Journal of Cleaner Production 228 (2019) 1206–1217

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

# Linking physical water consumption with virtual water consumption: Methodology, application and implications

Xinxin Zhang [a], Junguo Liu [b, *], Xu Zhao [a, **], Hong Yang [c, d], Xiangzheng Deng [e], Xiaohui Jiang [f], Yiping Li [a]

[a] Key Laboratory of Integrated Regulation and Resource Development on Shallow Lakes, Ministry of Education, College of Environment, Hohai University, Nanjing, 210098, China
[b] School of Environmental Science and Engineering, South University of Science and Technology of China, Shenzhen, Guangdong, China
[c] Eawag, Swiss Federal Institute of Aquatic Science and Technology, Duebendorf, Switzerland
[d] Department of Environmental Science, University of Basel, Basel, Switzerland
[e] Center for Chinese Agricultural Policy, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, 100101, China
[f] Yellow River Institute of Hydraulic Research, Yellow River Conservancy Commission, Zhengzhou, Henan, China

A R T I C L E  I N F O

*Article history:*
Received 22 May 2018
Received in revised form
17 March 2019
Accepted 23 April 2019
Available online 24 April 2019

*Keywords:*
Blue water
Green water
Water resources
Water scarcity
Water use

A B S T R A C T

Physical water consumption (PW) in economic sectors are linked with virtual water consumption (VW) embodied in the supply chain of commodities. It is important to quantitatively assess PW and VW in economic sectors and understand interconnections between them for supporting water resources management. Here, we applied an IO framework to analyse how the PW is linked to the VW from both production and consumption perspectives. A water scarce region consisting of Ganzhou, Linze, and Gaotai counties (GLG) in the Heihe river basin in China is used as a case study. The agricultural sector is broken down into seven sub-sectors represented by individual major crops. From production perspective, the results show that the agricultural sector accounted for 98.1% of total PW, which can be divided into 79.0% of final demand driven water consumption and 21% of intermediate demand driven water consumption. From consumption perspective, the VW of all the sub-sectors in the agricultural sector was largely attributed to the direct VW. The sector "Food and tobacco processing" (the downstream of the agricultural sector) has the largest indirect VW among all the sectors. Most PW in GLG was used to produce the low value added primary agricultural products to fulfil the final demand (VW) outside GLG. The results suggest that the water resources management in arid regions should guide the restructuring of economy from increasing agricultural production to increasing the economic value of the embodied virtual water, and reducing the export of the virtual water from the low economic value products.


## 1. Introduction

It is widely recognized that the ever growing human consumption of goods and services are the main drivers of water resource depletion (Hoekstra and Mekonnen, 2012; Munksgaard et al., 2005; Zhao et al., 2016a). Traditional water assessment and management often focused on the physical water (surface- and ground-water) consumptions of major economic sectors, such as agriculture, power production, and mining (e.g. Dalin et al., 2017; Northey et al., 2016; Zhang et al., 2017). In the last two decades, however, there has been increasing interest in the flows of "virtual water", which refers to water used to produce products for intermediate and final demand (Lenzen, 2009; Hoekstra et al., 2011; Zhao et al., 2010).

The physical and virtual water are interrelated. Once physical water is consumed in the production process, it turns to virtual water embodied in products and can flow across economic sectors and regions through supply chains. Recognizing this "physical-virtual water" interrelationship is the basis for managing the water resources under the competing demand in different economic sectors, which has been recently recognized by more countries. For example, in 2017, China has urged to find ways to "coordinate both physical

* Corresponding author.
** Corresponding author.
*E-mail addresses:* liujg@sustech.edu.cn (J. Liu), xuzhao@hhu.edu.cn (X. Zhao).

https://doi.org/10.1016/j.jclepro.2019.04.297

and virtual water" in order to "providing technological support to safeguard national water security" in its "13th Five-Year Special Plan on Scientific and Technological Innovation in Resource Areas" (Ministry of Science and Technology, 2017). This is the first time China incorporated virtual water into the national water strategy.

The existing researches linking physical and virtual water accounting have been conducted from two perspectives. One is the production perspective, which starts from the physical water consumption (PW) of a commodity from producing regions and trace how the embodied virtual water flows across regions (Lenzen, 2009). Another is the consumption perspective, where PW occurs along the chains of production and distribution is allocated to the final consumer of products (Wiedmann, 2009). Although not differentiated by authors, there are currently two types of consumption perspectives in virtual water study. First one focuses on local consumers and allocates the final consumption of local consumers to domestic and external production (imported products). Many studies have implemented such perspective (we call it "consumption perspectiveI"in this study) to show the impacts of consumers in one region on water resources in another through the consumption of imported goods (e.g. Zhao et al., 2009; Zhang et al., 2012; Feng et al., 2017). However, the related studies provide limited insight regarding policy options for local water resource management, because water managers always focus on how to rationally assign local water resources to different uses (Wichelns, 2010). Therefore, some researchers started to examine how the final demand of the producing region and other regions drives the PW of the producing region directly and indirectly (e.g. Guan et al., 2014; Zhao et al., 2016b). Such consumption perspective links the PW of producing regions with the VW of final demand (in this study we call it "consumption perspectiveII" to distinguish with previous consumption perspective). Both production perspective and consumption perspective II are more relevant to local water policies in producing regions. However, few studies have combined the two perspectives to address the connections between PW and VW.

Studies with a production perspective usually apply a bottom-up approach to account for the virtual water flows among different regions (Hoekstra and Mekonnen, 2012; Yang et al., 2006). A bottom-up approach starts from the smallest unit feasible in accounting for the virtual water flows and aggregates each unit to the desired scale and period (Yang et al., 2013). A bottom-up approach gives detailed process analysis mainly for agricultural products, such as crops and livestock, because agriculture is by far the largest water user (Dalin et al., 2017; Liu et al., 2009; Tamea et al., 2014). However, the bottom-up approach fails in describing industrial goods and services in detail, because it is not easy to trace the entire industrial supply chain with this approach (Feng et al., 2011). In addition, the bottom-up approach is unable to distinguish the intermediate and final demand of production. This on the one hand will incur truncation error, on the other hand, the results can not reflect the inter-sectoral relationships regarding the virtual water flows through supply chains (Feng et al., 2011).

In contrast, a top-down approach usually apply a life cycle assessment (Ridoutt and Pfister, 2010) or an input-output analysis to highlight the water consumption of both local and external consumers (Serrano et al., 2016; Zhang et al., 2011; Zhao et al., 2016). A top-down approach starts from the highest level defined by the system boundary, then breaks down to lower levels (Yang et al., 2013). The top-down input-output model is widely used in estimating the virtual water consumption (VW) (e.g. Zhang et al., 2011; Serrano et al., 2016; Zhao et al., 2018), because it can avoid the truncation error and facilitate water managers to trace the VW of entire industrial supply chain (Feng et al., 2011). However, a top-down approach is usually lack of sufficient details to consider individual components of the agricultural sector, such as different crops. In the previous studies with the input-output analysis within China, crop production has been generally treated as one sector due to data limitation (e.g. Zhang et al., 2011; Zhao et al., 2016b; Liu et al., 2018). Recent development of a hybrid approach appended the bottom-up satellite accounts with more detailed agricultural sectors to the top-down input-output model (Ewing et al., 2012). This hybrid approach has been used to study the VW at EU and global level (Steen-Olsen et al., 2012; Wang and Zimmerman, 2016). However, analysing indirect VW of detailed agricultural products with this approach is still not sufficient, which is constrained by the resolution of the original input-output table (Lenzen et al., 2013). Until recently, rare studies have applied a top-down input-output model with a breakdown of the agricultural sector to study the regional physical and virtual water interrelationship focusing on agriculture dominated economy.

Arid and semiarid areas are characterized by low rainfall and limited water resources. Irrigation for agriculture in most cases is the main consumer of water (Chai et al., 2014; Pauw et al., 2000). The increasing competition for water among different agricultural products and between agriculture and industrial sectors has become a bottleneck to economic growth in arid and semiarid areas (Kahil et al., 2016). Therefore, it is important to understand how the local PW of economic sectors turns into virtual water and redistributed among different sectors driven by final demand, thereby to identify the drivers of local PW from the view of virtual water (ref).

In this study, we applied a top-down input-output framework to analyse how the local PW is linked to the VW from both production and consumption perspectives. We selected an agriculture dominated economy in arid area of China for illustration. The region is in the Heihe river basin and consisting of Ganzhou, Linze, and Gaotai counties (GLG, Fig. 1). Our research here distinguishes from the previous studies by dividing the agricultural sector into seven subsectors in an input-output framework at county level, namely wheat, maize, oil crops, cotton, fruits, vegetables, and other agricultural production. A detailed analysis of the "physical-virtual water" linkage with different economic sectors especially for agriculture related sectors can help identify the main economic factors driving sectoral water consumptions in arid and semiarid regions. Hence, the analytical framework can be a promising tool in guiding the water management in arid and semiarid areas both in China and in other countries with similar conditions.

## 2. Methods and data in the case study area

### 2.1. The GLG region

The GLG region is located in the middle reach of the Heihe River Basin, which is the second largest inland river basin in China. The GLG region also belongs to the plain irrigation regions of a prefecture-level city Zhangye, contributing 70% of GDP of the city (Li et al., 2015). The GLG region is the main consumer of water resources, accounting for over 90% of total water consumption in the Heihe River Basin (Wei et al., 2008). The total cultivated area is 1727.5 $km^2$, of which the effective irrigation area is 958.5 $km^2$, more than 50% of the total cultivated area (Gansu Statistics Bureau, 2013). Located in the arid area, the region is facing severe water scarcity. With the growing population and rapid economic development, the competition for water between different economic sectors in GLG and environment of the river basin is getting ever intense.

Agricultural production not only consumes a large amount of blue water, but also consumes green water. Blue water refers to surface water and groundwater. In GLG, blue water was mainly supplied for agricultural production through rivers and groundwater. Green water is the soil moisture directly from precipitation, used by plants via evapotranspiration (Hoekstra et al., 2011). A large

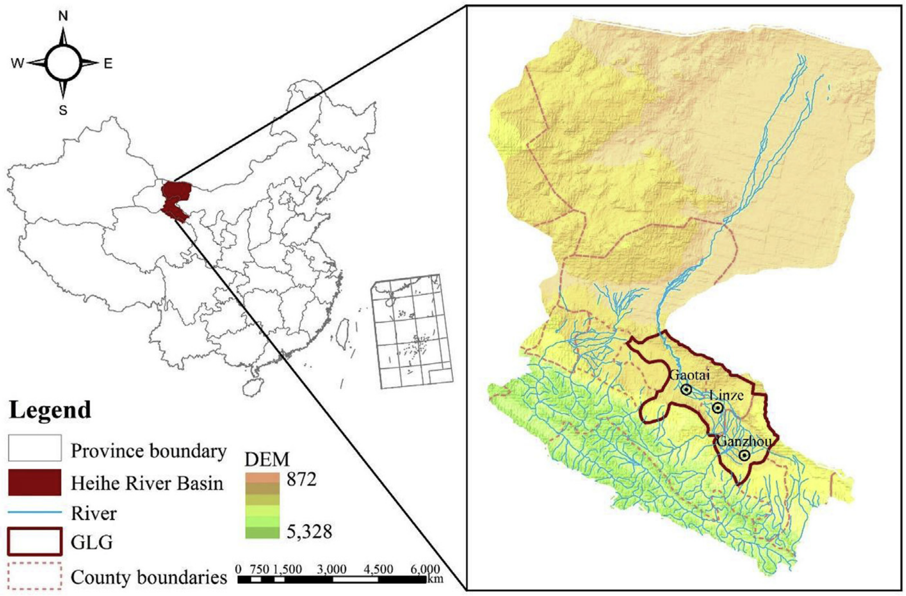


**Fig. 1.** Location of GLG in the heihe river basin, China.

quantity of blue and green water consumption is embodied in agricultural products as an intermediate input to other economic sectors. This process virtually reallocates water to other sectors. Therefore, a good understanding of the amount of both blue and green water embodied in the supply chain is important for an integrated water management concerning the entire economic system in the region.

### 2.2. Relationship between physical water and virtual water

Physical water consumption (PW) refers to water use from a river basin that renders it unavailable for further use in the same basin (Molden, 1997). It equals the water use minus return flow. Virtual water consumption (VW) refers to water used to produce raw material, auxiliary material, energy, and other inputs, which are required to produce products for final demand. Once physical water is consumed in the production process, it turns into virtual water embodied in products, and then consumed by final demand such as households within the region and outside of the region. The relationship between PW and VW from the production and consumption in this study is inspired by the input-output framework of accounting VW (Guan et al., 2014; Zhao et al., 2016b). Hence, from the production perspective, the amount of the total PW of a region is the same as the total VW (Fig. 2a).

$$\sum_i VW_i = \sum_i PW_i \tag{1}$$

where $PW_i$ denotes PW of sector $i$. The VW of sector $i$ is denoted by $VW_i$.

There are two types of demand for products: intermediate demand (e.g. an economic sector) and final demand (e.g. household and government consumption). In the production process, physical water turns into virtual water embodied in products. Then a part of virtual water embodied in products directly flows into final demand. VW during this process is called final demand-driven VW. Another part of virtual water embodied in products that are used as materials or inputs into intermediate demand and eventually ends in the final demand. This part of VW is called intermediate demand-driven VW.

For individual sectors (Fig. 2b), the water balance from the production perspective is expressed as:

$$PW_i = VW_{ii} + \sum_j VW_{ij} \tag{2}$$

where $VW_{ii}$ is the volume of virtual water embodied in products which are produced by sector $i$ and directly consumed by final demand of sector $i$, i.e., the final demand-driven water consumption. $VW_{ij}$ $(i{\neq}j)$ is the volume of virtual water embodied in products which are produced by sector $i$ and supplied to sector $j$ as input to produce final products, i.e., the intermediate demand-driven water consumption. From the consumption perspective, we look at the VW from final demand of each sector, which can be traced back to the PW consumed directly and indirectly in different sectors of GLG. In our case, since we only focus on the PW in GLG, the PW contributed to the VW from outside GLG is excluded. Therefore, the consumption perspective in our study represents the reverse direction of the production perspective (Fig. 2).

From the consumption perspective, for a sector, products which can be consumed by final demand directly require two types of input (Fig. 2b). One is the input from its own sector and the other is from other sectors. Hence, the VW of sector $i$ is the sum of water embodied in products directly for final demand that renders it unavailable for any intermediate demand (direct VW), and the water embodied in products from other sectors as inputs used by sector $i$ for final demand (indirect VW). For each sector, direct VW equals to final demand-driven VW and can be traced back to the PW of that sector (Fig. 2a). The sum of the indirect VW of all sectors equals to the sum of intermediate demand-driven VW. Hence, from the consumption perspective, the water accounting balance is expressed as:

$$VW_i = VW_{ii} + \sum_j \text{ or } VW_{ji} VW_i = PW_i - \sum_j VW_{ij} + \sum_j VW_{ji} \tag{3}$$

where $VW_{ji}$ $(i{\neq}j)$ is the volume of virtual water embodied in products which are produced by sector $j$ and supplied to sector $i$ as input to produce products for final demand, also called indirect VW.

An illustration of the above process was shown in Fig. 3. For

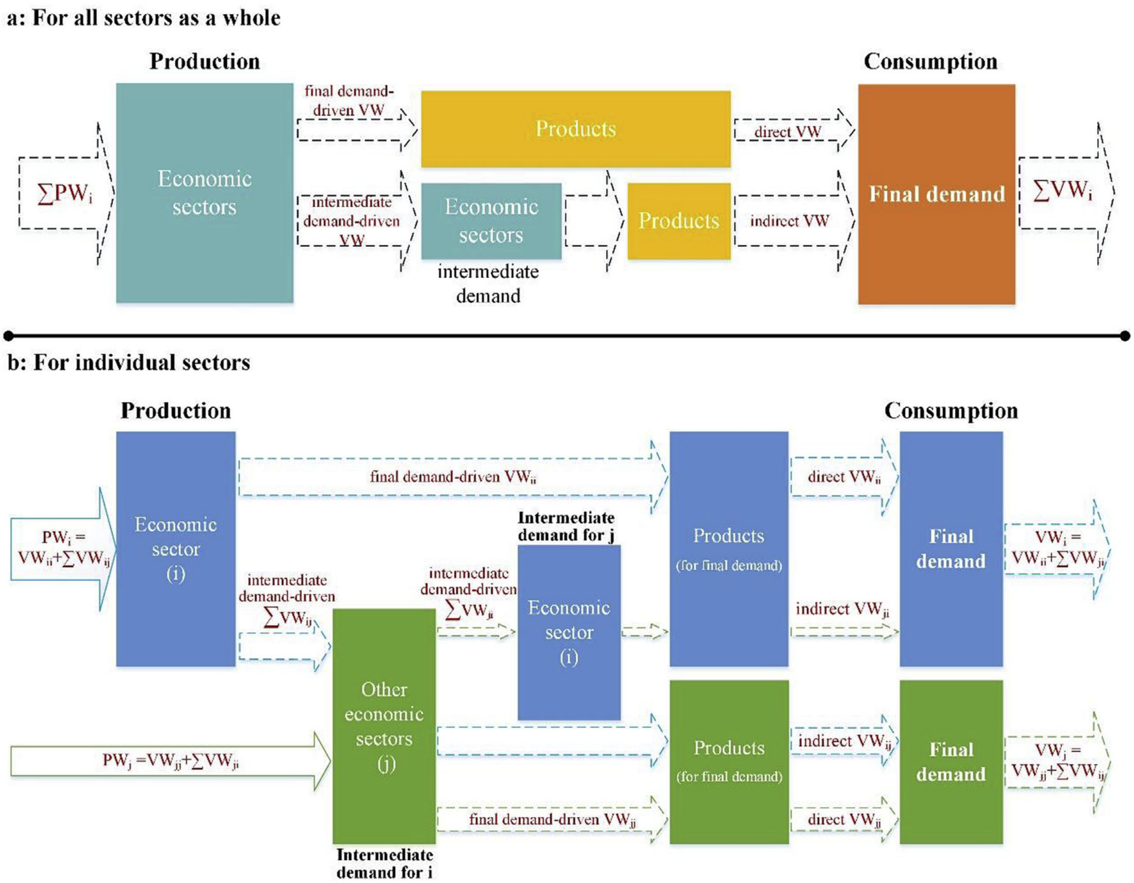


**Fig. 2.** Interpretation of water relationship between physical water and virtual water.

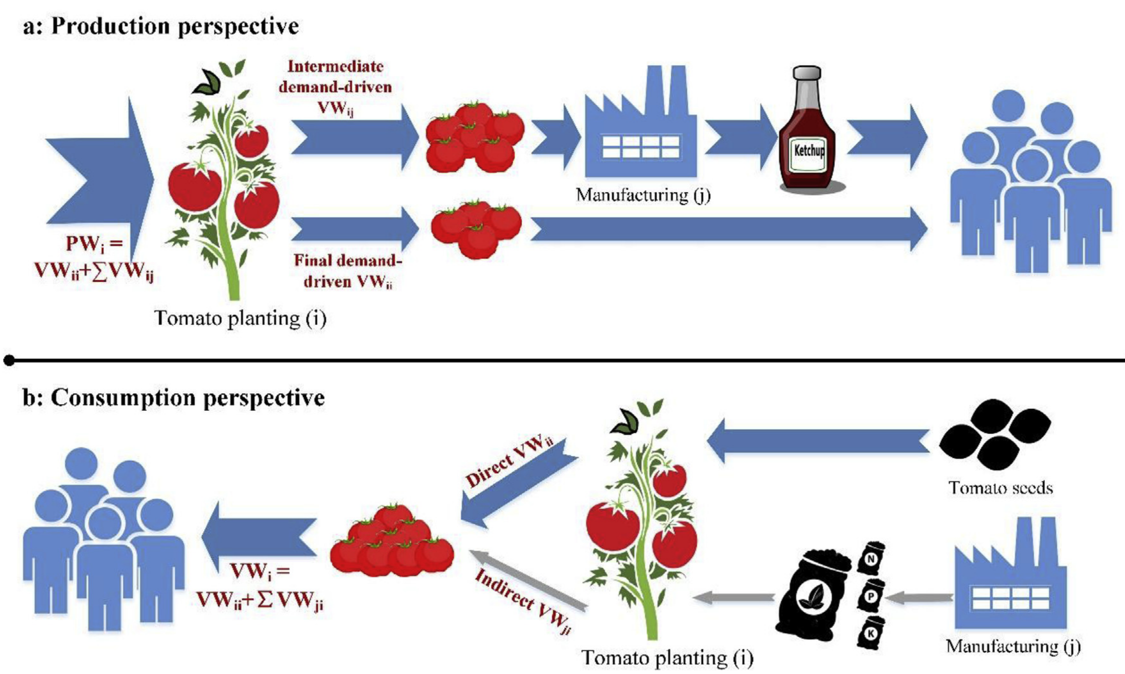


**Fig. 3.** Water relationship between physical and virtual water in tomato products.

example, from the production perspective, tomato can be directly consumed by household (Fig. 3a). Here, household represents the final demand for tomato. Meanwhile, tomato can also be used by the manufacture sector as input to produce ketchup. Here the manufacturing sector is intermediate demand for tomato. From the consumption perspective, as shown in Fig. 3b, in order to produce tomato for final demand, the tomato production not only requires the input from its own sector like seeds, but also requires input from other sectors, like fertilizer and electricity. Here, for the tomato production in the consumption perspective, virtual water embodied in seeds is direct VW, while virtual water embodied in fertilizer and electricity is indirect VW. Both direct and indirect VW can be traced back to the PW for individual sectors.

Finally, we define the difference between $VW_i$ and $PW_i$ as VW receiver or supplier:

$$VWi - PWi = \Sigma VWji - \Sigma VWij \tag{4}$$

$$\begin{bmatrix} VW_{11} & VW_{12} & \cdots & VW_{1i} \\ VW_{21} & VW_{22} & \cdots & VW_{2i} \\ \vdots & \vdots & \vdots & \vdots \\ VW_{i1} & VW_{i2} & \cdots & VW_{ii} \end{bmatrix} = \begin{bmatrix} \frac{PW_1}{X_1} & 0 & \cdots & 0 \\ 0 & \frac{PW_2}{X_2} & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & \frac{PW_i}{X_i} \end{bmatrix} \begin{bmatrix} L_{11} & L_{12} & \cdots & L_{1i} \\ L_{21} & L_{22} & \cdots & L_{2i} \\ \vdots & \vdots & \vdots & \vdots \\ L_{i1} & L_{i2} & \cdots & L_{ii} \end{bmatrix} \begin{bmatrix} Y_1 & 0 & \cdots & 0 \\ 0 & Y_2 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & Y_i \end{bmatrix} \tag{8}$$

where VW receiver refers to a sector's total input of virtual water is greater than the total output of virtual water, and vice versa for the VW supplier.

In this study, we focus on tracing the local water resources involved throughout the production and consumption chains. The intermediate and final demand for products can be the consumers within the region and outside of the region. Therefore, the water embodied in the products of the region for export, which represents virtual water export, should be considered in the water consumption process (Zhao et al., 2016b). The water embodied in the imported products is from other regions, which is not relevant to local water uses. Hence the virtual water import is not considered in the following analysis. Similar analysis can be found in the researches by Guan et al. (2014) and Zhao et al. (2016b).

## 2.3. The input-output model of water consumption

The basic equations of input-output model are shown below following Miller and Blair (2009):

$$X = AX + Y \tag{5}$$

where $\boldsymbol{X}$ is the vector of sectoral output. $\boldsymbol{A} = [\alpha_{ij}]$ is the matrix of technical coefficient ($\alpha_{ij}$), $\boldsymbol{Y}$ is the vector of final demand which includes rural and urban household ($\boldsymbol{f_1}$), government expenditure ($\boldsymbol{f_2}$), total capital formation ($\boldsymbol{f_3}$), and export ($\boldsymbol{f_4}$).

Given arbitrary Y, X can be solved as:

$$X = (I - A)^{-1} Y \tag{6}$$

where $\boldsymbol{I}$ is a matching identity matrix, $(\boldsymbol{I}\text{-}\boldsymbol{A})^{-1}$ is the Leontief inverse matrix.

The VW is achieved by linking the Leontief inverse with PW:

$$\mathrm{VW} = \frac{\mathrm{PW}}{\mathrm{X}} (\mathrm{I} - \mathrm{A})^{-1} (f_1 + f_2 + f_3 + f_4) \tag{7}$$

where $PW$ is the vector of physical water consumption in each economic sector.$\frac{PW}{X}(I - A)^{-1}$ refers to the economic water use intensity (EWUI).

Based on equation (7), the water transformation matrix between physical water and virtual water among economic sectors can be shown as:

where $L$ is Leontief inverse matrix, $L$=(I-A)$^{-1}$. $Y$ is final demand, $Y = f_1 + f_2 + f_3 + f_4$.

The matrix results of equation (8) can be further processed to reflect PW and VW balance shown in equations (2) and (3). Specifically, summing up all the columns on the left side of equation (8), we can have the water balance from production perspectives in the IO framework:

$$\begin{bmatrix} PW_1 \\ PW_2 \\ \vdots \\ PW_i \end{bmatrix} = \begin{bmatrix} VW_{11} + \sum_{j \neq 1} VW_{1j} \\ VW_{22} + \sum_{j \neq 2} VW_{1j} \\ \vdots \\ VW_{ii} + \sum_{j \neq i} VW_{ij} \end{bmatrix} \tag{9}$$

Summing up all the rows on the left side of equation (8), we can have the water balance from consumption perspectives in the input-ouput framework:

$$[VW_1 \quad VW_2 \quad \cdots \quad VW_i] = \left[ VW_{11} + \sum_{j \neq 1} VW_{j1} \quad VW_{22} + \sum_{j \neq 2} VW_{j2} \quad \cdots \quad VW_{ii} + \sum_{j \neq i} VW_{ji} \right] \tag{10}$$

### 2.4. Green and blue physical water consumption in the agricultural sector

We assume only the agricultural sector directly consumes green physical water for crop production. We are aware that blue and green water consumptions can be interrelated. For example, flow regulations and irrigation (blue water consumption) can change hydroclimatic features on land, leading to changes in green water consumption (Jaramillo and Destouni, 2015a, 2015b). In this study, the impact of blue water consumption on the changes of green water consumption is not considered, like in all other studies on virtual water. Investigating the interrelationship between blue and green water consumption is beyond the scope of this study.

The quantification of green and blue PW for the agricultural sector can be shown as follows (Zhao et al., 2017).

Green PW for the agricultural sector:

$$PW_{green} = \frac{\sum_k (ER_k \times h_k)}{\sum_k h_k} \times S_T \tag{11}$$

Blue PW for the agricultural sector:

$$PW_{blue} = \frac{\sum_k (Irr_k \times h_k)}{\sum_k h_k} \times S_T \tag{12}$$

where $ER_k$, $Irr_k$, $h_k$ are the effective rainfall, irrigation and harvested area of crop k, respectively, $S_T$ is the total harvested area of the studied area.

In this study, the CropWat model (available at: http://www.fao.org/land-water/databases-and-software/cropwat/en/) is used to simulate *ER* (effective rainfall) and *Irr* (irrigation requirement) of the seven types of crops in agricultural sectors (wheat, maize, oil crops, cotton, fruits, vegetables, and other agricultural production). Developed by the Food and Agriculture Organization (FAO), CropWat model uses the FAO Penman-Monteith method to calculate reference crop evapotranspiration which can be divided into *ER* and *Irr*. This model is a simple and widely used model to estimate green and blue PW of crops (e.g. Mekonnen and Hoekstra, 2011; Zhao et al., 2017; D'Odorico et al., 2019). Zeng et al. (2012) has used a bottom-up approach with the CropWat model to simulate *ER* and *Irr* for 12 crop types in the Heihe River Basin, where GLG is located. In this study, we considered seven types of crops using the results from Zeng et al. (2012). The rest types of crops and other agricultural products are bundled into “other agricultural production”. It should be noted that the blue PW of livestock is not included. Therefore, the Blue PW in “other agricultural production” is underestimated in this study.

### 2.5. Data

The 2012 input-output table for GLG was collected from the Heihe Data Research Group (http://www.heihedata.org/data/d29beb4a-ced3-456e-a7c5- a1debbf5076f). China's regional blue PW data with details of industrial sectors is not available in ordinary water statistics. In this study, the blue PW data of 39 secondary and tertiary sectors was collected from the Yellow River Conservancy Commission. This dataset was acquired based on the First National Census for Water, which is the only nationwide census currently covering detailed water consumption data of economies and society, and basic conditions of rivers and lakes etc. (Ministry of Water Resources, 2013). Since this census takes year 2011 as census period, the blue PW data with details of industrial sectors for GLG is only available in year 2011. Hence, we assume that the PW and EWUI in 2012 was the same as in 2011. The green and blue PW for different agricultural sector was estimated through CropWat model.

The original input-output table is adjusted to 46 sectors according to sectoral blue water consumption data, including 7 sectors of the primary industry, 25 sectors of the secondary industry, and 14 sectors of the tertiary industry (Appendix Table A1). In Gansu official statistics, the agricultural sector is the only component in the primary industry (Gansu Statistics Bureau, 2013). It should be mentioned that electricity can be supplied through both thermal plants and hydropower. However, the statistics only accounted for the water consumption from thermal plants. In our study, water consumption from hydropower through evaporation is not considered.

The PW, VW and EWUI are first quantified for the 46 sectors (Appendix Table A1). As the agricultural water consumption accounts for about 98% of the total water consumption in the region and the secondary and tertiary industries account for only very small amount of PW and VW, we made aggregation of the individual sectors in these two industries. The agricultural sector is divided into 7 sub-sectors: wheat, maize, oil crops, cotton, fruits, vegetables, and other agriculture production (respectively account for 8.4%, 50.6%, 0.7%, 0.2%, 16.3%, 13.2%, and 10.6% of cultivated area in the region). The secondary industry includes two sectors: food and tobacco processing and other secondary sector, and the tertiary industry is considered as one sector.

**Table 1**
Water consumption accounting within the GLG region.

| Economic sectors | PW (Mm3) | | | VW (Mm3) | | |
|---|---|---|---|---|---|---|
| | Total ($PW_i$) | Final demand -driven ($VW_{ii}$) | Intermediate demand-driven ($\sum VW_{ij}$) | Total ($VW_i$) | Direct ($VW_{ii}$) | Indirect ($\sum VW_{ji}$) |
| **Primary industry (Agricultural Sector)** | | | | | | |
| Wheat | 67.14 | 54.81 | 12.33 | 54.96 | 54.81 | 0.15 |
| Maize | 424.26 | 313.51 | 110.75 | 313.69 | 313.51 | 0.18 |
| Oil crops | 5.44 | 4.25 | 1.19 | 4.40 | 4.25 | 0.15 |
| Cotton | 15.98 | 12.87 | 3.11 | 12.87 | 12.87 | 0.01 |
| Fruits | 135.79 | 111.32 | 24.47 | 111.52 | 111.32 | 0.20 |
| Vegetables | 109.44 | 92.58 | 16.86 | 93.04 | 92.58 | 0.46 |
| Other agricultural production | 88.19 | 79.48 | 8.71 | 108.21 | 79.48 | 28.73 |
| **Secondary industry** | | | | | | |
| Food and tobacco processing | 3.41 | 3.28 | 0.13 | 147.06 | 3.28 | 143.78 |
| Other secondary sector | 11.62 | 7.19 | 4.43 | 11.07 | 7.19 | 3.87 |
| **Tertiary industry** | 1.00 | 0.90 | 0.10 | 5.45 | 0.90 | 4.55 |
| **Total** | 862.27 | 680.19 | 182.08 | 862.27 | 680.19 | 182.08 |

## 3. Results

### 3.1. Physical-virtual water linkage from the production perspective

Our results showed that the total PW was about 862.27 $Mm^3$ in the GLG region. The agricultural sector dominated the PW of GLG, consuming 98.1% of the total PW. "Maize" was the largest physical water consuming sub-sector in the agricultural sector, accounting for 50.1% of total PW in the sector and followed by "fruits" (16.0%), "vegetables" (12.9%), "other agricultural production" (10.4%), and "wheat" (7.9%). The PW of secondary and tertiary industries in GLG accounted for a very small percentage, only about 1.7% and 0.1% of total PW, respectively.

From the production perspective (Eq. (2) and (9)), the PW was virtually reallocated among economic sectors, which can be categorised as intermediate demand-driven VW and final demand-driven VW (Table 1). Summing up all sectors, there were 680.19 $Mm^3$ of final-demand driven VW, and 182.08 $Mm^3$ of intermediate-demand driven VW. The final demand-driven VW dominated the water consumption of the agricultural sector, accounting for 79.0% of total PW in agricultural sector. The results demonstrated that most products in agricultural sector of GLG were not used as raw materials for the production of final demand in other sectors, but were used for the consumption of final demand in their own sectors.

According to Eq. (7), the consumption of final demand can be further divided as domestic final demand and export (Appendix Table A.2-A.3). We found that about 92% of PW in GLG was virtually exported to other regions outside GLG, among which 98% was from the agricultural sector. The final-demand driven water consumption accounted for 67.8% of PW virtually directed to domestic final demand, but accounted for 80% of PW virtually directed to export. Hence, we can infer that the PW of GLG was mainly driven by the export of large proportion of final-demand driven virtual water from the agricultural sector, which implies the economic dependence of GLG on the export of primary agricultural products. While these primary agricultural products are characterized as low value added compared to the processed agricultural products (Whitton, 2004).

### 3.2. Physical-virtual water linkage from the consumption perspective

Based on Eq. (1), the total VW was equal to the total PW in the region. From the consumption perspective (Eq. (3) and (10)), the total VW can be divided into direct VW and indirect VW. The right side of Fig. 4 shows that the agricultural sector has the largest amount of VW, accounting for 81.0% of total VW in the region. Another sector with relatively large amount of VW were "food and tobacco processing" (17.0%). "Food and tobacco processing" stood out because its final demands were supplied mainly by the agricultural sector of GLG. The direct and indirect VW values are shown in Table 1. The VW of the all sub-sectors in the agricultural sector was largely attributed to the direct VW. The sub-sectors contributed most to the direct VW are "maize", "fruits", "vegetables", "other agricultural production", and "wheat". These five sub-sectors altogether accounted for 95.8% of direct VW (Table 1). "Food and tobacco processing" has the largest indirect VW (143.78 $Mm^3$) among all the sectors, accounting for about 79% of indirect VW. Most of this indirect VW can be traced back to the PW of agricultural sector as intermediate input.

Comparing the results from the production and consumption perspectives, we can identify if a sector is a virtual water supplier or a receiver. We found that most sub-sectors in the agricultural sector are virtual water suppliers except for "Other agricultural production" which ranked second as the virtual water receiver (Fig. 5). This may be because this sub-sector includes livestock production, which consumes a large amount of grain, such as maize and wheat (Ermgassen et al., 2017). As a result, the indirect VW in "Other agricultural production" was largely linked to the PW in other sub-sectors of agricultural sector, making it higher than other sub-sectors of the agricultural sector. The sectors ranking first and third as virtual water receivers are "Food and tobacco processing" and the tertiary industry, the indirect VW of which can be also linked to the PW of the agricultural sector.

### 3.3. Linking green water consumption in agriculture to virtual water consumption of all sectors

From the production perspective, only the agricultural sector

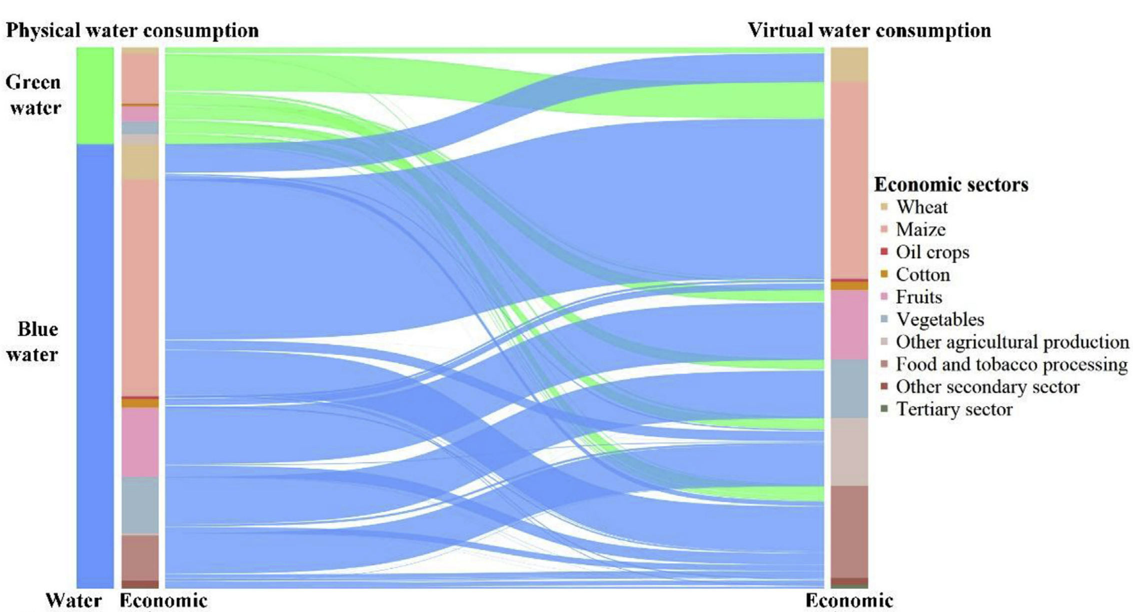


**Fig. 4.** Virtual water flows among economic sectors.

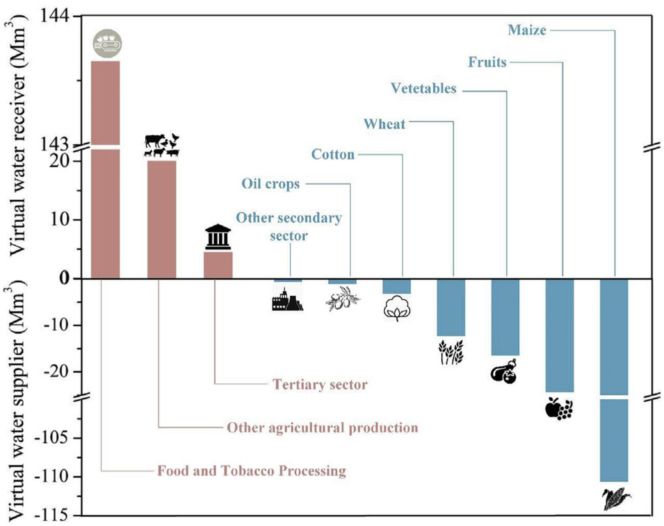


**Fig. 5.** Virtual water receiver and supplier of economic sectors. The value of economic sector which is lower than 0.2 is not shown in the graph.

consumed green water that amounted to about 154.23 $Mm^3$, accounting for 17.9% of total PW (Fig. 4). The relatively small amount of green PW is related to the arid climate in the region.

From the production perspective, the green physical water entered into the agricultural sector of GLG and was divided into 121.78 $Mm^3$ of final demand-driven virtual water and 32.45 of $Mm^3$ intermediate demand-driven virtual water. The ratio of intermediate demand-driven VW to the PW in different sectors ranged from 10% (Other agricultural production) to 26% (Maize). The sector with the largest intermediate demand-driven VW was also Maize (20.56 $Mm^3$). This means Maize contributed most to the indirect VW of other sectors.

From the consumption perspective, the direct green VW of the secondary and tertiary industries were zero, but the indirect green VW of these industries accounted for 84% of total indirect green VW. In contrast, there are 121.78 $Mm^3$ of the direct green VW in the agricultural sector, but only 5.19 $Mm^3$ of indirect green VW.

## 4. Discussion

### *4.1. Linking physical water and virtual water in a unified accounting framework*

This study illustrated the transformation of physical water to virtual water and explored how properties of VW in water resources management compared with PW with an input-output model. There are also a few previous studies focusing on the PW or VW of GLG or Zhangye city where GLG is located using an input-output model (e.g. Wang et al., 2009; Feng et al., 2017). These studies addressed the typical conflicts between growing human demand and aggravated water stress in arid area. Our results have confirmed several previous findings. First, agriculture is responsible for the largest part of blue PW in Zhangye and GLG. Wang et al. (2009) found that 95% of blue PW for producing goods and services was directed to agricultural sector of Zhangye in 2002. While our study showed that 97.8% of blue PW for production was attributed to agricultural sector of GLG in 2012. Second, most of the PW of agricultural products are virtually exported to other regions outside GLG. A decomposition analysis have shown that virtual water export of agricultural sector contributed the most to PW increase in Zhangye (Feng et al., 2017). While our study found that about 92% of PW in GLG was virtually exported, among which 98% was from the agricultural sector.

Apart from the above findings, this study distinguishes itself from existing literature with two aspects. First, this study disaggregated agricultural sector in an input-output framework. It helps water resource managers to judge if the crops are suitable to plant in terms of their impact to limited local water resources. Under the input-output framework, this can be achieved through examining PW, VW and EWUI. For the six crops considered, their PW and VW have the same ranking, which were “maize”, “fruits”, “vegetables”, “wheat”, “cotton”, and “oil crops” (Table 1). While the rankings of EWUI were “maize”, “cotton”, “fruits”, “wheat”, “vegetables”, and “oil crops” (Appendix Table A1). Since “maize” had the largest value of PW, VW, and EWUI among all the sectors, and high EWUI represents low economic value of water intensive products (Zhao et al., 2016a). Substituting “maize” production with crops with lower value of EWUI, such as “vegetables” and “oil crops” may be recommended.

Second, our framework can identify multiple relevant determining factors contributing to VW derived from local PW through recognizing the following differences. (i) The VW is driven by either domestic final demand or export; (ii) The sectoral PW can be assigned to either final or intermediate demand-driven VW; (iii) The final or intermediate demand-driven VW from the PW of the same sector has different EWUI. The third difference can be illustrated through the following case. For example, the EWUI of “maize” in GLG is the highest among all sectors. While the EWUI of “food and tobacco processing” in GLG is 12 $m^3$/thousand CNY (Table A1). This means 1 $m^3$ of virtual water can produce 3.9 CNY of products from “maize” but 83.3 CNY of products belong to the sector of “food and tobacco processing”. Hence, same amount of virtual water embodied in “maize” that sell to consumers will generate less economic value than the virtual water embodied in “maize” that used as raw materials for “food and tobacco processing”. In another word, the final demand-driven VW of “maize” has higher EWUI than the part of intermediate demand-driven VW of “maize” directed to “food and tobacco processing”.

Combing the above differences in the GLG case, we found that about 92% of local PW turned into the virtual water export to other regions outside GLG, among which 98% was from the agricultural sector. In the meanwhile, 80% of exported virtual water from agricultural sector is final demand-driven VW. Hence, it can be concluded that most PW in GLG was used to produce the low value added primary agricultural products to fulfil the final demand outside GLG. This finding can be used to direct some actions towards the water conservation in GLG. First, cutting the products export from the agricultural sector is the key to conserve the limited water resources in GLG. Second, the results showed the necessity of changing the current final demand-driven economy of the agricultural sector in GLG, or in other words increasing the rate of intermediate demand-driven VW of the agricultural sector. These goals can be achieved through stimulating some new economic growth engines, thereby to guide the restructuring of the economy. Specifically, this means the GLG government can choose to develop the secondary and tertiary industries that need large input of indirect VW from the agricultural sector. This action is actually to increase the economic water productivity of the VW derived from the PW of agricultural sector. This on the one hand will increase the economic value of the embodied virtual water in the agricultural sector, on the other hand will reduce the export of the current products from the local agricultural sector. The development of the secondary and tertiary industries will also provide new employment opportunities and direct the farmers to voluntarily leave agriculture to pursue more lucrative employment, as a result, reducing the VW losses from the agricultural sector.

### 4.2. Limitations

Although our analysis improved the understanding of the relationship between PW and VW, there are several limitations that require future research. One of the limitations is we only consider blue and green water, and ignore the grey water (or water pollution) in our analysis. This is mainly because of lack of data. Wastewater generated during the production can pollute surface water and groundwater, resulting in a decrease in the useable freshwater, which can be regarded as additional physical water use (Zhao et al., 2010). However, a precise calculation of grey water in the IO framework needs to consider each sector's composition of pollutants and the dilution capacity of water bodies to those pollutants. Collection of such data is beyond the scope of this study. The second limitation is due to the application of single-region input-output analysis. Consequently, the study only provides information on water consumption among economic sectors within GLG, but is unable to provide detailed results of water consumption among economic sectors beyond the study area. The third limitation is that this study did not distinguish surface water and groundwater for the blue physical water resources. The exploitation of groundwater has increased dramatically in the irrigation districts of the GLG region. This problem is also common in many parts of the world. It's significant to distinguish the dependence of economic sectors on surface water and groundwater in the future study. The fourth limitation is that we assumed PW and EWUI in GLG are consistent between 2011 and 2012. This is mainly because PW data with sector details in GLG is only available for year 2011. But we argue that this assumption is reasonable because on the one hand the economic output of Primary, Secondary, and Tertiary sectors in GLG have not changed a lot between 2010 and 2011, according to Zhangye Statistic Yearbook (Zhangye Statistic Bureau, 2012). On the other hand, since GLG is located in the middle reach of the Heihe River Basin, and water allocation to the middle reach is almost fixed since 2000 (Shi et al., 2014), this leads to minor changes of the PW in GLG and Zhangye. According Feng et al. (2017), the largest change rate of blue PW in Zhangye between any adjacent years among 2001–2010 is 1.6%. Last but not least, although other crops, livestock and other agricultural products are bundled into the sector of “other agricultural production”, the blue PW of livestock and other agricultural products is not included in this sector. Such mismatch between PW and economic production distorts the interrelationship between VW of this sector and VW of other sectors, which could be corrected in the future through improved estimation of PW in different agricultural sub-sectors.

## 5. Conclusion

In this study, we provided a comprehensive framework to account for the “physical-virtual water” linkages among different economic sectors from both production and “consumption perspectiveII” for an agriculture dominated region. Based on input-output analysis, the framework can help to understand that the local PW of one sector is actually driven by the VW embodied in the final demand of all different sectors, thereby to identify the drivers of local PW with regard to economic sectors. Specifically, from the production perspective, one can investigate how much PW of a sector turns into the final or intermediate demand-driven VW of all different sectors, while from the consumption perspective one can know how much PW of all different sectors contributes to the VW of this sector. In addition, our framework also highlighted the inter-sectoral redistribution of both the blue and green virtual water for final demand derived from local physical water supply. As a result, one can identify if a sector is a virtual water receiver or a supplier through the virtual water redistribution. Our results showed that, as an agriculture dominated arid region, the economy of GLG has largely relied on low value added primary agricultural productions. And these productions are mostly directed to fulfil the final demand of regions outside GLG. As a results, a great amount of agricultural PW in GLG was transferred to final demand-driven VW and virtually exported to regions outside GLG. Such results along with other studies focusing on agriculture dominated arid and semi-arid regions (e.g. Velázquez, 2007; Lenzen, 2009; Zhao et al., 2015), raised a widespread concern that how to deal with the scarce water leakage due to producing exported products (Hoekstra and Mekonnen, 2012; Zhao et al., 2018). Based on both production perspective and “consumption perspectiveII”, the framework we offered in this study can be promisingly associated with the policies in producing regions, helping to identify key agricultural subsectors and offer waster saving solutions towards agricultural production structure adjustment. Future research can extended the current framework to a multi-region input-output model to compare the trade-off between water savings of importing regions and water losses of exporting regions, adding global perspective to current framework.

## Acknowledgements

This study was supported by the National Natural Science Foundation of China (41625001, 41571022, 51711520317). Additional support was provided by the Guangdong Provincial Key Laboratory of Soil and Groundwater Pollution Control (Grant No. 2017B030301012), State Environmental Protection Key Laboratory of Integrated Surface Water-Groundwater Pollution Control, the Fundamental Research Funds for the Central Universities (No. 2016B13814), and A Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions. The present work was partially developed within the framework of the Panta Rhei Research Initiative of the International Association of Hydrological Sciences by the working group “Water Scarcity Assessment: Methodology and Application”. The input data of green and blue water consumption, as well as the raw data for the input-output analysis are available via a repository (https://doi.org/10.6084/m9.figshare.6005234.v1).

## Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.04.297.

**Table A.1**
Economic Water Use Intensities (EWUI) Unit: m3/thousand CNY

| | Sectors | Blue EWUI | Green EWUI | EWUI |
|---|---|---|---|---|
| **Primary industry (Agricultural sector)** | | | | |
| 1 | Wheat | 69.78 | 13.51 | 83.30 |
| 2 | Maize | 207.17 | 47.22 | 254.39 |
| 3 | Oil crops | 4.35 | 0.95 | 5.30 |

**Table A.1** (*continued* )

| | Sectors | Blue EWUI | Green EWUI | EWUI |
|---|---|---|---|---|
| 4 | Cotton | 183.58 | 40.81 | 224.38 |
| 5 | Fruits | 106.85 | 23.73 | 130.58 |
| 6 | Vegetables | 32.75 | 7.26 | 40.01 |
| 7 | Other agricultural production | 10.87 | 2.40 | 13.27 |
| **Secondary industry** | | | | |
| 8 | Coal Mining and Dressing | 0.27 | 0.03 | 0.31 |
| 9 | Petroleum and Natural Gas Extraction | 0.00 | 0.00 | 0.00 |
| 10 | Metals Mining and Dressing | 0.12 | 0.00 | 0.13 |
| 11 | Nonmetal Minerals Mining and Dressing | 3.88 | 0.01 | 3.88 |
| 12 | Food and Tobacco Processing | 9.78 | 2.10 | 11.88 |
| 13 | Textile Industry | 0.00 | 0.00 | 0.00 |
| 14 | Garments, Leather, Furs, Down and Related Products | 0.00 | 0.00 | 0.00 |
| 15 | Timber Processing and Furniture Manufacturing | 14.16 | 0.01 | 14.17 |
| 16 | Papermaking, Cultural, Educational and Sports Articles | 0.69 | 0.07 | 0.77 |
| 17 | Petroleum Processing and Coking | 0.65 | 0.00 | 0.65 |
| 18 | Chemicals | 0.32 | 0.01 | 0.33 |
| 19 | Nonmetal Mineral Products | 0.66 | 0.01 | 0.66 |
| 20 | Smelting and Pressing of Metals | 0.29 | 0.00 | 0.30 |
| 21 | Metal Products | 0.26 | 0.00 | 0.26 |
| 22 | General and Specialized Machinery | 0.27 | 0.00 | 0.27 |
| 23 | Transportation Equipment | 0.00 | 0.00 | 0.00 |
| 24 | Electric Equipment and Machinery | 0.00 | 0.00 | 0.00 |
| 25 | Electronic and Telecommunications Equipment | 0.00 | 0.00 | 0.00 |
| 26 | Instruments, Meters Cultural and Office Machinery | 0.00 | 0.00 | 0.00 |
| 27 | Artwork and other Manufacturing Products | 0.05 | 0.00 | 0.05 |
| 28 | Recycling and disposal of waste | 0.00 | 0.00 | 0.00 |
| 29 | Electricity and Heating Power Production and Supply | 1.53 | 0.00 | 1.54 |
| 30 | Gas production and supply | 0.00 | 0.00 | 0.00 |
| 31 | Tap water production and supply | 78.06 | 0.01 | 78.07 |
| 32 | Construction | 0.51 | 0.05 | 0.56 |
| **Tertiary industry** | | | | |
| 33 | Transport, storage, and postal services | 0.76 | 0.15 | 0.91 |
| 34 | Information transfer, computer services, and software | 0.19 | 0.01 | 0.19 |
| 35 | Wholesale and retail trades | 0.12 | 0.02 | 0.14 |
| 36 | Accommodation and catering | 0.59 | 0.11 | 0.70 |
| 37 | Finance | 0.15 | 0.01 | 0.16 |
| 38 | Real estate | 0.19 | 0.01 | 0.20 |
| 39 | Leasing and commercial services | 0.19 | 0.00 | 0.20 |
| 40 | Scientific research, polytechnic services, and geological prospecting | 0.32 | 0.01 | 0.33 |
| 41 | Administration of water, environment, and public facilities | 1.08 | 0.23 | 1.31 |
| 42 | Resident and other services | 0.42 | 0.07 | 0.49 |
| 43 | Education | 0.55 | 0.00 | 0.56 |
| 44 | Health care, social insurance/welfare | 0.28 | 0.00 | 0.28 |
| 45 | Culture, sports, and entertainment | 0.18 | 0.01 | 0.18 |
| 46 | Public administration and social organizations | 0.20 | 0.01 | 0.20 |

**Table A.2**
Physical and virtual water consumption from export

| Economic sectors | *PW* ($Mm^3$) | | | *VW* ($Mm^3$) | | |
|---|---|---|---|---|---|---|
| | Total ($PW_i$) | Final demand -driven ($VW_{ii}$) | Intermediate demand-driven ($\sum VW_{ij}$) | Total ($VW_i$) | Direct ($VW_{ii}$) | Indirect ($\sum VW_{ji}$) |
| **Agricultural sector** | | | | | | |
| Wheat | 61.58 | 50.92 | 10.66 | 51.06 | 50.92 | 0.13 |
| Maize | 402.90 | 306.78 | 96.12 | 306.96 | 306.78 | 0.18 |
| Oil crops | 5.17 | 4.14 | 1.03 | 4.29 | 4.14 | 0.15 |
| Cotton | 15.60 | 12.87 | 2.73 | 12.87 | 12.87 | 0.01 |
| Fruits | 120.98 | 99.62 | 21.36 | 99.79 | 99.62 | 0.18 |
| Vegetables | 96.64 | 82.07 | 14.57 | 82.48 | 82.07 | 0.41 |
| Other agricultural production | 73.18 | 65.53 | 7.65 | 89.22 | 65.53 | 23.69 |
| **Secondary industry** | | | | | | |
| Food and tobacco processing | 3.04 | 2.93 | 0.11 | 131.54 | 2.93 | 128.61 |
| Other secondary sector | 6.37 | 3.24 | 3.13 | 4.91 | 3.24 | 1.67 |
| **Tertiary industry** | 0.24 | 0.16 | 0.08 | 2.59 | 0.16 | 2.42 |
| **Total** | 785.70 | 628.26 | 157.44 | 785.70 | 628.26 | 157.44 |

**Table A.3**
Physical and virtual water consumption from domestic final demand

| Economic sectors | *PW* ($Mm^3$) | | | *VW* ($Mm^3$) | | |
|---|---|---|---|---|---|---|
| | Total ($PW_i$) | Final demand -driven ($VW_{ii}$) | Intermediate demand-driven ($\sum VW_{ij}$) | Total ($VW_i$) | Direct ($VW_{ii}$) | Indirect ($\sum VW_{ji}$) |
| **Agricultural sector** | | | | | | |
| Wheat | 5.56 | 3.89 | 1.67 | 3.90 | 3.89 | 0.01 |
| Maize | 21.36 | 6.73 | 14.63 | 6.74 | 6.73 | 0.00 |
| Oil crops | 0.27 | 0.11 | 0.15 | 0.12 | 0.11 | 0.00 |
| Cotton | 0.38 | 0.00 | 0.38 | 0.00 | 0.00 | 0.00 |
| Fruits | 14.81 | 11.70 | 3.10 | 11.72 | 11.70 | 0.02 |
| Vegetables | 12.80 | 10.51 | 2.29 | 10.56 | 10.51 | 0.05 |
| Other agricultural production | 15.02 | 13.95 | 1.07 | 18.99 | 13.95 | 5.04 |
| **Secondary industry** | | | | | | |
| Food and tobacco processing | 0.37 | 0.35 | 0.02 | 15.52 | 0.35 | 15.18 |
| Other secondary sector | 5.25 | 3.95 | 1.30 | 6.16 | 3.95 | 2.20 |
| **Tertiary industry** | 0.77 | 0.74 | 0.02 | 2.87 | 0.74 | 2.13 |
| **Total** | 76.58 | 51.94 | 24.64 | 76.58 | 51.94 | 24.64 |

**Table A.4**
Blue water consumption accounting within the GLG region

| Economic sectors | *BPW* ($Mm^3$) | | | *BVW* ($Mm^3$) | | |
|---|---|---|---|---|---|---|
| | Total ($PW_i$) | Final demand -driven ($VW_{ii}$) | Intermediate demand-driven ($\sum VW_{ij}$) | Total ($VW_i$) | Direct ($VW_{ii}$) | Indirect ($\sum VW_{ji}$) |
| **Agricultural sector** | | | | | | |
| Wheat | 56.24 | 45.91 | 10.33 | 46.04 | 45.91 | 0.13 |
| Maize | 345.48 | 255.30 | 90.18 | 255.46 | 255.30 | 0.17 |
| Oil crops | 4.45 | 3.48 | 0.97 | 3.61 | 3.48 | 0.14 |
| Cotton | 13.07 | 10.53 | 2.54 | 10.53 | 10.53 | 0.01 |
| Fruits | 111.09 | 91.07 | 20.02 | 91.25 | 91.07 | 0.18 |
| Vegetables | 89.53 | 75.74 | 13.79 | 76.15 | 75.74 | 0.41 |
| Other agricultural production | 72.15 | 65.03 | 7.13 | 88.66 | 65.03 | 23.64 |
| **Secondary sector** | | | | | | |
| Food and tobacco processing | 3.41 | 3.28 | 0.13 | 121.05 | 3.28 | 117.77 |
| Other secondary sector | 11.62 | 7.19 | 4.43 | 10.36 | 7.19 | 3.17 |
| **Tertiary sector** | 1.00 | 0.90 | 0.10 | 4.91 | 0.90 | 4.01 |
| **Total** | 708.05 | 558.42 | 149.63 | 708.05 | 558.42 | 149.63 |

**Table A.5**
Green water consumption accounting within the GLG region

| Economic sectors | *GPW* ($Mm^3$) | | | *GVW* ($Mm^3$) | | |
|---|---|---|---|---|---|---|
| | Total ($PW_i$) | Final demand -driven ($VW_{ii}$) | Intermediate demand-driven ($\sum VW_{ij}$) | Total ($VW_i$) | Direct ($VW_{ii}$) | Indirect ($\sum VW_{ji}$) |
| **Agricultural sector** | | | | | | |
| Wheat | 10.90 | 8.90 | 2.00 | 8.92 | 8.90 | 0.01 |
| Maize | 78.78 | 58.22 | 20.56 | 58.23 | 58.22 | 0.01 |
| Oil crops | 0.99 | 0.77 | 0.22 | 0.79 | 0.77 | 0.01 |
| Cotton | 2.91 | 2.34 | 0.57 | 2.34 | 2.34 | 0.00 |
| Fruits | 24.70 | 20.25 | 4.45 | 20.27 | 20.25 | 0.02 |
| Vegetables | 19.91 | 16.84 | 3.07 | 16.89 | 16.84 | 0.05 |
| Other agricultural production | 16.04 | 14.46 | 1.58 | 19.55 | 14.46 | 5.09 |
| **Secondary sector** | | | | | | |
| Food and tobacco processing | 0.00 | 0.00 | 0.00 | 26.01 | 0.00 | 26.01 |
| Other secondary sector | 0.00 | 0.00 | 0.00 | 0.70 | 0.00 | 0.70 |
| **Tertiary sector** | 0.00 | 0.00 | 0.00 | 0.54 | 0.00 | 0.54 |
| **Total** | 154.23 | 121.78 | 32.45 | 154.23 | 121.78 | 32.45 |

## References


Chai, Q., Qin, A., Gan, Y., Yu, A., 2014. Higher yield and lower carbon emission by intercropping maize with rape, pea, and wheat in arid irrigation areas. Agron. Sustain. Dev. 34, 535–543.

Dalin, C., Wada, Y., Kastner, T., Puma, M.J., 2017. Groundwater depletion embedded in international food trade. Nature 543 (7647), 700–704.

D'Odorico, P., Carr, J.A., Dalin, C., Dell'Angelo, J., Konar, M., Laio, F., Ridolfi, L., Rosa, L., Suweis, S., Tamea, S., Tuninetti, M., 2019. Global virtual water trade and the hydrological cycle: patterns, drivers, and socio-environmental impacts. Environ. Res. Lett. https://doi.org/10.1088/1748-9326/ab05f4.

Ermgassen, E.K.H.J., Phalan, B., Green, R.E., Balmford, A., 2017. Reducing the land use of EU pork production: where there's swill, there's a way. Food Policy 58, 35–48.

Ewing, B.R., Hawkins, T.R., Wiedmann, T.O., Galli, A., Ertug Ercin, A., Weinzettel, J., Steen-Olsen, K., 2012. Integrating ecological and water footprint accounting in a multi-regional input–output framework. Ecol. Indic 23, 1–8.

Feng, K., Chapagain, A., Suh, S., Pfister, S., Hubacek, K., 2011. Comparison of bottom-up and top-down approaches to calculating the water footprints of nations. Econ. Syst. Res. 23 (4), 371–385.

Feng, L., Chen, B., Hayat, T., Alsaedi, A., Ahmad, B., 2017. The driving force of water footprint under the rapid urbanization process: a structural decomposition analysis for Zhangye city in China. J. Clean. Prod. 163, S322–S328.

Gansu Statistics Bureau, 2013. Gansu Development Yearbook. Gansu.

Guan, D., Hubacek, K., Tillotson, M., Zhao, H., Liu, W., Liu, Z., Liang, S., 2014. Lifting China's water spell. Environ. Sci. Technol. 48, 11048–11056.

Hoekstra, A.Y., Chapagain, A.K., Aldaya, M.M., Mekonnen, M.M., 2011. The Water Footprint Assessment Manual: Setting the Global Standard. Earthscan, London.
Hoekstra, A.Y., Mekonnen, M.M., 2012. The water footprint of humanity. Proc. Natl. Acad. Sci. U. S. A 109, 3232–3237.
Jaramillo, F., Destouni, G., 2015a. Comment on “Planetary boundaries: guiding human development on a changing planet”. Science 348, 1217.
Jaramillo, F., Destouni, G., 2015b. Local flow regulation and irrigation raise global human water consumption and footprint. Science 350, 1248.
Kahil, M.T., Dinar, A., Albiac, J., 2016. Cooperative water management and ecosystem protection under scarcity and drought in arid and semiarid regions. Water Resour. Econ. 13, 60–74.
Lenzen, M., 2009. Understanding virtual water flows: a multiregion input-output case study of Victoria. Water Resour. Res. 47, W09416.
Lenzen, M., Moran, D., Bhaduri, A., Kanemoto, K., Bekchanov, M., Geschke, A., Foran, B., 2013. International trade of scarce water. Ecol. Econ. 94, 78–85.
Li, N., Wang, X., Shi, M., Yang, H., 2015. Economic impacts of total water use Control in the Heihe river basin in northwestern China—an integrated CGE-BEM modeling approach. Sustainability 7, 3460–3478.
Liu, J., Zehnder, A.J.B., Yang, H., 2009. Global consumptive water use for crop production: the importance of green water and virtual water. Water Resour. Res. 45 (5), W05428.
Liu, J., Zhao, X., Yang, H., Liu, Q., Xiao, H., Cheng, G., 2018. Assessing China's "developing a water-saving society" policy at a river basin level: a structural decomposition analysis approach. J. Clean Prod 190, 799–808.
Mekonnen, M.M., Hoekstra, A.Y., 2011. The green, blue and grey water footprint of crops and derived crop products. Hydrol. Earth Syst. Sci. 15, 1577–1600.
Miller, R.E., Blair, P.D., 2009. Input-output Analysis Foundations and Extensions, second ed. Cambridge University Press.
Ministry of Science and Technology, 2017. 13th five-year special plan on scientific and technological innovation in resource areas. available at: http://www.most.gov.cn/mostinfo/xinxifenlei/fgzc/gfxwj/gfxwj2017/201705/t20170517_132852.htm.
Molden, D., 1997. Accounting for Water Use and Productivity. SWIM Pap.1. Int. Irrig. Manage. Inst., Colombo.
Munksgaard, J., Wier, M., Lenzen, M., Dey, C., 2005. Using Input-Output analysis to measure the environmental pressure of consumption at different spatial levels. J. Ind. Ecol. 9, 169–185.
Northey, S.A., Mudd, G.M., Saarivuori, E., Wessman-Jääskeläinen, H., Haque, N., 2016. Water footprinting and mining: where are the limitations and opportunities? J. Clean. Prod. 135, 1098–1116.
Pauw, E.D., Göbel, W., Adam, H., 2000. Agrometeorological aspects of agriculture and forestry in the arid zones. Agric. For. Meteorol. 103, 43–58.
Ridoutt, B.G., Pfister, S., 2010. A revised approach to water footprinting to make transparent the impacts of consumption and production on global freshwater scarcity. Glob. Environ. Chang. 20 (1), 113–120.
Serrano, A., Guan, D., Duarte, R., Paavola, J., 2016. Virtual water flows in the EU27: a consumption-based approach. J. Ind. Ecol. 20 (3), 547–558.
Shi, M., Wang, X., Yang, H., Wang, T., 2014. Pricing or quota? A solution to water scarcity in oasis regions in China: a case study in the Heihe river basin. Sustainability 6, 7601–7620.
Steen-Olsen, K., Weinzettel, J., Cranston, G., Ercin, A.E., Hertwich, E.G., 2012. Carbon, land, and water footprint accounts for the European Union: consumption, production, and displacements through international trade. Environ. Sci. Technol 46, 10883–10891.
Tamea, S., Carr, J.A., Laio, F., Ridolfi, L., 2014. Drivers of the virtual water trade. Water Resour. Res. 50 (1), 17–28.
Velázquez, E., 2007. Water trade in Andalusia. Virtual water: an alternative way to manage water use. Ecol. Econ. 63, 201–208.
Wang, Y., Xiao, H.L., Lu, M.F., 2009. Analysis of water consumption using a regional input–output model: model development and application to Zhangye City, Northwestern China. J. Arid Environ. 73, 894–900.
Wang, R., Zimmerman, J., 2016. Hybrid analysis of blue water consumption and water scarcity implications at the global, national, and basin levels in an increasingly globalized world. Environ. Sci. Technol 50, 5143–5153.
Wei, Z., Jin, H., Lan, Y., Hu, X., Wu, J., Yang, S., Ji, Y., 2008. Analysis of the change of groundwater resources due to water allocation in the irrigation areas of the middle Heihe River. J. Glaciol. Geocryol. 30 (2), 344–350 (in Chinese).
Whitton, C., 2004. Processed agricultural exports led gains in U.S. agricultural exports between 1976 and 2002. USDA Outlook Report No. FAU8501. Available at: http://www.ers.usda.gov/publications/fau/feb04/fau8501/.
Wichelns, D., 2010. Virtual water and water footprints offer limited insight regarding important policy questions. Int. J. Water Resour. Dev. 26 (4), 639–651.
Wiedmann, T., 2009. A review of recent multi-region input–output models used for consumption-based emission and resource accounting. Ecol. Econ. 69 (2), 211–222.
Yang, H., Pfister, S., Bhaduri, A., 2013. Accounting for a scarce resource: virtual water and water footprint in the global water system. Curr. Opin. Environ. Sustain. 5, 599–606.
Yang, H., Wang, L., Abbaspour, K.C., Zehnder, A.J.B., 2006. Virtual water trade: an assessment of water use efficiency in the international food trade. Hydrol. Earth Syst. Sci. 10 (3), 443–454.
Zeng, Z., Liu, J., Koeneman, P.H., Zarate, E., Hoekstra, A.Y., 2012. Assessing water footprint at river basin level: a case study for the Heihe River Basin in northwest China. Hydrol. Earth Syst. Sci. 16, 2771–2781.
Zhang, X., Liu, J., Tang, Y., Zhao, X., Yang, H., Gerbens-Leenes, P.W., van Vliet, M.T.H., Yan, J., 2017. China's coal-fired power plants impose pressure on water resources. J. Clean. Prod. 161, 1171–1179.
Zhang, Z., Yang, H., Shi, M., 2011. Analyses of water footprint of Beijing in an interregional input–output framework. Ecol. Econ. 70 (12), 2494–2502.
Zhao, X., Chen, B., Yang, Z.F., 2009. National water footprint in an input-output framework – a case study of China 2002. Ecol. Model. 220, 245–253.
Zhao, X., Li, Y.P., Yang, H., Liu, W.F., Tillotson, M.R., Guan, D., Yi, Y., Wang, H., 2018. Measuring scarce water saving from interregional virtual water flows in China. Environ. Res. Lett. 13, 054012.
Zhao, X., Liu, J., Liu, Q., Tillotson, M.R., Guan, D., Hubacek, K., 2015. Physical and virtual water transfers for regional water stress alleviation in China. Proc. Natl. Acad. Sci. U. S. A 112 (4), 1031–1035.
Zhao, X., Liu, J., Yang, H., Duarte, R., Tillotson, M.R., Hubacek, K., 2016a. Burden shifting of water quantity and quality stress from megacity Shanghai. Water Resour. Res. 52, 6916–6927.
Zhao, X., Tillotson, M., Yang, Z., Yang, H., Liu, J., 2016b. Reduction and reallocation of water use of products in Beijing. Ecol. Indicat. 61, 893–898.
Zhao, X., Tillotson, M.R., Liu, Y.W., Guo, W., Yang, A.H., Li, Y.F., 2017. Index decomposition analysis of urban crop water footprint. Ecol. Model. 348, 25–32.
Zhao, X., Yang, H., Yang, Z., Chen, B., Qin, Y., 2010. Applying the input-output method to account for water footprint and virtual water trade in the haihe river basin in China. Environ. Sci. Technol. 44, 9150–9156.