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Assessment of interstate dynamics of virtual water trade flows in primary crops production: Empirical evidence from India

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Abstract

This study examines the interstate virtual water trade flows embodied in wheat and rice products across India's different states and union territories during 1994–2017. Using the extended Leontief's input-output model, this study links the net virtual water trade flows with water scarcity concentration in Indian states. The input-output analyses decompose the water consumption into domestic demand and exports by the states. Empirical results show that the northern states have massive wheat and rice production, leading to the highest virtual water outflows to western and southern water-scarce states in India. Further, results exhibit that virtual water trade has substantial pressure on water-scarce states to become water-saving states. However, we find that water endowments, unsustainable water flows, and diversity lead to water scarcity concentration in water-abundant states.

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1. Introduction

Water is one of the essential substances for production activities in India. However, the spatial variability of freshwater makes it a finite and vulnerable resource. With the growing effects of economic globalization, the issues related to freshwater availability, use, and management have received profound recognition globally. Food and Agriculture Organization (FAO, 2015) reports that globally, water resources are sufficient to produce the food required for the world's growing population of 9 to 10 billion by 2050. However, many regions would face substantial water scarcity. Besides, the erratic rainfall and seasonal differences in water availability cause temporal food emergencies; floods and droughts can cause the most intensive food emergencies in developing countries. This situation of water scarcity would increase the competition for water between different sectors through the water-food-energy nexus. World Economic Forum (2019) reports that water is the most significant global risk factor for countries, environments, and people in the future. Hence, water must be considered an economic good (Hoekstra and Hung, 2005).

Agriculture is the largest water user globally, accounting for more than half of withdrawals from rivers, lakes, aquifers, and developing countries, often accounting for 70 percent or more water withdrawals (FAO, 2009 and 2011). The increasing agricultural water demand for irrigation purposes is over-exploiting the groundwater, which depletes the world's major aquifers. Millions of water pumps are currently extracting groundwater at an unsustainable rate globally, for instance, China, Nepal, and India (United Nations, 2003). Further, climate change impacts agricultural yields and water resources because of the spatially heterogeneous biophysical effects on climate (Baldos et al., 2019). Similarly, in India's case, southern peninsular regions are hotter than the northern part (Taraz, 2018). The impact of climate change can be mitigated by long-run adaptation, for instance, changing cropping patterns, investing in irrigation, adjusting fertilizer, and other agricultural inputs (Huang and Sim, 2020; Nordhagen and Pascual, 2013). The long-run adaptation also reduces the potential loss of farming profits due to climate change.

India is a water-abundant country, which accounts for about 4 percent of the world's water resources. Monsoon is the lifeline of India in recharging its water resources and agriculture practices.[1] However, there is a wide variation in precipitation across different regions of the country. The Ganges and Indus river basins alone account for 43 percent of India's blue water, contributing to wheat production in India's northern states (Central Water Commission, 2015). India is an agrarian country and globally the second-largest wheat and rice producer — the world's primary food grains consume the most substantial portion of water resources (Food and Agriculture Organization Statistics (FAOSTAT, 2018). As a result, there is a considerable increase in India's net export of agricultural products over the past decades. The agriculture sector itself contributes 11.76 percent to India's total exports in 2018-19, in which wheat and rice exports are estimated as 226.23 and 12014.36 thousand tonnes, respectively (Directorate General of Commercial Intelligence & Statistics (DGCIS), 2018-19).

After the green revolution in early 1960, India's agricultural growth has gained popularity to produce water-intensive food grains such as wheat, rice, maize, millets, pulses, and sugarcane. The primary food grains-producing states are Uttar Pradesh, Haryana, and Punjab in northern India. Besides, the primary food grains producing states are Gujarat, Maharashtra, and Madhya

[1] India receives about 4,000 billion cubic meters (BCM) of average annual precipitation during the monsoon season (June-September). As a result, India's total yearly utilizable water resources are 1123 BCM (690 BCM surface water plus 433 BCM groundwater).

Pradesh in western India; Bihar and West Bengal in eastern India; and Andhra Pradesh, Tamil Nadu, and Karnataka in southern India (see Table 1). However, this increased agricultural production raises the pressure on surface water and increases groundwater withdrawal by digging more wells (Banerji et al., 2012). The decreasing groundwater table in several areas, especially in northern India, has raised the question of efficiency and sustainability use of groundwater in agriculture. Therefore, the Indian Government introduced inter-river linking projects to solve water scarcity in drier regions (National Water Development Agency, NWDA, 2006).

Virtual water (VW) and Water footprint (WF) are two concepts that are considered to be valuable tools to address the water crisis issue. The main difference between the two ideas is that VW is defined from the production perspective, while WF is determined from the consumption perspective.[2] VW represents the physical amount of water within the product and the amount of water required to produce a product (Allan, 1997). When a product is exchanged through trade, then VW flow takes place.[3] Further, virtual water trade (VWT) occurs as the volume of water embodied in the products is exchanged internationally (Duarte et al., 2014).[4] The water-rich and water-poor countries' actual water trade or water transfer projects are generally quite expensive due to the long distances and associated transportation and infrastructure costs (Webber et al., 2017). However, trade-in water-intensive products are realistic in the present day.

The key contributions of this study to the existing literature are discussed as follows. More specifically, this study addresses the importance of spatial-temporal refinement of VWT flows in resolving the issues related to water availability, food security, and water use efficiency in India. This study examines the interstate VWT flows embodied in wheat and rice products, i.e., wheat, wheat flour, rice in the husk, and rice not in the husk across the different states/ Union Territories (UTs) in India during the period 1994–2017.[5] This study's novel approach applies the extended Leontief's input-output (I-O) model by considering water consumption as input for computing VW of different states in India. Further, this novel approach considers both direct and indirect water consumption during the production process, supposed to be the most preferred measure to evaluate the VW flows (Ercin et al., 2013). Finally, this study primarily links the VWT flows with water scarcity concentration in Indian states to know whether the water scarcity is caused by domestic consumption or by exporting agricultural products from one state to another.

Moreover, this study explicitly considers the primarily produced food grains — wheat and rice for VWT assessment in India during 1994-2017. Therefore, taking into the significance of wheat and rice production, we take the VWT appraisal of wheat and rice products only using the

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[2] Hoekstra and Hung (2002) introduced the concept of WF to identify human pressure on water resources. The WF is defined as the total volume of freshwater used to produce the goods consumed by the nation's people. Thus, WF represents the domestic demand for water resources in a country by calculating the volume of water embodied in the consumed products.

[3] The VWT flows are estimated by multiplying per trade commodity or the trade volume by the respective average water footprint per tonne of product in the exporting nation (Hoekstra and Hung, 2005).

[4] The primary policy of VWT is that countries with limited freshwater resources available can offset their use in the agricultural sector by importing water-intensive goods from water-abundant countries and minimizing the internal water shortage (Hoekstra and Hung, 2002).

[5] This study considers 27 states, namely Andhra Pradesh, Assam, Arunachal Pradesh, Bihar, Chhattisgarh, Goa, Gujarat, Haryana, Himachal Pradesh, Jammu and Kashmir, Jharkhand, Karnataka, Kerala, Madhya Pradesh, Maharashtra, Manipur, Meghalaya, Mizoram, Nagaland, Odisha, Punjab, Rajasthan, Tamil Nadu, Tripura, Uttarakhand, Uttar Pradesh and West Bengal; and 3 UTs, namely Chandigarh, Delhi, and Puducherry. Besides, the study excludes the two states, Sikkim and Telangana, and 2 UTs, Andaman and Nicobar Islands, Lakshadweep, due to data unavailability.

familiar Leontief (1970) I-O coefficients matrix.[6] Therefore, we hope that the wheat and rice food grains for VWT assessment would be more rigorous for developing countries like India.

Table 1. Major food grains producing states of India

Foodgrains	North	West	East	South	North-east
Wheat	Uttar Pradesh, Punjab, Haryana, Rajasthan, Uttarakhand	Gujarat, Maharashtra, Madhya Pradesh,	West Bengal, Bihar	Karnataka	
Rice	Uttar Pradesh, Punjab, Haryana	Madhya Pradesh, Chhattisgarh, Maharashtra,	West Bengal, Bihar, Odisha, Jharkhand	Andhra Pradesh, Karnataka, Tamil Nadu	Assam
Maize and millets	Uttar Pradesh, Rajasthan, Himachal Pradesh, Uttarakhand	Maharashtra, Madhya Pradesh, Gujarat, Chhattisgarh	Bihar, Jharkhand	Andhra Pradesh, Karnataka, Tamil Nadu	Tripura, Arunachal Pradesh
Pulses	Uttar Pradesh, Rajasthan	Gujarat, Maharashtra, Madhya Pradesh, Chhattisgarh	Bihar, Jharkhand, Odisha	Andhra Pradesh, Karnataka, Tamil Nadu	Assam
Jowar and Bajra	Haryana, Jammu and Kashmir, Uttar Pradesh, Rajasthan	Madhya Pradesh, Chhattisgarh, Gujarat, Maharashtra,		Andhra Pradesh, Karnataka, Tamil Nadu	
Oilseeds	Haryana, Rajasthan, Uttar Pradesh	Gujarat, Madhya Pradesh, Maharashtra	West Bengal	Andhra Pradesh, Karnataka, Tamil Nadu,	

Source: Authors' computation using the food grains production data over the period 1994-2017.

The rest of the paper is organized as follows. Section 2 discusses the empirical strategy, data, and methodology of the study, while Section 3 presents the empirical results and discussion. Finally, Section 4 concludes the study.

[6] Note that the I-O coefficients are pretty challenging to construct and plot for all food grains in each state in India. Therefore, we consider taking the VWT assessment of wheat and rice products only.

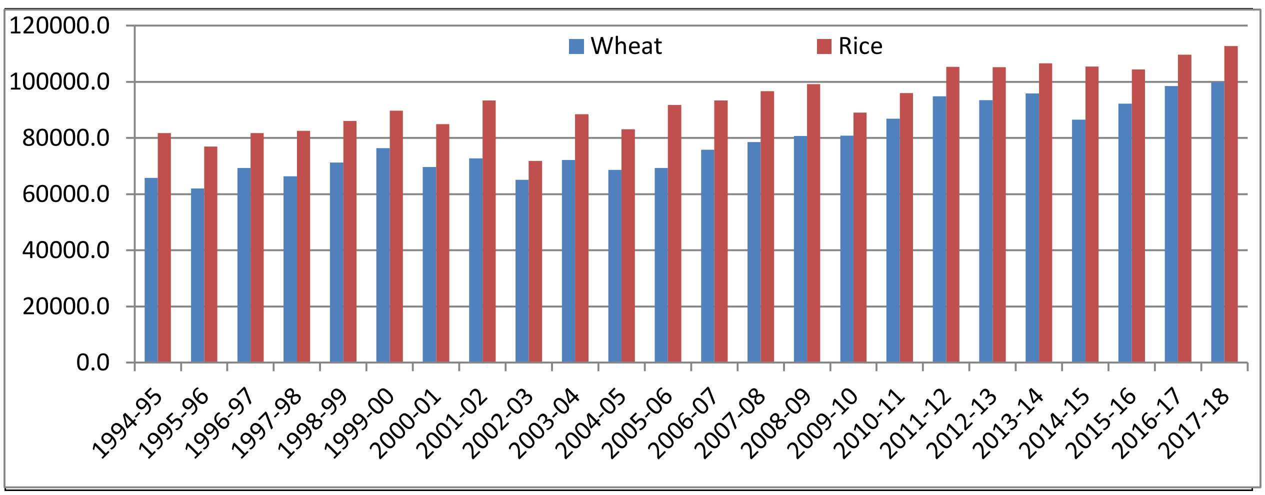
2. Empirical framework

This section discusses this study's empirical strategy and data description to estimate the VWT flows embodied in India's wheat and rice products.

2.1. Empirical strategy

Initially, we estimate the total production of wheat and rice in India during 1994-2017 to calculate each state's total output. Figure 1 shows the wheat and rice production in India during the period 1994-2017. First, it exhibits that more rice is produced in India than wheat. Second, we estimate the final demand for wheat and rice products by subtracting the total exports from total production to distinguish the extra volumes of food grains produced by Indian states. Finally, however, it extracts the water volumes from water-rich states to water-scarce states.

Fig. 1 India's wheat and rice production during the period 1994-2017 (in '000 tonnes)



Source: Authors' computations using wheat and rice production data in India for 1994-2017.

Next, this study examines the interstate VWT flows of wheat and rice products in India using the extended Leontief's I-O model with water consumption (WC) over 1994-2017. The WC coefficients capture the differences in crop productivity among the states, and it is necessary for the VWT assessment in India. This study uses the WF coefficients (m^3/tonne), state-wise in India, for the period 1996-2004 estimated by Mekonnen and Hoekstra (2011). Precisely, to estimate the WF coefficients after 2004, the following steps are followed, which are discussed below.

Following the assumption that WF is a function of yield,[7] we estimate the WF from 2005 through 2013 based on WF of 1996–2004 using Eq. (1) (Duarte et al., 2014 and Katyaini and

[7] The crops' yield is determined by the climate factors such as precipitation, evapotranspiration, and agriculture technology (Duarte et al., 2014). Therefore, yields reflect the differences in resource use and the level of agriculture production technologies (Cui et al., 2018). Also, the yield of a crop depends upon the particular area where the crop is grown. The evapotranspiration and yield data only account for the water consumption, which is required for crop production. Hence, WF is a function of yield. In India, many varieties of wheat and rice are cultivated. Still, the crop water requirement depends on the climate parameters, which determine potential evapotranspiration, crop characteristics, and soil water availability (Allen et al., 1998).

Barua, 2017; Katyaini and Barua, 2020).[8] Further, there are uncertainties in predicting the global climate models, mainly predicting the climate variability (Katyaini and Barua, 2017). Therefore, an improvement in the yield of all the food grains is considered to be estimated for 1996-2004 to 2005-2013. However, there is a concern about a decrease in the yield due to climate variability. Therefore, a decline in the yield in the future would impact food security. Also, the Indian agriculture sector is rainfed agriculture and is more vulnerable to climatic changes.

Further, it is necessary to calculate WF coefficients for the period 2005–2013 based on WF of 1996–2004 because yield varies between the two periods but has remained constant within each period.[9] Besides, for the remaining years from 2014 to 2017, we estimate the WF coefficients' based on the availability of the data sets. Therefore, this study considers the WF coefficients as WC coefficients for India's different states/UTs. The procedure to calculate the WF coefficients over the period 2005–2013 is given as follows:

$$WF_{2005-2013} = WF_{1996-2004} \times \frac{Yield_{1996-2004}}{Yield_{2005-2013}} \tag{1}$$

Modeling for VW requires an extended I-O table to account for WC coefficients by the different states/UTs in India. The I-O table structure is a matrix that lists Indian states/ UTs in the same sequence, both vertically and horizontally (see Table 2).[10] The I-O model assumes that each state produces only one output. Consequently, if a state has more than one output, then the analysis is done one by one product or aggregation. Hence, we follow one-by-one product analyses, i.e., wheat, wheat flour, rice in the husk, and rice not in the husk. Further, the study also incorporates the exports, imports, and final demand of each state for the VWT assessment of wheat and rice products.

[8] This study uses the WF of 1996-2004 following the previous literature (Duarte et al., 2014 and Katyaini and Barua, 2017) and assumptions provided by Allen et al. (1998) for crop growth under non-optimal conditions. Allen et al. (1998) estimated the grid-based dynamic water-balance model using the CROPWAT approach. The merit of this approach is that it computes a daily soil water balance and calculates crop water requirements, actual crop water use, and actual yields. Also, another merit of this approach is that this model is applied globally using a five-by-five arc minutes' spatial resolution (Mekonnen and Hoekstra, 2011). Further, this approach takes care of the uncertainties of climate change factors like precipitation, temperature, and evapotranspiration, which might affect the crop growth life cycle, soil-water content, field capacity, yield response factors, and maximum yield.

[9] Following the previous studies (Katyaini and Barua, 2020; Duarte et al., 2014), we do not compute the ratio, Yield 1996-2004/Yield 2005-2013, in a reverse way.

[10] The suitability of the I-O approach in this study is the dataset which is structured in a matrix form. It represents the food grains' movement from one state to another, both vertically and horizontally. We need to estimate the total requirement matrix for the final demand of other states, which is computed by Leontief's inverse matrix in the I-O model. VW modeling requires an extended I-O table to account for WC for the different states/UTs in India. This method is a bottom-up approach which is significant for assessing VW-flows of agricultural products based on the advantage of high spatial processes (Mekonnen and Hoekstra, 2011). The bottom-up approach makes it convenient to study inter-state VW-flows embedded in agricultural products at the lower disaggregate level. However, the primary limitation of this approach is that it does not account for the weight of the intermediate inputs. Therefore, one limit in this research is that our empirical inference could have changed if we apply weights to the intermediate inputs in the Leontief inverse matrix, which takes the relative share of different states in India. Further, the possible alternative method could be the multi-regional input-output model, applicable if one state goods movement exists within the regions. However, we have not applied this multi-regional input-output model of one-state goods movements within a region because our analysis is based on the inter-state movement of food grains vertically and horizontally.

Table 2. Extended I-O Model with water consumption

↓Exports to	Exports from →	States using (X_j) 1 2 3 4 5 6	Total Exports (E_i)	Final demand (D_i)	Total output (X_i)
	1				
	2				
States Producing (X_i)	3				
	4				
	5				
	6				
	Total Imports (M_j)		Net Exports		
	Water consumption (WC_j)				

Source: Authors' computations based on Leontief (1970)

The structure of the I-O model based on Table 2 is discussed as follows. If we denote the total output of a state i by X_i and its final demand by F_i, then

$$X_i = \sum X_{ij} + F_i \qquad i = 1,2,3, \ldots \ldots \ldots \ldots \ldots \ldots \ldots .30 \tag{2}$$

X_{ij} represents the output of state i consumed by another state j, including all types of consumption. In this study, we take the number of regions, including state and UTs is 30, so i and j vary from regions 1 to 30. Further, the proportion of each input (required in producing the output of a state) to the output of a state is denoted by:

$$a_{ij} = {}^{X_{ij}}\!/_{X_j} \qquad i = 1,2,3, \ldots \ldots \ldots \ldots \ldots \ldots \ldots .30 \tag{3}$$

The a_{ij}'s are called the structural matrix or technical coefficients and represent the *i*th state's direct input requirement for producing one unit output of the j^{th} state. So Eq. (2) can be rewritten in the matrix notation:

$$X = AX + F \tag{4}$$

Further, Eq. (4) can be written as:

$$X = (I - A)^{-1} \times F \tag{5}$$

$(I-A)^{-1}$ is known as the Leontief inverse matrix (L_{ij}) or matrix multipliers. Here, each coefficient represents one state's output required directly and indirectly for one unit of other states' final demand. Hence, this matrix is also called as total requirements coefficients matrix.

Next, this study extends the I-O model, as shown in Table 2, to estimate VWT flows by adding a row of WC coefficients by producing states to meet other states' final demand. The WC coefficients (m^3/tonne) indicate water per unit of output produced by each state. The VW coefficients can then be estimated by multiplying the WC coefficients with the Leontief inverse matrix (L_{ij}).

$$VW_j = \sum_i WC_i \times L_{ij} \tag{6}$$

The VW coefficients (m^3/tonne) represent the water consumes by the state j for generating one unit of final demand in other states. The coefficients will link the final demand for a product with direct and indirect water use, as we discussed before.

Further, we estimate the VWT flows associated with intermediate exports and imports of wheat and rice products among the states/UTs in India, following the classical approach developed by Hoekstra and Hung (2005). Following the Hoekstra and Hung (2005) approach, some recent studies estimated the VWT flows to analyze VW's volume embodied in agricultural commodities across different countries contexts (e.g., Lenzen et al., 2013; Duarte et al., 2014; and Katyaini and Barua, 2017). The VW flows (m^3/year), associated with exports of product *p* from each state *s* for the year *t* to other states, can be estimated as follows.

$$VWX(s,t) = \sum_p WC_p^s(s,p,t) \times X_p^s(s,p,t) \tag{7}$$

where, WC_p^s represents the VW content for each product in the exporting state *s* for the product *p* and X_p^s is the physical quantity of product p exported from state *s*. Similarly, the VW flows associated with imports of product *p* from each state *r* for the year *t* to other states are estimated using Eq. (8).

$$VWM(r,t) = \sum_p WC_p^r(r,p,t) \times M_p^r(r,p,t) \tag{8}$$

where, WC_p^r represents the VW content for each product in the importing state *r* of the product *p* and M_p^r is the physical quantity of product p imported from state *r* for the year *t*. Therefore, the VWT balance (VWB) of a state can be calculated by taking the difference between VW exports and imports, which is given as follows:

$$VWB(s,t) = VWX(s,t) - VWM(r,t) \tag{9}$$

2.2. Data description

This study uses the dataset of interstate movement of goods by Indian railways in 1994-2017 to estimate the interstate VWT flows. The majority of inter-state transportations of food grains are shipped by Indian railways. However, roadways are used to transport the food grains from the regional grain markets to the warehouses/godowns of the state. From warehouses/godowns, the required amount of food grains is again transported to other states through railways. The airways are used for the export of food grains to other countries. The limitation of airways data is that it is not segregated into different types of food grain shipments. One of the principal factors limiting air freight volume in India is the lack of significant two-way activity, indicating there is no official record of origin or destination, which is crucial for assessing the VWT flows in India. Therefore, the inter-state shipment of food grains through railways has been considered a significant mode of transport to estimate the VWT flows in India.

The interstate movement of goods data is obtained from the DGCIS, Kolkata, Government of India. The data set is structured in matrix form to represent the movement of goods in export and import from one state to another.[11] This study considers wheat, wheat flour, rice in the husk, and rice not in the husk products to represent wheat and rice products for VWT flows. We compile wheat and rice production based on the yearly dataset at India's state level to evaluate each state's total output. Similarly, we compile the yield data of wheat and rice product of each state. Moreover, the corresponding data is collected from the agricultural statistics published by the Directorate of Economics and Statistics, New Delhi, India.

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[11] We estimate the final demand for wheat and rice products by subtracting the total exports from total production to distinguish the extra volumes of food grains produced by Indian states. It is relevant to know each state’s food requirement and how much extra quantity is available, after consuming, for the internal trade to earn extra profit primarily and for food sustainability in India. However, the re-export trade and value addition data are not available by the DGCIS, Kolkata, India. So, we do not include the re-export trade or value addition data while we estimate the final demand for wheat and rice products. Therefore, re-export trade and value addition do not have any empirical consequence on VWT flows and evaluated WF in this study.

3. Results and discussions

3.1. VW coefficients of wheat and rice products in India

Empirical results of VW coefficients of wheat and rice products of 30 states/UTs in India are reported in Tables 3 and 4, respectively. Columns 1 and 3 show the direct water-input coefficient, which indicates the direct amount of WC (m^3) per tonne production of food grains by different states in India. This coefficient represents direct or first-round effects of sectoral interaction in the economy, suggesting that water is consumed directly and indirectly to produce by-products like wheat flour, rice flour, bread, biscuits, etc. (Guan and Hubacek, 2007). There is a difference in the WC coefficients of wheat and rice products across India's states based on the production process's spatial-temporal requirement. Further, we estimate the coefficients of VW by multiplying the WC_i coefficients with L_{ij} elements. It is also known as VW multipliers. Summing up the columns, we get the total amount of VW required per final tonne demand of products in other states between 1994 and 2017 (see Columns 2 and 4, Tables 3 and 4).

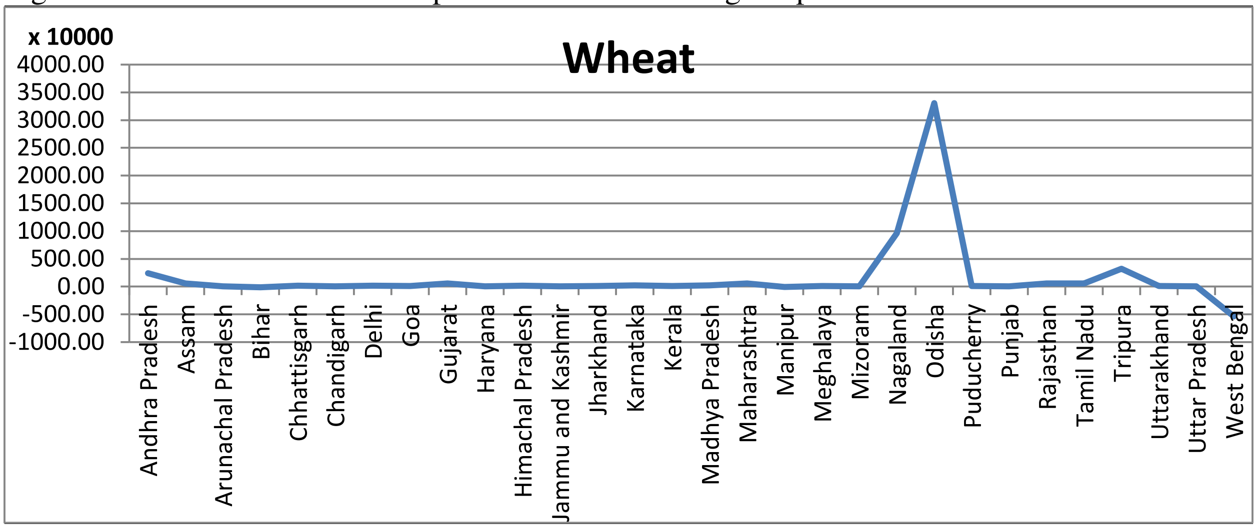
The empirical results show heavy water consumption by wheat compared to wheat flour (see Table 3). Generally, wheat has been used as an intermediate good for producing multiple by-products instead of wheat flour. Figure 2 shows VW's combined consumption for wheat products, i.e., taking VW's combined use for wheat and wheat flour across the different states/ UTs in India during 1994-2017. Empirical results exhibit that the major VW-consuming states are Odisha, Nagaland, Tripura, Andhra Pradesh, and Gujarat. The less VW consumption states are West Bengal, Bihar, Manipur, Chandigarh, and Mizoram. This suggests that these states are mainly involved in the movement of wheat products to generate other states' final demand. West Bengal, Bihar, Manipur, and Tamil Nadu have negative VW consumption in wheat, suggesting that these states import higher volumes of wheat instead of domestically produce it (see Table 3, Column 2). However, empirical findings reveal that this variation is quite different in the VW coefficients of wheat flour.

Table 3. VW embodied in wheat products across different states in India

Products	Wheat		Wheat flour	
	1	2	3	4
States	WC (m^3/ton)	VW (m^3/ton)	WC (m^3/ton)	VW (m^3/ton)
Andhra Pradesh	61748	2317585	62482	73480
Assam	40720	522450	41204	42502
Arunachal Pradesh	29053	43969	29398	29539
Bihar	41044	-177273	41532	41731
Chhattisgarh	92678	106057	93780	93780
Chandigarh	16229	16229	16422	16422
Delhi	21340	140963	21594	21604
Goa	66919	66919	67714	67714
Gujarat	53889	530792	54530	54553
Haryana	38938	37937	39401	39419
Himachal Pradesh	33916	158032	34320	34320
Jammu & Kashmir	27400	37635	27726	27727
Jharkhand	56609	45037	57282	57305
Karnataka	57641	178248	58326	58352
Kerala	51887	51887	52504	52504
Madhya Pradesh	90351	157440	91425	91425
Maharashtra	87309	470595	88347	88364
Manipur	22942	-97809	23215	23215
Meghalaya	44172	44172	44697	44697
Mizoram	21933	21933	22193	22193
Nagaland	57466	9572491	58149	61471
Odisha	45335	33033492	45874	49714
Puducherry	51364	51364	51975	51975
Punjab	29339	31564	29688	29689
Rajasthan	54196	491674	54840	54845
Tamil Nadu	51364	-9058	51975	583001
Tripura	66869	3158979	67664	71032
Uttarakhand	33058	93850	33452	33826
Uttar Pradesh	38533	28226	38991	38992
West Bengal	38579	-5464310	39037	105567
India	47718	45661071	48286	2060959

Source: Authors' estimations using Eq. (1) and (6) are obtained through programming using MATLAB R2020a for wheat products from 1994-2017. *Note:* 1cubic metre (m^3) = 10^{-6} Gigaliters (GL).

Fig. 2. VW coefficients of wheat products in India during the period 1994-2017



Source: Authors' computation is obtained using VW coefficients of wheat products in India during the period 1994-2017

Similarly, empirical results exhibit that in the case of rice products, there is more water consumption by rice not in the husk as compared to rice in the husk (see Table 4). The rice not in the husk as a final product has been traded by Indian states based on massive demand by other states in India. Moreover, by summing the VW coefficients of rice products over the sample period, empirical results exhibit a significant VW consumed by the states like Kerala, Delhi, Gujarat, Goa, and Karnataka. The less consumed VW across the states and UTs in India are Chandigarh, Odisha, Arunachal Pradesh, Chhattisgarh, and Meghalaya. This suggesting that these states are majorly involved in India's rice products' VW outflows and inflows. Figure 3 shows the variation in the VW multipliers of rice products across India's different states during 1994-2017.[12]

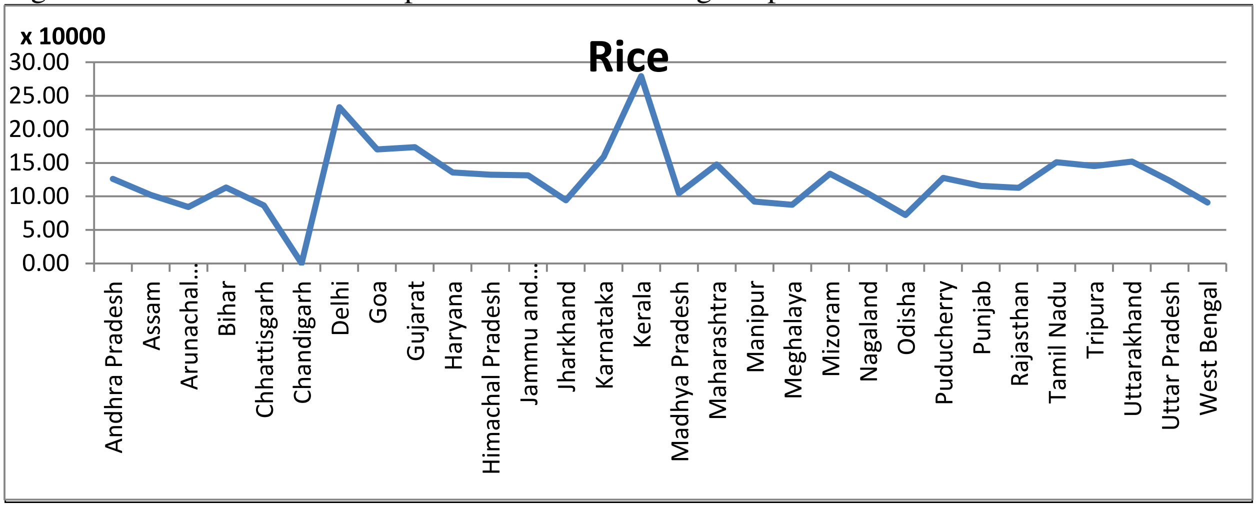
[12] Note that the VW coefficients of Chandigarh are zero due to missing data of WC coefficients. Further, Fig. 3 depicts VW coefficients' combined consumption, including the rice in the husk and rice not in the husk.

Table 4. VW embodied in rice products across different states in India

Products	Rice in the husk		Rice not in the husk	
	1	2	3	4
States	WC (m^3/ton)	VW (m^3/ton)	WC (m^3/ton)	VW (m^3/ton)
Andhra Pradesh	51750	51912	67208	74110
Assam	34568	34574	44893	67593
Arunachal Pradesh	28264	28266	36706	55654
Bihar	45959	45980	59687	67389
Chhattisgarh	37670	37675	48923	48951
Chandigarh	0	0	0	0
Delhi	41768	41850	54244	191472
Goa	68786	68807	89333	101390
Gujarat	55459	55784	72025	117754
Haryana	58756	59156	76306	76609
Himachal Pradesh	55347	55347	71879	76782
Jammu & Kashmir	44924	45014	58342	86405
Jharkhand	37247	37283	48372	56781
Karnataka	56334	56421	73161	102678
Kerala	54154	54491	70330	224790
Madhya Pradesh	42700	42710	55454	61949
Maharashtra	52478	52681	68154	95088
Manipur	39040	39040	50702	53357
Meghalaya	37978	37978	49322	49349
Mizoram	54171	54171	70352	79544
Nagaland	32135	32135	41734	72734
Odisha	30931	30934	40170	41390
Puducherry	46245	47233	60058	80445
Punjab	50163	50225	65146	65199
Rajasthan	46310	46559	60143	66414
Tamil Nadu	48060	50550	62416	100398
Tripura	56278	56627	73088	88693
Uttarakhand	57377	57380	74516	94612
Uttar Pradesh	52498	52512	68179	70539
West Bengal	38303	38315	49745	52338
India	45700	1361608	59351	2420406

Source: Authors' estimations using Eq. (1) and (6) are obtained through programming using MATLAB R2020a for rice products from 1994-2017.

Fig. 3. VW coefficients of rice products in India during the period 1994-2017



Source: Authors' computation is obtained using VW coefficients of rice products in India for the period 1994-2017

3.2. VWT flows: Water saving and loss of wheat and rice in India

Finally, we analyze the significance of VWT inflows and outflows of wheat and rice products from the highest water resources state to the lowest water-scarce states in India during 1994-2017. Table 5 reports the estimated net VWT flows (GL) of water-saving and water-loss in wheat and rice products across India's states. The reported results suggest a significant outflow of net VWT embodied in the wheat product from Punjab, Madhya Pradesh, and Haryana. This suggesting that these states are the highest water-losing states as the substantial VW is exported from the water-abundant states to water-scarce states. Further, by empirically evaluating the inflows of net VWT embodied in wheat products, Maharashtra, Gujarat, West Bengal, Karnataka, and Bihar are becoming the five major water-saving states in India during the period 1994-2017.

Further, empirical results exhibit that Madhya Pradesh was a water-saving state during 1994-2005; however, its status has changed to the water-losing state during 2006-2017. One inevitable reason is that there has been a substantial increase in food grains production after 2004-05 in India, facilitating Madhya Pradesh to convert water-saving states to water-losing states. In contrast, empirical results indicate that Uttar Pradesh was the water-losing state during 1994-2005; however, it has transformed into a water-saving state during 2006-2017. This suggests the state government of Uttar Pradesh's stringent policy implication of water policy in 1999, whose primary intention is to minimize the water loss in food grains production. Notwithstanding, results indicate that Meghalaya is the only exceptional state in India where the estimated figure of VW is neutral, which means VWB is found to be zero for wheat production.

Table 5. Net VWT flows (GL), water-saving, and loss of wheat and rice products in India

States/ Products	Rice in the husk	Rice not in the husk	Wheat	Wheat flour
Andhra Pradesh	-2441	122782	-32444	-175
Assam	-14	-51453	-16513	-97
Arunachal Pradesh	0	-1218	-50	0
Bihar	1	-41616	-34060	0
Chhattisgarh	4046	71903	-7390	32
Chandigarh	0	0	-121	5
Delhi	21	835	-1989	301
Goa	-4	-2143	-538	0
Gujarat	-316	-38126	-61288	18
Haryana	-927	106240	96060	36
Himachal Pradesh	0	-671	-4328	0
Jammu & Kashmir	-43	-11997	-3227	0
Jharkhand	-43	-17961	-6997	20
Karnataka	-371	-104620	-40272	-6
Kerala	-268	-66095	-7362	-3
Madhya Pradesh	1246	2195	98765	23
Maharashtra	-783	-67151	-126955	11
Manipur	0	-894	-14	0
Meghalaya	0	-4	0	0
Mizoram	0	-805	-1	-1
Nagaland	0	-4970	-1415	-10
Odisha	327	7976	-15247	-7
Puducherry	932	-603	-392	0
Punjab	466	303401	157573	22
Rajasthan	-14	8058	-2417	10
Tamil Nadu	-5243	-151092	-24670	-537
Tripura	-270	-9868	-1451	-16
Uttarakhand	-2	4065	-1283	-3
Uttar Pradesh	1172	-10130	-1258	2342
West Bengal	49	-25520	-55830	-2488
India	-2478	20519	-95115	-525

Source: Authors' computations are obtained through programming using MATLAB R2020a using Net VWT flows of wheat and rice products during 1994-2017.

Next, empirical results exhibit the significant net VWT outflows embodied in rice products from Punjab, Andhra Pradesh, Haryana, Chhattisgarh, and Odisha to the water-scarce states, i.e., Tamil Nadu, Karnataka, Maharashtra, Kerala, and Assam during the period 1994-2017. In a similar streamline to the wheat products, our results remain unchanged for rice products. For instance, results indicate that Uttar Pradesh was a water-losing state during 1994-2005; however, it has changed to a water-saving state during 2006-2017 following the state-level stringent water policy, which primary motivation is to minimize water consumption. In contrast, Odisha was a water-saving state during 1994-2005; however, it has transformed into a water-losing state during 2006-2017. Therefore, this suggests that the states like Odisha have experienced a substantial increase in food grains production after 2006 to meet the rise in domestic demand for food consumption.

Notwithstanding, empirical results indicate that Maharashtra is the second-most populous state in India and a net VW importer embodied in wheat and rice products despite being a significant food grain producer. This suggests that the high food demand has shoved the water-scarce state to imports from other states to meet their excess food requirement. Further, Tamil Nadu is another state in India that has the uppermost water-saving and sizeable arable land. However, despite becoming the primary food grain producer, this state depends on Punjab and Haryana to fulfill their large population's food demand. The empirical assessment suggests that Punjab and Haryana states become the water-scarce state very shortly. These states are the major net VWT exporters of wheat and rice products in India. These states are highly productive in food grains production and efficient in irrigation facilities in India. However, due to the continuous low average rainfall, these states heavily rely on and exploit their groundwater to the maximum level for food grains production. This suggests that these states are using water sustainably policy in the agriculture sector. Therefore, results indicate that Punjab and Haryana are securing India's food demand on the verge of its scarce water resources and heavy groundwater consumption.

4. Conclusions

This study investigates an empirical assessment of interstate VWT flows embodied in wheat, wheat flour, rice in the husk, and rice not in the husk products across the 30 states/UTs in India using the extended Leontief's I-O model with water consumption (input) during the period 1994–2017. Empirical results exhibit that a substantial amount of VWT flows of wheat and rice products have been exported from the water-abundant states to water-scarce states in India. The significant net VW exporters of wheat crops are Punjab, Madhya Pradesh, Haryana, and Uttar Pradesh in India, indicating that these states are water-losing states. Further, following the estimated net VWT inflows of wheat production in India, we find that the major water-saving states are Maharashtra, Gujarat, West Bengal, Karnataka, and Bihar in India during the period 1994-2017. Notwithstanding, these concerned states have fulfilled their excess demand for food from other states in India, although some major producing states have an acute shortage of water reservoirs and resources. Nevertheless, empirical findings reveal that substantial net VWT outflows embodied in rice products are from Punjab, Andhra Pradesh, Haryana, Chhattisgarh, and Odisha to Tamil Nadu Karnataka, Maharashtra, Kerala, and Assam during the period 1994-2017.

In sum, we find that the practice of exporting excess produced food grains from one state to other states in India awaken the water resources problem of highly productive states very shortly. Moreover, Punjab and Haryana states are the major net VWT exporters of wheat, and India's rice products states are at a high risk of water scarcity soon. In contrast, results suggest that Maharashtra and Tamil Nadu are the net VW importer embodied in wheat and rice products, even if these states are the primary producer of food grains. This further indicates that some concerned states in India continually try to preserve their water resources by importing excess food requirements from other states. Therefore, this comparative analysis of Indian states reveals a different production structure, varying from one state to another. One basic limitation in this research is that our empirical inference would have changed if we apply weights to the Leontief inverse matrix's intermediate inputs, which take the relative share of different states in India. This could be interesting if we consider taking the weights to the Leontief inverse matrix's intermediate inputs. Therefore, we have preserved this dimension of research for the future.

References

Allan JA (1997) "Virtual water: A long term solution for water-short Middle Eastern economies?" London: School of Oriental and African Studies, University of London.

Allen RG, LS Pereira, D Raes and M Smith (1998) "Crop Evapotranspiration-Guidelines for computing crop water requirements" FAO Irrigation and drainage paper 56.

Baldos UL, TW Hertel and FC Moore (2019) "Understanding the spatial distribution of welfare impacts of global warming on agriculture and its drivers" *American Journal of Agricultural Economics* 101(5), 1455-1472.

Banerji A, JV Meenakshi and G Khanna (2012) "Social contracts, markets, and efficiency: Groundwater irrigation in North India" *Journal of Development Economics* 98(2), 228-237.

Central Water Commission (2015) Integrated Hydrological Data Book. Hydrological Data Directorate, Information Systems Organization, Water Planning & Projects Wing, Ministry of Water Resources, Government of India, New Delhi.

Cui RY, K Calvin, L Clarke, M Hejazi, S Kim, P Kyle, P Patel, S Turner and M Wise (2018) "Regional responses to future, demand-driven water scarcity" *Environmental Research Letters* 13(9), 094006.

Directorate General of Commercial Intelligence and Statistics (DGCIS) (2018) *Inter-state movements/flows of goods by rail, river, and air*. Ministry of Commerce and Industry, Government of India.

Duarte R, V Pinilla and A Serrano (2014) "The effect of globalization on water consumption: A case study of the Spanish virtual water trade, 1849–1935" *Ecological Economics* 100, 96-105.

Ercin AE, MM Mekonnen and AY Hoekstra (2013) "Sustainability of national consumption from a water resources perspective: The case study for France" *Ecological Economics* 88, 133-147.

FAO (2011) *The state of the world's land and water resources for food and agriculture (SOLAW) – Managing systems at risk*. Food and Agriculture Organization of the United Nations, Rome, Italy, and Earthscan, London.

FAO (2015) *Towards a Water and Food Secure Future – Critical Perspectives for Policy-makers*. Food and Agriculture Organization of the United Nations, Rome, Italy, and the World Water Council, Marseille.

FAO, Water (2009) Water at a Glance. The relationship between water, agriculture, food security, and poverty. Water Development and Management Unit, Food and Agriculture Organization of the United Nations, Rome. http://www.fao.org/nr/water/docs/waterataglance.pdf

FAOSTAT Statistics Database (2018) Food and Agriculture Organization of the United Nations, Rome, Italy. http://www.fao.org/faostat/en/#data

Guan, D and K. Hubacek (2007) "Assessment of regional trade and virtual water flows in China" *Ecological Economics* 61(1), 159-170.

Hoekstra, AY and PQ Hung (2002) "Virtual Water Trade: A quantification of virtual water flows between nations in relation to crop trade" Value of Water Research Report Series, 11, UNESCO- IHE, Institute for Water Education, Delft, Netherlands.

Hoekstra, AY and PQ Hung (2005) "Globalization of water resources: international virtual water flows in relation to crop trade" *Global Environmental Change 15(1)*, 45-56.

Huang, K and N. Sim (2020) "Adaptation May Reduce Climate Damage in Agriculture by Two Thirds" *Journal of Agricultural Economics 72*(1), 47-71.

Katyaini, S and A. Barua (2017) "Assessment of interstate virtual water flows embedded in agriculture to mitigate water scarcity in India (1996–2014)" *Water Resources Research 53(8)*, 7382-7400.

Katyaini S, A. Barua and R. Duarte (2020) "Science-policy interface on water scarcity in India: Giving visibility to unsustainable virtual water flows (1996–2014)" *Journal of Cleaner Production, 275*, 124059.

Lenzen M, D Moran, A Bhaduri, K Kanemoto, M Bekchanov, A Geschke and B Foran (2013) "International trade of scarce water" *Ecological Economics* 94, 78-85.

Leontief W (1970) "Environmental repercussions and the economic structure: an input-output approach" *Review of Economics and Statistics* 52(3), 262-271.

Mekonnen, M.M., and A.Y. Hoekstra (2011) "The green, blue, and grey water footprint of crops and derived crop products" *Hydrology and Earth System Sciences* 15(5), 1577-1600.

National Water Development Agency (NWDA) (2006) Inter Basin Water Transfer Proposals. A Society under Ministry of Water Resources, Government of India, New Delhi.

Nordhagen S and U. Pascual (2013) "The impact of climate shocks on seed purchase decisions in Malawi: implications for climate change adaptation" *World Development* 43, 238-251.

Taraz V (2018) "Can farmers adapt to higher temperatures? Evidence from India" *World Development* 112, 205-219.

United Nations (2003) Water for People, Water for Life. World Water Development Report (WWDR), UNESCO and Berghahn Books, United Nations.

Webber M, Crow-Miller B, Rogers S (2017) "The South-North water transfer project: Remaking the geography of China" *Regional Studies* 51(3), 370-382.

World Economic Forum (WEF) (2019) The Global Risks Report 2019 https://www.weforum.org/reports/the-global-risks-report-2019