic output loss, as an economy is usually able to continue extracting water even if WSI \( \geq 1 \) by damaging the environment and depleting water resources (Hoekstra et al., 2012). Without more in-depth information on water supply to nation-sectors, it is supposed that sectors in high WSI countries will more possibly confront water scarcity. For the countries with WSI \( \geq 1 \), such countries must have withdrawn all its renewable water resource, and therefore we assume that, under climate change, the fraction of water withdrawal reduction of water users to be equal to the fraction of water availability resources reduction (\( \sigma = 1 \)). For countries with WSI < 1, greater water stress implies less adaptive capacity to deal with water scarcity under climate change. The fraction of water withdrawal reduction of the country will have to be closer to the fraction of water availability reduction. Therefore, \( \sigma \) is defined to be \( \sigma = WSI^p \).

Here the parameter \( \sigma \) represents the overall adaptive capacity of all countries. A smaller value of the parameter \( \sigma \) leads to a smaller value of \( \sigma \), meaning that a country can better adapt to water availability change. Fig. S1 in Supporting Information illustrates the values of WDRs computed by WSI and the fraction of reduced water availability under the business as usual scenario utilizing different values of the parameter \( \sigma \) for countries with WSI ranging from 5% to 100%. According to the literature, a country suffers water scarcity if WSI is higher than 20%, and significant and severe water scarcity as WSI is higher than 30% and 40% (Hoekstra et al., 2012). As Fig. S1 illustrates, when \( \sigma = 2 \), the countries with WSI higher than 20% and relatively higher fraction of water resources reduction have WDRs values over 1%. The WDRs values with \( \sigma \) in the range of [1.5, 2.5] will also be calculated in the Sensitivity Analysis section. When \( \sigma = 1.5 \), most countries (countries with WSI higher than 5%) have non-ignorable WDRs. When \( \sigma = 2.5 \), countries with relatively higher fraction of reduced water resources (higher than 70%) and WSI ranging from 5% to 20% have low WDRs. Thus, we suppose \( \sigma = 2 \) for the main presented results.

2.1.2. Water dependency

Water dependency (WD) evaluates the proportion of a sector's output reduction (compared to the benchmark level) brought by 1% less water consumption. The highest value of this indicator is supposed to be 1, which means water is utterly irreplaceable. Based on a recent literature (Thomas et al., 2015) on water importance, water intensity (WI) is utilized to assess a sector's dependence on water resources. WI is the ratio of water consumption to unitary economic output. We use a nation-sector's WI (in \([0, \infty]\)) to calculate its WD (in \([0, 1]\)):

\[ WD_k = f_{WD}(WI_k; \alpha) = \frac{1}{1 + e^{-\alpha WI_k(\frac{WD}{1-WD}) - 1}} \]  

(4)

where \( WI_k \) and \( WD_k \) represent water intensity and water dependency in sector \( k \), \( \alpha \) is the parameter regulating the critical value of WI greater than which WD will grow rapidly to 1.

A larger \( \alpha \) leads to a higher critical value of WI, which means less sectors are classified as high WD. Fig. S2 in the Supporting Information illustrates WI and the corresponding WD of nation-sectors with WI > 0.1 m³/$, calculated using parameter values \( \alpha = 13 \), \( \alpha = 14 \), which is the value underlying the calculation in Results Section, and \( \alpha = 15 \). As plotted in Fig. S2, although the WI of Sudan's Agriculture sector (8608 m³/$) is much higher than that of Pakistan's Agriculture sector (29 m³/$), they are all classified as the most water-dependent sectors with both WD values very close to 1. For the sectors with very low (close to 0) water intensity, WD values are near the minimum (i.e., smaller than 0.001). Hence, the function is carefully constructed, reflecting that more water intensive sectors usually highly depend on water. When \( \alpha = 14 \), sectors with WI > 1 m³/$ have the maximum WD values (which are higher than 0.999), and sectors with WI < 0.01 m³/$ are treated to have the minimum WD values (which are close to 0.001).

2.2. Global trade

Global multi-regional input-output (MRIO) model investigates the interdependence among nation-sectors (Miller and Blair, 2009). Global MRIO table displays column balances illustrating that every sector's input equals the sums of all intermediate inputs and value added, which can be described as:

\[ x = ez + v \]  

(5)

where \( x \) is a \( 1 \times n \) vector representing the total input of every sector, the \( 1 \times n \) vector \( v \) contains the value added of every sector, \( n \times n \) matrix \( Z \) contains transactions amount among sectors. Elements of \( n \times n \) vector \( e \) equal 1.

An \( n \times n \) matrix \( B \) contains the direct output coefficients, defined as the products assignment ratio from one sector to all sectors, which can be written as Equation (6). Substituting (6) into (5), we obtain Equation (7).

\[ B = (x)^{-1}Z \]  

(6)

\[ x = (I - B)^{-1}v \]  

(7)

The matrix \((I - B)^{-1}\) is the Ghosh inverse matrix (Ball, 1965;...
Elements of a row or column include the total (both direct and indirect) outputs of sectors induced by unitary value added to the sector demonstrated by this row. The Ghosh inverse matrix is utilized in this study to assess the influences of LWSR on global trade system as in Equation (8).

$$\Delta x = LWSR^{-1}(I - B)^{-1}$$  

(8)

where vector $\Delta x$ is a $1 \times n$ vector for the direct and indirect output reduction of each sector, due to LWSR of all nation-sectors. The $1 \times n$ vector $LWSR$ represents LWSR of every sector.

As shown in Equation (9), the matrix $\Delta X$ is calculated via diagonalizing vector $LWSR$ in Equation (8). Elements in each row for matrix $\Delta X$ denote output reduction of each sector brought about by LWSR of the sector demonstrated by this row.

$$\Delta X = \text{diag}(LWSR)(I - B)^{-1}$$  

(9)

Suppose there are $m$ countries in the world, and $N$ is an $m \times m$ matrix with element $n_{ij}$ representing the effects of country $i$’s LWSR on country $j$’s output.

$$n_{ij} = \sum_{k \in \text{nation } i.} \Delta x_{kj}$$  

(10)

where $\Delta x_{kj}$ is the effects of LWSR in nation-sector $k$ on sector $i$’s output.

VWSR exports of a country, represented by $VWSR^{ex}$, and VWSR imports of a country, represented by $VWSR^{im}$, are calculated by:

$$VWSR^{ex}_i = \sum_{i \neq j} n_{ij}$$  

(11)

$$VWSR^{im}_i = \sum_{j \neq i} n_{ij}$$  

(12)

In short, Ghosh model describes the effects prompted by supply in the economic system (Dietzenbacher, 2010; Liang et al., 2016a, 2016b). Water resource is integral to economic production, and water scarcity can directly influence water-using production and then indirectly influence downstream sectors’ activities.

2.3. Assessing the concentration of VWSR imports

The vulnerability of a country to its VWSR imports can be further analyzed with the Herfindahl index $Herf_i$, which assesses the concentration of VWSR imports of country $i$ (Hirschman, 1964; Ludema and Mayda, 2013). Higher concentration of a country’s VWSR import implies greater vulnerability of it to water shortage in upstream countries. The Herfindahl index is calculated as:

$$Herf_i = \sum_{j \neq i} \left( \frac{n_{ij}}{\sum_{j \neq i} n_{ij}} \right)^2$$  

(13)

3. Data sources

The implementation of the above methodology requires several data sources. They include global MRIO data, water consumption of all nation-sectors, and water availability of each country (or region) currently and under future climate change.

3.1. International MRIO data

Widely-used global MRIO databases include Eora database (Lenzen et al., 2013; Manfred et al., 2012), World Input-Output Database (WIOD) (Dietzenbacher et al., 2013; Timmer et al., 2015), EXIOPOL database (Tukker et al., 2013), and GTAP database (Andrew and Peters, 2013). For GTAP database, it does not contain water consumption data. For WIOD, it only contains 41 countries data which is less than Eora database’s 189 countries. For EXIOPOL database, it only includes water consumption data in restricted periods (2000 and 2007). Therefore, we select Eora database containing 189 countries with 26 economic sectors in basic price for the environmentally extended input-output analysis (Lenzen et al., 2013; Manfred et al., 2012). Since we need to analyze the impacts of water scarcity under climate change in future, we employ the most recent data for the year of 2015 to characterize the structure of international trade.

3.2. Water consumption of nation-sectors

This research focuses on blue water (i.e., surface water plus groundwater), which is the primary water resource for industry and agriculture. According to the satellite account of Eora database, the total blue water footprint data in 2015 of all nation-sectors are used as water consumption data.

3.3. Water availability data of nations

For water availability data under future climate change, we utilize the WRI Aqueduct database (WRI, 2018), which is based on ensembles of CMIP5 models and covers average water resources changes from the baseline period (1950–2010) to the future period of 2020–2040 under two climate change scenarios: RCP (Representative Concentration Pathways) 8.5 as the business as usual (BAU) scenario and RCP 4.5 as the optimistic scenario. We sum up total blue water in all catchments in each nation, and then deduct the overlaps in water supply across different basins, based on basins identifications in the dataset. The water availability volume of each catchment is divided according to the area of different catchments accounted by various countries, thus the average water availability data of each country in the period of 2020–2040 under two scenarios can be determined.

For current water availability data, we collect the indicator ‘total renewable water resources’ from FAO AQUASTAT (FAO, 2015; Hoekstra et al., 2012), which is commonly employed in water scarcity measurements, reflecting environmental requirements. The data of current water availability updated in 2014 are annual values averaged over decades.

4. Results

4.1. Overall pattern of climate change-induced WSRs

About 8% of the global WSR is delivered through international trade under both the BAU scenario and the optimistic scenario. Also, under the two scenarios, the shares of each country’s VWSR import in the total risk its economic system faces are very close (as demonstrated in Fig. S3 and Table S1). For 61 countries, more than 20% of WSR originates in foreign countries, such as Ethiopia (62%), Belarus (55%), and Belgium (40.47%) (as illustrated in Fig. S3). Meanwhile, all the WSRs of 47 countries are derived from VWSR imports (shown in Table S1). These countries have low water stress indices but import intermediate inputs from water-scarce regions that will have even less water resources under climate change.
4.2. Mapping climate change-induced WSRs

4.2.1. Country level analysis

Fig. 1 presents the world maps of climate change-induced VWSR export and import, demonstrating the transmission of WSRs via international trade under the BAU scenario. Maps for the optimistic scenario are displayed in Fig. S4. As in Fig. 1A and S4A, VWSR primarily originates from a few countries, such as India, Iran, Syria, Pakistan, Kazakhstan, China, Uzbekistan, and Morocco, which pose significant threats to foreign countries via VWSR exports. This is due to these countries' roles as primary commodity manufacturers and exporters (WorldBank, 2015), their current water scarcity (for example, the WSI of Iran and Uzbekistan is 1.37 and 1.90), the negative impacts of climate change on their water resources, and the global economic structure in relation to them. Furthermore, the largest differences in VWSR exports between the two scenarios exist in Uzbekistan, Saudi Arabia and Qatar, which export 71.77 million dollars, 49.36 million dollars, and 12.43 million dollars less VWSR respectively under the optimistic scenario due to a smaller reduction in water availability.
To further analyze VWSR exports independent of economic scales, the values of VWSR export per unit economic output (i.e., normalizing the VWSR export of each country by total output) are also presented in Table S2. Moldova, Ethiopia, Syria, Belarus, Kyrgyzstan, Uzbekistan, Kazakhstan, and Yemen are regarded as the riskiest countries for global trade under climate change, owing to the relatively high proportions of VWSR export in unitary economic output.

Fig. 1B and Fig. S4B illustrate the VWSR imports of countries under the BAU and the optimistic scenarios, respectively. Different from the concentrated sources of VWSR exports, VWSR imports distribute more extensively in the global trade system. China, Russia, Germany, the United States of America, South Korea, Saudi Arabia, Italy, Japan, Spain, Turkey, France, Netherlands, and United Arab Emirates are the top VWSR importing nations under the two scenarios. They are the primary commodity importers from regions getting drier under climate change, their economies are sensitive to upstream countries’ LWSR. Compared with the VWSR imports under the optimistic scenario, VWSR imports of most countries under the BAU scenario are greater. The VWSR import of Russia under the BAU scenario is 3238 million dollars and decreases to 3194 million dollars under the optimistic scenario, which is the most substantial gap of VWSR imports among all countries between the BAU scenario and the optimistic scenario. Only the VWSR import of Libya increases from 35.21 million dollars under the BAU scenario to 35.34 million dollars under the optimistic scenario.

To eliminate the influences of economic scales on VWSR imports, we normalize the VWSR imports of 189 regions by their economic output. The VWSR imports unitary output values are listed in Table S2. It can be found that Zimbabwe, Belarus, Kyrgyzstan, Lebanon, Jordan, Tajikistan, Sao Tome and Principe, Mauritius, Uzbekistan, Saudi Arabia, Moldova, and Turkmenistan are induced to be the most vulnerable countries to insufficient water supply under two scenarios of their upstream countries.

Fig. 2A and Fig. S5A demonstrate the changes of rankings of VWSR imports and LWSRs for top 15 countries with the highest VWSR imports under the BAU scenario and the optimistic scenario, respectively. We can discover that countries such as Russia, Germany, the United States of America, South Korea, and Italy are much less resilient to foreign WSRs, as their VWSR imports rank at top level while their LWSRs rank at a relatively low level. Among top 15 countries of VWSR imports, under the BAU scenario, Turkey ranks 9th with 1386 million dollars VWSR imports followed by Spain with 1377 million dollars VWSR imports, while under the optimistic scenario, Spain ranks 9th with 1361 million dollars followed by Turkey with 1356 million dollars VWSR imports. However, the LWSR of Turkey ranks 13th and that of Spain ranks 19th under both BAU and optimistic scenarios. For Japan, its LWSR ranks 78th with only about 0.35 million dollars under both scenarios, while its VWSR imports ranks 8th with 1753 million dollars under the BAU scenario and 1737 million dollars under the optimistic scenario. This indicates that economic sectors in Japan highly rely on importing commodities from water scarcity countries, and hence these sectors should seek substitutions domestically or from other countries with adequate water supply to reduce the vulnerability to foreign WSRs.

Fig. 2B and Fig. S5B illustrate the changes of rankings of VWSR exports and LWSRs for top 15 countries with the highest VWSR exports under the BAU scenario and the optimistic scenario, respectively. We can find that the rankings of VWSR exports are relatively close to those of LWSR. Countries such as India, Iran, Syria, Pakistan, Kazakhstan, and China with high LWSRs also deliver
much WSRs to other countries via exporting commodities. Under the BAU scenario, the VWSR exports of Saudi Arabia ranks 9th, followed by Yemen and Tunisia, while under the optimistic scenario, the VWSR exports of Yemen ranks 9th, followed by Tunisia and Saudi Arabia, and the rankings of LWSR for Saudi Arabia, Yemen and Tunisia are 8th, 12th, and 14th under both BAU and optimistic scenarios. For India and Iran, both of LWSRs and VWSR exports of them rank top 2 under BAU and optimistic scenarios, therefore, the downstream countries need to reduce importing commodities from these countries to improve their resilience to foreign WSRs.

4.2.2. Nation-sector level analysis

The top 100 VWSR transmission links between sectors under the BAU and optimistic scenarios are listed in Table S3 and Table S4, respectively. The top 100 vulnerable sectors (independent of economic output scales) under the BAU scenario and the optimistic scenario are illustrated in Tables S5 and S6. Like the results at the national level, the destinations of VWSR transmissions are relatively extensive compared with the concentrated origins. Through analyzing the top 100 VWSR transmission links between sectors under the two scenarios, we can discover that inadequate available water of the Agriculture sector in Syria, Pakistan, Kazakhstan, India, Uzbekistan, Iran, Yemen, and China can exert severe influences on manufacturing sectors in various countries through global supply chains, such as Food & Beverages sector in Saudi Arabia, the United States of America, Russia, Germany, Spain, Italy, and China, Textiles and Wearing Apparel sector in China, Italy, South Korea, and Turkey, and Petroleum, Chemical and Non-Metallic Mineral Products sector in China, the United States of America, South Korea, Japan, Germany, and Saudi Arabia. Through analyzing the top 100 sectoral vulnerabilities to trade under the BAU and optimistic scenarios, inadequate available water of Agriculture sector in several countries can not only influence manufacturing sectors in many other countries, but also exert impacts on Private Households of Georgia and Zimbabwe, Re-export & Re-import sector in Moldova, the United States of America, Saudi Arabia, Zimbabwe, Serbia, and Spain, Hotels and Restaurants sector in Zimbabwe, and Wholesale Trade sector in Kyrgyzstan.

Table S7 and Table S8 demonstrate the top 30 sectors with the largest VWSR exports and VWSR imports values, respectively, under both BAU and optimistic scenarios. Similar to the above analysis, most of top 30 VWSR exports sectors are Agriculture sector in various countries including India, Iran, Pakistan, Syria, Kazakhstan, China, Uzbekistan, and Yemen. Moreover, Food & Beverages sector of Syria ranks 10th under both BAU and optimistic scenarios, while that of Tunisia and India ranks 22nd and 25th under the BAU scenario, respectively, and 21st and 24th under the optimistic scenario. Fishing sector of Kazakhstan ranks 12th under the BAU scenario, but it ascends to 11th under the optimistic scenario. Financial Intermediation and Business Activities sector of Belarus and Mining and Quarrying sector of Iran rank 29th and 30th under the BAU scenario and move up one place under the optimistic scenario, respectively. Agriculture sector of Egypt falls out of top 30 VWSR exports, while Food & Beverages sector of Iran rises to 30th under the optimistic scenario. For top 30 sectors with the largest VWSR imports, most of them are manufacturing sectors, such as Food & Beverages sector, Textiles and Wearing Apparel sector, Petroleum, Chemical and Non-Metallic Mineral Products sector, and Electrical and Machinery sector, distributed in Russia, Saudi Arabia, China, the United States of America, Germany, Italy, and South Korea. There also exist sectors attributed to the tertiary industry ranking top 30 of VWSR imports, such as Re-export & Re-import sector in Germany and Netherlands, and Hotels and Restaurants sector in Saudi Arabia.

Of particular interest is China's Construction sector. Under the economic boom in large Chinese cities, massive building construction projects in the past few years have brought about shortage of domestic resources (Huang et al., 2013) which led to the high dependence on imports. It turns out that a significant share of such imports comes from water-stressed regions where situation will further deteriorate under climate change. Therefore, VWSR imports of China's Construction sector ranks 18th under both BAU and optimistic scenarios.

VWSR transmissions through the international trade are of two types corresponding to different ways to mitigate VWSRs. The influences from the Agriculture sector are primarily transmitted through substitutable products sold in the world market. On the other hand, the VWSR from the Electrical and Machinery sector travels through the trade network differently. Instead of direct trade, such VWSR is delivered via industrial sectors. Fig. 4 and Fig. S6 illustrate the transmission pathways from China and Spain's Electrical and Machinery sector to several intermediate sectors under the BAU and optimistic scenarios, respectively. For example, the VWSR of China's Electrical and Machinery sector can be transmitted to the United States of America's Electrical and Machinery sector via China's Other Manufacturing sector, Transport sector, Electricity, Gas and Water sector, Petroleum, Chemical and Non-Metallic Mineral Products sector, Transport Equipment sector, and Financial Intermediation and Business Activities sector. Therefore, the adverse effects in China may bring about the economic production reduction in China's various sectors, which will in turn influence the United States of America's Electrical and Machinery sector's economic activities which greatly import inputs from China. Such type of VWSR is challenging for mitigation by international markets, as the intermediate products may have unique designs for the downstream user and therefore cannot be reproduced in the short term (Rauch, 1996). Thus, production disruptions due to resource shortage in upstream sectors will readily translate into production losses in downstream sectors.

Fig. 4A and Fig. S7A illustrate the change of rankings for VWSR imports and LWSRs for top 20 sectors with the largest VWSR imports, under the BAU scenario and the optimistic scenario respectively. It can be discovered that the Food & Beverages sector in Russia, Saudi Arabia, Germany, the United States of America, Spain, Italy, and South Korea, as well as the Re-export & Re-import sector of Germany and Netherlands are much more vulnerable to WSRs in upstream sectors owing to their top ranks of VWSR imports and relatively low ranks of LWSRs under both BAU and optimistic scenarios. For the Food & Beverages sector in Russia, it is the most vulnerable sector to WSRs in upstream sector with 1062 million dollars VWSR imports under the BAU scenario and 1047 million dollars VWSR imports under the optimistic scenario, while the LWSR of this sector only ranks 870th with only 0.1791 million dollars under the BAU scenario and ranks 851th with 0.1788 million dollars under the optimistic scenario. This implies that the Food & Beverages sector in Russia greatly relies on importing inputs commodities from water scarcity upstream sectors. Therefore, the Food & Beverages sector in Russia should seek replaceable commodities domestically or appeal to the international economic trade system to find alternatives from other upstream sectors with adequate available water to improve the resilience to upstream sectors' WSRs.

Fig. 4B and Fig. S7B illustrate the change of rankings of VWSR exports and LWSRs for top 20 sectors with the largest VWSR exports, under the BAU scenario and the optimistic scenario respectively. Rankings of VWSR exports are relatively close to those of LWSR. The Agriculture sector in India, Iran, Kazakhstan, China, Pakistan, Uzbekistan, and Syria with high LWSRs also transmit much WSRs to other manufacturing sectors via exporting commodities. Under the BAU scenario, the VWSR export of Saudi Arabia's Agriculture sector ranks 11th followed by Kazakhstan’s Fishing sector.
sector, while under the optimistic scenario, the VWSR export of Kazakhstan's Fishing sector ranks 11th followed by Saudi Arabia's Agriculture sector, and the rankings of LWSR for Saudi Arabia's Agriculture sector and Kazakhstan's Fishing sector are 7th and 10th, respectively, under both BAU and optimistic scenarios. For India's Agriculture sector and Iran's Agriculture sector, both of LWSRs and VWSR exports of them rank top 2 under BAU and optimistic scenarios, hence, the downstream sectors are required to reduce importing commodities from these sectors to decrease their vulnerabilities to upstream sectors’ WSRs and improve the resilience of the whole international economic trade system to WSRs.

4.3. Concentration of VWSRs

Aiming at better indicating the vulnerability of countries to WSRs in foreign countries, we measure the concentration of VWSR imports of each country. Lower concurrence of upstream disruptions implies higher resilience of the economic system to maintain operation under external shocks (Kharrazi et al., 2015). Specifically, if a country import commodities from a small number of supplies which possibly experience production disruptions simultaneously, then the downstream countries are at high risk. Herfindahl index (Hirschman, 1964; Ludema and Mayda, 2013) is applied to assess

![Diagram](image_url)
the concentration degree of VWSR imports from upstream countries. The higher the Herfindahl index is, the more vulnerable of a country will be to LWSRs abroad.

Fig. 5 illustrates the Herfindahl indices (both with and without trading with India) for Pakistan, Cyprus, Kuwait, Algeria, Libya, Venezuela, and Jordan under the BAU scenario (Fig. 5A) of which the Herfindahl indices with India are much lower than those without India under both BAU and optimistic scenarios, and the
Herfindahl indices (both including and excluding India) for Sri Lanka, Bangladesh, Kenya, Nigeria, Tanzania, Uganda, and North Korea under the BAU scenario (Fig. 5B) of which the Herfindahl indices with India are much higher than those without India under two scenarios. Relevant data are listed in Table S9. The large scale of VWSR exports of India in the global trade system can bring about contrary impacts. On the one hand, it can increase the diversities of import resources, and hence make countries more resilient to foreign WSRs. On the other hand, it makes countries greatly rely on importing commodities from India, and hence makes them more vulnerable to foreign WSRs. In empirical analysis, if the Herfindahl index of a country trading with India is higher than that excluding India, trading with India would increase the vulnerability to foreign WSRs.

As demonstrated in Fig. 5A and B and Table S9, the massive scale of India’s economy diversifies import resources for Pakistan, Cyprus, Kuwait, Algeria, Libya, Iran, Spain, and Russia. However, countries including Sri Lanka, Kenya, Nigeria, Tanzania, Uganda, North Korea, Brazil, United Kingdom, Canada, US, Germany, and China rely too much on imports from India, increasing their vulnerability to decreasing water availability in India under climate change.

4.4. Sensitivity analysis

To verify the validity of the results, the robustness of sector rankings is analyzed in this section. The value of $\sigma$ in Equation (3) is changed in the range of $[1.5, 2.5]$, and the value of $\alpha$ in Equation (4) is changed in the range of $[13, 15]$. Then we recalculate the results of the established model utilized more than 10,000 $(\sigma, \alpha)$ pairs. Rankings of sectors for LWSR (Fig. 6A and Fig. S8A), VWSR exports (Fig. 6B and Fig. S8B), and VWSR imports (Fig. 6C and Fig. S8C)
Fig. 6. Kendall rank correlation coefficients for nation-sector rankings with different $\sigma$ and $\alpha$ values compared the main results presented in Results Section ($\sigma = 2$ and $\alpha = 14$, the BAU scenario). Panel A is for LWSR, Panel B is for VWSR exports, and Panel C is for VWSR imports, all at the nation-sector level.
under BAU and optimistic scenarios are discussed. The Kendall correlation coefficients based on the benchmark case (where $\sigma = 2$ and $\alpha = 14$) are computed for $(\sigma, \alpha)$ pairs. If the coefficient's value is close to 1 (as the red color areas illustrated), rankings of sectors for the related variable are much close to those of the benchmark case.

As the Fig. 6, measurements for LWSR and VWSR exports rankings at the sector level are reasonably robust, and measurements for VWSR imports rankings at the sector level are highly robust. This is primarily resulting from the systematic estimation pattern for VWSR imports which is quite different from the single-point measurements for VWSR exports and LWSRs. With the changes of $(\sigma, \alpha)$ pairs values, values of WDR and WD for some sectors may vary significantly, as their LWSR and VWSR exports values are sensitive to parameters values. Contrarily, values of VWSR imports are summarized based on a significant number of foreign sectors as origin sectors with output reduction impacted by water scarcity, and the errors of single measurements could be canceled out via adding through the international economic trade system.

5. Discussion

Climate change will have significant impacts on the availability of water resources around the world. Through the global supply network, local water scarcity matters for distant nations and sectors. This research investigates how climate change may affect the global trade system via the redistribution of global water resources. Results demonstrate that local water resources management can be critical to trade relations between countries. The “hotspot” countries and sectors with the most significant influences of local water scarcity on foreign economies are identified. For example, we show that Agriculture sector in Syria, Pakistan, Kazakhstan, India, Uzbekistan, Iran, Yemen, Morocco, and China are crucial for improving the resilience of the global trade system to WSRs under both BAU and optimistic scenarios. Therefore, decision makers should concentrate on managing water resources in these hotspots.

Countries and sectors with the most substantial VWSR imports indicating vulnerability to foreign WSRs under climate change are also identified. Manufacturing sectors in various countries, such as Food & Beverages sector in Saudi Arabia, the United States of America, Russia, Germany, Spain, Italy, and China, Textiles and Wearing Apparel sector in China, Italy, South Korea, and Turkey, and Petroleum, Chemical and Non-Metallic Mineral Products sector in China, the US, South Korea, Japan, Germany, and Saudi Arabia, are the largest VWSR importers under both BAU and optimistic scenarios. Through identifying sectors vulnerable to upstream sectors’ WSRs without the influence of economic scales, we find that in addition to the above-mentioned manufacturing sectors, sectors in the tertiary industry, including Hotels and Restaurants sector in Zimbabwe, Wholesale Trade sector in Kyrgyzstan, Private Households of Georgia and Zimbabwe, and Re-export & Re-import sector in Moldova, the United States of America, Saudi Arabia, Zimbabwe, Serbia, and Spain are vulnerable to changing water resources abroad induced by climate change. This research calls attention to the governments, enterprises, and decision makers in these vulnerable sectors the risks from global supply chain they face and enables them to explore strategies to eliminate the potential risks, such as diversifying upstream suppliers in their supply chains.

We also compare the change of rankings of VWSR imports, VWSR exports, and LWSRs at the country and the sector level under both scenarios. The rankings of VWSR exports are relatively close to those of LWSRs under the two scenarios. The Agriculture sector in India, Iran, Kazakhstan, China, Pakistan, Uzbekistan, and Syria with high LWSRs also transmit more WSRs to other manufacturing sectors in various countries via exporting commodities. Remarkably, the rankings of VWSR imports are quite different from those of LWSRs. Countries with abundant water availability, such as Russia, Germany, the US, South Korea, and Italy (WSIs are all smaller than 0.07), are vulnerable to the upstream countries’ VWSRs induced by climate change. Governments of these countries and business decision makers of the vulnerable sectors should realize the risks and explore strategies to mitigate such risks, such as appealing to international markets to find substitutions, reducing the use of water-intensive inputs and diversifying trade partners.

The methodology also explores critical origins and destinations linkages at the sector level. With some critical exporting countries getting drier under global warming, firms of VWSR importing sectors should understand water scarcity risks confronted by the exporting firms. For example, firms in Food & Beverages sector of Saudi Arabia, Russia, Germany, and the US should explore strategies to minimize the influences of WSRs in the Agriculture sector of Syria, Kazakhstan, and India. Countries should cooperatively manage and protect the critical water resources for their supply chains.

Decision makers in governments and businesses may be unaware of the threat to their supply chains brought about by the redistribution of global water resources under climate change. Therefore, this paper concludes with several recommendations.

1. National governments could manage water resources cooperatively. Production in various sectors is only related to local water shortage but also affected by foreign water shortages. For example, Japan is a country with adequate available water (WSI < 0.01), but it dramatically relies on importing commodities from foreign countries, leading to the high rank of VWSR import. India and Iran are countries predicted to suffer severe water scarcity under climate change, and they also export commodities to foreign countries, making them top VWSR exports for the global economic system. Based on the results of this study, VWSR importers and VWSR exporters could manage the supply chain-relevant water resources collectively. A tiny share of the global trade value would dramatically improve water resource management in critical regions.

2. Nation-sectors with high VWSR imports may reduce the reliance on water-intensive products and diversify importing sources. For instance, the Food & Beverages sector in Russia, Saudi Arabia, Germany, the US, Spain, Italy, and South Korea are much more vulnerable to the worsening of foreign water scarcity under climate change than to their domestic water scarcity. Hence, decision makers in such sectors can seek substitutions domestically or appeal to international market to diversify their input sources to improve their resilience to climate change-induced water shortage.

3. National governments can encourage residents to change consumption patterns. To reduce WSRs, we should also focus on water demand side management. A further phase of water demand side management should be to change consumption patterns of residents which finally drive the consumption for water. Some studies have verified that educating water users and raising water-saving consciousness among people can help to reduce water consumption (Baki et al., 2018; Russin et al., 2013). Moreover, products labels can be designed to inform consumers not only about the water footprint of a product, but also about the water scarcity risks for its production, which could affect consumers’ choices and thus mitigate WSRs.
6. Conclusions

The AR5 of the IPCC has concluded that climate change will have significant influences on the availability of global water resources. Since the risk of output reduction caused by water scarcity can be transmitted to distant nations and sectors through the global supply network, this research investigates how climate change may affect the global economy via reducing available water resources in some regions. The primary conclusions are obtained as below.

(1) Agriculture sector in Syria, Pakistan, Kazakhstan, India, Uzbekistan, Iran, Yemen, Morocco, and China are “hotspot” sectors with the most significant influences of local water scarcity on foreign countries, which are significant to improve the resilience of the global trade network to WSRs.

(2) Manufacturing sectors in various countries, such as Food & Beverages sector in Saudi Arabia, the United States of America, Russia, Germany, Spain, Italy, and China, Textiles and Wearing Apparel sector in China, Italy, South Korea, and Turkey, and Petroleum, Chemical and Non-Metallic Mineral Products sector in China, the US, South Korea, Japan, Germany, and Saudi Arabia, are the largest VWSR importers, which are much more vulnerable to foreign WSRs under climate change.

(3) Through comparing the change of rankings of VWSR imports, VWSR exports, and LWSRs at both country and sector level, we found that the rankings of VWSR exports are relatively close to LWSRs, while the rankings of VWSR imports are quite different from LWSRs. Countries with abundant available water, such as Russia, Germany, the US, South Korea, and Italy, are vulnerable to the upstream countries’ VWSRs induced by climate change.

Based on the conclusions summarized above, several recommendations are concluded for decision makers in governments and businesses to help them mitigate the potential risks they may face.

(1) National governments could manage the supply-chain relevant water resources cooperatively.

(2) Nation-sectors with high VWSR imports may reduce the reliance on water-intensive products and diversify importing sources.

(3) National governments can encourage residents to change consumption patterns by educating water users, raising water-saving consciousness among people, and designing products labels informing consumers the water scarcity risks for its production.

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Appendix A. Supplementary data

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