AGU PUBLICATIONS

Water Resources Research

RESEARCH ARTICLE

10.1002/2016WR020247

Key Points:

- Interstate virtual water flows are unsustainable in India as water scarcity is being concentrated in already highly water scarce states
- Absence of state-specific water policies cripples water governance and management
- Creating policy relevant knowledge is crucial to support well-informed policies to bridge the knowledge-governance gap

Supporting Information:

- Supporting Information S1

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Citation:
Katyaini, S., and A. Barua (2017), Assessment of interstate virtual water flows embedded in agriculture to mitigate water scarcity in India (1996–2014), *Water Resour. Res.*, *53*, doi:10.1002/2016WR020247.

Received 12 DEC 2016
Accepted 24 JUL 2017
Accepted article online 1 AUG 2017

Assessment of interstate virtual water flows embedded in agriculture to mitigate water scarcity in India (1996–2014)

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Abstract India is the largest global freshwater user despite being highly water scarce. Agriculture is largest consumer of water and is most affected by water scarcity. Water scarcity is a persistent challenge in India, due to a gap in science and policy spheres. Virtual Water (VW) flows concept to mitigate water scarcity is at the science-policy interface. The paper aims to address the gap in VW research in India by first analyzing the interstate VW-flows embedded in food grains, and then linking these VW-flows with the water scarcity situation in the states, and elements of state and national water policies for the postreforms, and recovery periods of India's agriculture. There were net water savings (WS) of 207.5 PL during 1996–2014, indicating sustainable flows at the national level. WS increased from 11.2 TL/yr (1996–2005) to 25931.7 TL/yr (2005–2014), with the increase in interstate movement of food grains, and yield. However, unsustainable flows are seen at subnational scale, as VW-flows are from highly water-scarce states in North to highly water-scarce states in West and South. These flows are causing a concentration of water scarcity in water-scarce zones/states. Net VW imports were found to be driven by larger population and net VW exports by arable land. Further, the absence of state water policy cripples water management. Therefore, the paper argues that there is a need to rethink policy decisions on agriculture at the national and state level by internalizing water as a factor of production, through VW research.

Plain Language Summary Water scarcity has been a persistent challenge in India. Agriculture is most affected by it as agriculture is the largest water user in India. The challenge has not been resolved because there is a gap between the knowledge and governance on water scarcity. This research aims to address the gap by first analyzing the water flows embodied (virtual/hidden) in agriculture products moving between states of India to create the knowledge on the flows. Second, by linking it with the water scarcity situation, and some elements of water policy to understand the gaps in knowledge and governance to mitigate water scarcity. The research is unique because it demonstrates the importance of bridging the knowledge governance gap to mitigate water scarcity through virtual water (VW) flows assessment. Some VW-flows between the states were found to be unsustainable as they are from highly to other highly water scarce zones/states and are leading to concentration of water scarcity in already highly water scarce zones/states. In contrast, sustainable flows, i.e., from low to high water scarcity zones/states lead to distribution of water scarcity. Absence of well-informed water policy reflect the knowledge governance gap, which leads to unsustainable VW flows hence water scarcity

1. Introduction

Freshwater is an essential resource for sustaining life, development, and environment. However, it is a finite and vulnerable resource, as it constitutes barely 0.1% of total global water resources [*Allan*, 2011; *International Conference on Water and the Environment*, 1992]. Freshwater scarcity is a challenge to achieve water security, therefore, recently formed sustainable development goals (SDG); acknowledge the significance of sustainable use of freshwater. Further, 12th SDG "ensure sustainable consumption and production patterns," prioritizes sustainable use of freshwater in agriculture production in developing countries to achieve economic growth and sustainable development [*United Nations*, 2015]. This is because agriculture consumes approximately 70% of freshwater resources. In order to determine sustainability of freshwater use in agriculture, there is a need to assess the quantum of "water embedded in goods and services" which is known as virtual water (VW) [*Allan*, 2011]. VW was conceptualized by Tony Allan to capture the economically invisible and politically silent link between water demand for water-intensive goods, and water endowment of both the exporting and importing geographical locations [*El-Sadek*, 2010; *Sadaf and Zaman*, 2013]. Hence, VW concept is based on the rationale of "distribution of water scarcity," enhancing "global water use efficiency" and "water savings." Therefore, VW is considered as a policy relevant concept [*Global Water Partnership*, 2017; *Lenzen et al*., 2013; *Roth and Warner*, 2008].

Although the origin of VW concept is rooted in Economics, its evolution has been transdisciplinary in nature with inputs from geography, environmental, ecological, economic, social, political, institutional, and cultural disciplines. As a result of this, VW assessment refers to the physical flows between environmental and economic systems rather than monetary flows [*Beltrán and Velázquez*, 2015; *Daly*, 2003; *Lenzen et al*., 2013]. Therefore, terms VW-flows, VW-transfer, or VW-movement are preferred over VW-trade flows [*Antonelli and Sartori*, 2015; *Hoekstra and Mekonnen*, 2012].

VW-flows conceptual and analytical framework consists of water footprint (WF), which captures environment's role as a "source" as well as "sink," to the economy. While environment as a "source" to the economy is reflected in green and blue WF, environment as a "sink" of the economy is represented as grey WF. In the context of agriculture, which is the largest direct water user, green WF refers to the contribution of rainfall in the growing period of crop under consideration; whereas, blue WF refers to the surface water and groundwater consumed in irrigation of crops. Gray WF captures the wastewater produced through quantum of freshwater needed to assimilate agricultural runoff, consisting of nutrients and pesticides. This assimilative capacity of environment is captured through ambient water quality standards [*Hoekstra et al*., 2011].

Through the VW-flows assessment, the rationale of enhancing net water savings (WS) is being achieved. WS can be gauged from difference in quantum of water used and wastewater generated at the site of production and export, and water which would have been used and wastewater which would have been generated in production of the good at the site of consumption and import [*El-Sadek*, 2011; *Hoekstra and Chapagain*, 2004]. Real WS result from movement of water-intensive goods from a relatively water plenty to relatively water-scarce area [*Hoekstra*, 2003]. WS are important as they can be used to produce higher value agricultural crops, support environmental services, conserve environmental flows or serve growing domestic needs [*Chapagain et al*., 2006]. Therefore, VW-flows assessment is crucial to support policy decisions on prioritizing WS strategies by tracing the unsustainable "hot spots" where there is an imbalance in water endowments and water use. These WS strategies are production of those goods which are most suited to local environmental as well as socioeconomic conditions; reducing unsustainably high VW, and coordination between VW importers and exporters [*Wichelns*, 2010; *Zhang et al*., 2011; *Zhao et al*., 2009].

VW was empirically tested on international food trade and movement of food grains from semiarid and arid regions of Middle East and North Africa (MENA) [*Allan*, 1993, 1997, 2011]. As VW-flows assessment reveals the invisible unsustainable flows, it has been assessed at various governance scales in MENA nations, Spain, Australia, and China and to some extent in India [*Guan and Hubacek*, 2007; *Lenzen and Foran*, 2001; *Velázquez*, 2006]. Interestingly, these assessments indicate that VW-flows are unsustainable as they are not aligned with water endowments and are therefore aggravating water scarcity. For instance, relatively water-scarce North China exports water-intensive products to relatively water rich South China [*Guan and Hubacek*, 2007]. These unsustainable flows have also led to creation of pollution haven in water-scarce North China. Existing VW research indicates that there is an urgent need for integration of water as an input, in economic planning at global, regional, national, and subnational scale for sustainable water use specifically for emerging economies [*Guan and Hubacek*, 2007; *Manfred Lenzen and Foran*, 2001; *Velázquez*, 2007].

Among the emerging economies, India is an interesting case as India is among the largest global water users. In fact, India was highest water user in 1995, i.e., 13% of global water use, and second highest in 2008, i.e., 12.2% [*Arto et al*., 2012]. Agriculture sector has the highest share of water use in the economy, i.e., approximately 65–70%, for some states it is as high as 90% [*Indian Agriculture Research Institute*, 2010; *Parihar and Idnani*, 2012]. In India, high water use in agriculture is attributed to low water use efficiency (WUE), which is merely 30% [*Antonelli and Sartori*, 2015]. Further, agriculture is primary source of livelihood for nearly 70% of population in Ind*ia* [*Government of India*, 2011a, 2011b]. Therefore, with many states in India facing water scarcity there is a concern over sustainable water use in agriculture for food and livelihood security, in addition to, water security [*Allan*, 2011; *Schultz and Uhlenbrook*, 2007].

India figures as an exporter of scarce water resources from the VW-flows assessments carried out at the global scale [*Hoekstra and Hung*, 2002]. VW concept is found to be relevant at global, regional, national, and even at the subnational scales. However, VW research at subnational scale has received little emphasis despite its importance in strategic mitigation of water scarcity [*Hoff et al*., 2014]. Its importance emerges from the significant variations in water endowments and agroclimatic conditions at subnational scale. Further, *Mubako* [2011] and *Earle and Turton* [2003] suggest that for a diverse nation like India national average of VW-flows need to be further examined at subnational scale to formulate judicious water policies at both subnational and national scales. In agreement, *V Kumar and Jain* [2007] and *Horlemann and Neubert* [2007] suggest that subnational VW assessment would lead to improved policy direction on food production and water management as it can aid in planning favorable agricultural growth, and assessing ecological impacts of agriculture water use. The only subnational assessment of VW-flows for India was carried out by *Verma et al*. [2009] for the period of 1997–2001. There is a research gap in linking VW-flows with water scarcity situation at subnational scale to frame meaningful policy recommendations on sustainable water use [*Lenzen et al*., 2013; *Yang and Zehnder*, 2007].

Hence, this paper aims to address this research gap through an assessment of interstate VW-flows embedded in food grains in India to demonstrate its relevance in formulating evidence based water policies at subnational scale for enhancing sustainable water use. State was identified as a suitable subnational scale for VW-flows assessment in India because both water resources and agriculture are state subjects according to the Constitution of India [*Government of India*, 2014a].

The main contributions of this research are: (a) Analysis of interstate VW-flows embedded in food grains to determine the quantum of WS. (b) Temporal and spatial refinement in VW research in India by assessing the VW-flows for the period 1996–2014 and considering states of Central and North-East zones as separate entity which were clubbed with West and East zone, respectively, in *Verma et al*. [2009]. (c) Discussing the sustainability of interstate VW-flows in the context of relative water scarcity situation in states, and water policies to understand how sustainability in water use can be integrated in policy decisions.

The research paper is structured in five sections. An overview of unique features of agriculture sector of India is discussed in section 2. Section 3 comprises data and research method used for the VW-flows assessment. The analytical outcome of interstate VW-flows assessment is discussed in section 4. The last section comprises key conclusions of the research.

2. India's Agriculture Sector

India has largest extent of rainfed agriculture in the world with 67% of net sown area under rainfed agriculture. This reflects that there is a significant contribution of green WF to agriculture production [*Government of India*, 2012c; *Kannan et al*., 2000; *Venkateswarlu*, 2011]. Agriculture is a climate-sensitive sector; predictions indicate that dry zones are becoming drier and wet zones wetter in India. This impacts productivity of rainfed agriculture and is a huge concern for food security [*Chauhan et al*., 2014; *Sivakumar and Stefanski*, 2011]. Remaining 33% of agriculture is irrigated, which is measured as blue WF. Irrigated agriculture is predominantly through groundwater, i.e., 60%. In fact, India is the largest groundwater user in the world [*Amarasinghe and Xenarios*, 2009; *The World Bank*, 2015]. High groundwater use has led to its over-exploitation, particularly in states of North-West zone which were considered suitable to promote high agriculture productivity according to the IX Five Year Plan (FYP) of Indian economy (1997–2002) [*Government of India*, 2006b, 2013e; *Amarasinghe and Xenarios*, 2009; *Katyaini and Barua*, 2016]. Further, several mega infrastructure projects, such as National River Linking Project (NRLP), are being pursued to enhance irrigation water supply. However, they are heavily criticized for inadequate assessment of socioecological sustainability of the proposed interventions [*International Water Management Institute*, 2008]. In addition to the concerns associated with the water as a source to agriculture, there are also concerns associated with water as a sink to agriculture, i.e., the wastewater generated due to fertilizer and pesticide application, referred to as gray WF. Usage of fertilizers and pesticides was intensified during Green Revolution in 1960s. The focus of Green Revolution was on achieving self-sufficiency in food grains production to prevent famine. However, optimal usage of fertilizers was not ensured [*Government of India*, 2008a; *Kumar et al*., 2007; *The World Bank*, 2012; *Yedla and Peddi*, 2003].

Table 1. Major Food Grains Producing States.

Food Grains	North	North-East	East	Central	West	South
	Major Food Grains Producing States Zone-Wise					
Rice	Haryana, Punjab, Uttar Pradesh	Assam	Bihar, Orissa, West Bengal	Chhattisgarh		Andhra Pradesh, Karnataka, Tamil Nadu
Wheat	Haryana, Punjab, Uttar Pradesh, Uttaranchal		Bihar, West Bengal	Madhya Pradesh	Gujarat, Maharashtra, Rajasthan	
Jowar Bajra	Haryana, Jammu and Kashmir, Uttar Pradesh			Chhattisgarh, Madhya Pradesh	Gujarat, Maharashtra, Rajasthan	Andhra Pradesh, Karnataka, Tamil Nadu
Maize and millet	Himachal Pradesh, Uttar Pradesh, Uttaranchal	Arunachal Pradesh	Bihar, Jharkhand	Chhattisgarh, Madhya Pradesh	Gujarat, Maharashtra, Rajasthan	Andhra Pradesh, Karnataka, Tamil Nadu
Gram	Haryana, Uttar Pradesh		Bihar, Jharkhand	Chhattisgarh, Madhya Pradesh	Gujarat, Maharashtra, Rajasthan	Andhra Pradesh, Karnataka
Pulses other than gram	Uttar Pradesh		Bihar, Jharkhand, Orissa	Chhattisgarh, Madhya Pradesh	Gujarat, Maharashtra, Rajasthan	Andhra Pradesh, Karnataka, Tamil Nadu
Other sorts of grains (Barley)	Haryana, Himachal Pradesh, Jammu and Kashmir, Punjab, Uttar Pradesh, Uttaranchal		Bihar, Jharkhand, West Bengal	Chhattisgarh, Madhya Pradesh	Rajasthan	Tamil Nadu

[a]Source: Compiled from *Government of India* [2015a].

Food grains form the largest share of agriculture produce in India because of its importance in achieving food security. It is at the core of India's food security agenda, evident from The National Food Security Act, 2013; National Policy for Farmers, 2007; and first National Agriculture Policy (NAP), 2000 of India [*Food and Agicultural Organization* (*FAO*), 1995; *Government of India*, 2000a, 2007, 2010, 2013c; *Sivanappan*, 1984]. As an outcome of Green Revolution, India has both the largest area under production of wheat and rice, and highest quantity produced. In addition to rice and wheat, maize, pulses, and millets are major food grains produced (Table 1). Rainfed agriculture contributes about 44% of food grains produced in India [*Venkateswarlu*, 2011]. Major food grains producing states are Haryana, Punjab, Uttar Pradesh in North; Bihar in East; Madhya Pradesh in Central; Gujarat, Maharashtra, and Rajasthan in West; and Andhra Pradesh, Karnataka, and Tamil Nadu in South (Table 1).

Since independence, India's agriculture sector has experienced five different phases of growth. These are classified as pregreen revolution period (1950–1951 to 1967–1968); early green revolution period (1968–1969 to 1985–1986); period of wider dissemination (1986–1987 to 1996–1997); postreform period (1996–1997 to 2005–2006); and period of recovery (2006–2007 to 2009–2010/2011) [*Government of India*, 2014b]. For examining sustainability of VW-flows embedded in interstate movement of food grains in India, last two phases, i.e., postreforms period (1996–1997 to 2005–2006) and period of recovery (2006–2007 to 2009–2010/2011) are most significant. This is because impacts of institutional and technological reforms, introduced as part of Green Revolution (phase 2) and wider dissemination of technology (phase 3), on water use and its sustainability can be understood through VW-flows assessment of these last two phases. At the beginning of postreforms period, in 1996–1997, agriculture growth was at its highest after a decade. However, from 1998 till 2005–2006, i.e., end of postreforms period, agriculture growth decelerated. This deceleration is attributed to shift in focus and resources away from agriculture to manufacturing and services sector [*Government of India*, 2014b]. Therefore, postreforms period is characterized by a decrease in public and private investment in agriculture, resulting in stagnation of area under irrigation, decrease in use of fertilizers, and reduced provision of electricity for agriculture [*Chand and Parappurathu*, 2011].

From 2006–2007 to 2010–2011, the agriculture growth accelerated giving rise to the period of recovery in agriculture evident in increase in yield of the food grains (Figure 1). The period upto 2014 was characterized by several important reforms in agriculture as poor governance and management of water resources started becoming visible. Most significant for sustainable agriculture water use was decentralized decision-making; renewed focus on rainfed agriculture; emphasis on technology; sustainable and efficient groundwater use; and provision of extension activities through agriculture universities, and research [*Government of India*, 2006a; *Unger*, 2014]. For instance, NAP (2000) and XI FYP (2007–2012) emphasize on decentralization for effective implementation and management of agriculture at state and national level [*Government of India*, 2008a, 2010]. National Food Security Act, 2013 encourages decentralized decision-making by considering monitoring and evaluation of food security programmes as a responsibility of state governments [*Government of India*, 2013c]. Second reform was to facilitate renewed focus on rainfed agriculture for which

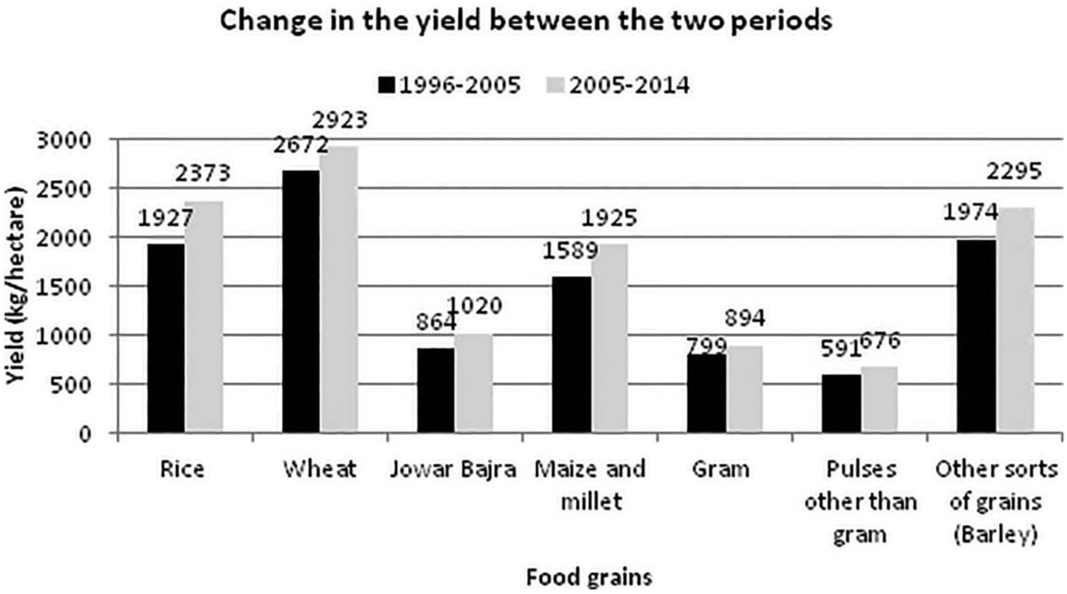

Figure 1. Change in the yield between the two periods. Data Source: Ministry of Agriculture publications.

National Rainfed Area Authority (NRAA) was established in 2007, and through it Rainfed Area Development Programme (RADP) was implemented in 22 states during 2012–2013. RADP was designed as an integrated approach to farming also known as "end to end approach" [*Government of India*, 2014b]. It was a crucial program as 67% of arable land in India is under rainfed agriculture which contributes around 44% of food grains. Pulses, maize, and millets are the most cultivated food grains in rainfed dry lands. A technology mission was also introduced to enhance their productivity [*Government of India*, 2006b, 2013a] (Table 4). Efficient groundwater use was encouraged through a proposal to regulate water-intensive food grains crops.

Further, period of recovery coincides with the XI FYP (2007–2012), which prioritized agriculture growth and environmental sustainability for inclusive growth [*Government of India*, 2008c]. Current FYP (2012–2017), emphasizes on "*inclusive and sustainable*" growth and considers water along with agriculture as one of the eight major categories for allocating financial resources. Current FYP is unique because water features as a major category in it for the first time, since inception of FYP [*Government of India*, 2013a]. These transitions reflect a paradigm shift toward integration of water in economic planning and crucial policy decisions. Assessment of VW-flows through interstate movement of food grains would strengthen this transition in India toward sustainable water use [*Tillotson et al*., 2014].

3. Data and Methodology

3.1. Data and Data Sources

To assess interstate VW-flows embedded in food grains, there are three parameters on which data is required. The first data set is interstate movement of food grains in India for the period of assessment (1996–2014). This was collected from Directorate General of Commercial Intelligence & Statistics (DGCIS), Government of India (Table 2).

The second data set is on the WF of producing the food grains in various states of India. *Mekonnen and Hoekstra [2010;* 2011*]*, have estimated the WF at the subnational scale, i.e., state level in India for the postreforms period (1996–2005). These WF estimates capture the differences in productivity among the states. Therefore, these WF estimates were used by the authors to carry out this state-level VW assessment in India.

WF for period of recovery (2005–2014) was estimated based on these WF data set of 1996–2005 based on the assumption that WF is a function of yield, through using equation (1). Yield of a crop is determined by the climate factors such as precipitation and reference evapotranspiration, and the agriculture technology [*Duarte et al*., 2014; *El-Sadek*, 2011]. Recalculating WF coefficients for 2005–2014 based on 1996–2005 was considered crucial because yield varies between the two periods but has remained constant within each

Table 2. Details of Parameters on Which Data Were Collected

Parameter		Interstate Movement Food Grains	WF of Food Grains	Yield
Description		Interstate movements/flows of goods by rail, river, and air for 12 months ending march	Green, blue, and gray WF, Total WF is referred to as VW	Yield to estimate WF of 2005–2014 from 1996 to 2005
Time period		1996–2014 (annual)	1996–2005 (average)	1996–2014 (annual) Estimated average for two periods 1996–2005 and 2005–2014
Categories of food grains for which data was collected	Rice	Rice in the husk	Rice in the husk (paddy or rough)	Rice
		Rice not in the husk	Rice, husked (brown)	
	Wheat			
	Wheat	Wheat (Durum wheat, Wheat nes. and meslin)	Wheat	
		Wheat flour	Wheat or meslin flour	
	Gram	Gram and gram products		
	Chickpeas, dried, shelled, whether or not skinned or split	Gram		
	Pulses other than gram	Pulses other than gram	Urd, mung, black/green gram beans dried shelled, whether/not skinned/split	Pulses
	Jowar and Bajra	Jowar and Bajra	Sorghum and Millet	Jowar and Bajra
	Maize and Millets	Maize and Millet	Maize and Millet	Maize and Millet
	Other sorts of grains	Other sorts of grains	Millets and Barley	Small millets (ragi)
Data Source/Organizations		DGCIS, Ministry of Commerce and Industry, Government of India	*Mekonnen and Hoekstra* [2010, 2011]	Ministry of Agriculture

period (Figure 1) [*Duarte et al*., 2014; *El-Sadek*, 2011; *Government of India*, 2014b]. Therefore, the third data set required for the assessment is of yield of the food grains for the period of assessment (1996–2014). The data on yield were collected from the Ministry of Agriculture, Government of India (Table 2) (yield data per state and its change over the two periods is provided as supporting information Table S1).

$$WF_{2005-2014} = WF_{1996-2005} * \left(\frac{Yield_{1996-2005}}{Yield_{2005-2014}}\right) \tag{1}$$

3.2. Methodological Aspects

Among several methodological approaches to quantify VW-flows, WF based approach is a *classical approach* to assess VW-flows between states of India. This is because it has evolved since 2002 when it was proposed by Hoekstra and Hung, and has been found to be relevant to application at various governance scales [*Lenzen et al*., 2013]. Even the latest VW-flows assessment of water-scarce nations is based on this methodological approach [*Duarte et al*., 2014].

Using the data on total WF of each food grain category, VW-flows embedded in food grains (p) *exported from* each state (s), in a year (t) to other states was estimated through equation (2).:

$$\mathrm{VWX}(s,t) \;= \sum\nolimits_{\mathrm{p}} \mathrm{VWC}^{\mathrm{s}}_{\mathrm{p}}(s,p,t) * x^{s}_{p}(s,p,t) \tag{2}$$

where VWC^s_p is the virtual water content (WF coefficient) in the state s of food grains p and x^s_p refers to the quantity of food grains p exported. Similarly VW-flows embedded in food grains *exported to* each state from other states r is estimated using equation (3):

$$\mathrm{VWM}(s,t) \;= \sum\nolimits_{p} VWC^{r}_{p}(r,p,t) * m^{r}_{p}(r,p,t) \tag{3}$$

where VWC^r_p is the virtual water content (WF coefficient)in the state r of food grains p and m^r_p is the quantity of food grains p imported from state r for the year t.

In equations (2) and (3), each year refers to financial year, e.g., 2003–2004 is April 2003 to March 2004, because interstate movement of agricultural goods data is recorded for financial years and WF data is available as a 9 years average, i.e., for the period of 1996–2005.

VW balance of a state is gauged from the difference between VW exports and imports (equation (4))

$$VWB(s,t) = VWM(s,t) - VWX(s,t) \tag{4}$$

Net National water savings ΔS_n (m^3/yr) through interstate movement of food grains p from an exporting state s_e to an importing state s_i is estimated by using equation (5)

$$\Delta S_n[s_e, s_i, p] = T[s_e, s_i, p] * (VWC[s_i, p] - VWC[s_e, p]) \tag{5}$$

where T refers to the amount of product which is moved between states. Summing up the national WS of each category of food grains gives total national WS. WS result from differences in water productivities, for instance, if water needed at the site of production (exported from/export) is lower than the site of consumption (exported to/import) [*Chapagain and Hoekstra*, 2004; *Chapagain et al.*, 2006; *Wang et al.*, 2015]. This means water is saved in movement of goods from higher to lower water productivity.

4. Results and Discussion

This section is organized in two subsections, first dwells upon WF of food grains, and assessment of VW-flows at *national* level. Second is a discussion on *subnational*, i.e., zone and state level assessment of VW-flows for the postreform period (1996–2005), and period of recovery (2005–2014). The discussion on VW-flows assessment at the national and subnational scale is linked with the water scarcity situation and the water policies.

4.1. VW-Flows of Food Grains at National Level

There has been a decrease in the WF of food grains from 1996–2005 to 2005–2014 due to the improvement in yield of food grains. Improvement in yield is due to increased efficiency in use of inputs, including water, and is crucial for the long-term agriculture growth [*Government of India*, 2014b]. Increasing WUE is recognized as an important goal for sustainability of water resources in all the three National Water Policies of India, i.e., 1987, 2002, and 2012 [*Katyaini and Barua*, 2016]. It is important to mention here that the water footprint which is a crucial part of the virtual water assessment framework and indicates water productivity is a very new concept in the water policy discussions in India. It has been recognized in the National Water Policy (NWP) (2012). Further, the National Action Plan on Climate Change (NAPCC) of *Government of India* [2008b] has prioritized increasing WUE by 20% as it would help in coping with the uncertainty of climate change impacts on water and agriculture sectors, both of which are climate-sensitive sectors and are at high risk.

Among food grains produced in India, sorghum, and millet have highest WF in both the periods, i.e., 5028 m^3/ton during 1996–2005 and 3669 m^3/ton in 2005–2014. About 94% of it is green WF as it is cultivated during rainy and postrainy season (Table 3). Sorghum and millets are drought tolerant and are cultivated in semiarid and arid areas of North, West, and South India [*Indian Institute of Millets Research*, 2015]. When rainfall (green WF) is insufficient to meet the crop water requirements, irrigation (blue WF) is required [*Novo et al.*, 2009]. Among the food grains considered for the research, wheat has the highest proportion of blue WF, i.e., 56%. Wheat is a staple cereal in North, West, and Central India and irrigating the crop was

Table 3. Average WF of Producing Food Grains in India, Proportion of Different Types of WF, and Zones Where States Have Highest and Second Highest WF

	Average WF of India (m^3/ton)		Proportion of Different Types of WF (%)			Zones Where States Have the Highest and Second Highest WF			
						1996–2005		2005–2014	
Food Grains	1996–2005	2005–2014	Green	Blue	Gray	Highest	Second Highest	Highest	Second Highest
Rice in the husk	2070	1925	67	22	11	West	North	West	South
Rice not in the husk	2688	2183	67	22	11	West	North	West	South
Wheat	2100	1920	30	56	14	Central	South	Central	South
Wheat flour	2125	1943	30	56	14	Central	West	Central	South
Gram and gram products	4026	3599	79	2	19	West	North	North	South
Pulses other than gram	3550	3099	59	10	31	South	West	South	West
Sorghum and millet	5028	3669	94	2	4	West	South	East	South
Maize and millets	3283	2742	91	3	7	West	South	South	North
Other sorts of grains	3076	2713	81	14	5	West	North	West	East

[a]Data source: compiled from *Mekonnen and Hoekstra* [2010, 2011] and estimations using equation (1).

important to provide a predictable water supply for improving its yield. To accelerate the progress of irrigation schemes for enhancing its production along with other food grains, accelerated irrigation benefit programme (AIBP) was initiated in 1996–1997 by Government of India. Production of wheat is also associated with high wastewater generation reflected by grey WF, i.e., 14%. The highest grey WF is of pulses other than gram, i.e., 31%, followed by gram and gram products, 19%. High gray WF leads to creation of "pollution havens" in the producing states. Among the food grains, production of wheat, rice, and pulses (including gram and gram products) is prioritized to achieve National Food Security Mission, 2007–2008 [*Government of India*, 2014b].

It is important to emphasize here that the states in West, South, and North are among major producers of food grains, despite facing high water scarcity [*Katyaini and Barua*, 2016] (Tables 1 and 3). While the states in East and North-East are not major producers even though they are relatively well endowed with water resources, i.e., less water scarce. This indicates that there is a mismatch in existing food grains production patterns and water scarcity at subnational scale in India. VW assessment is intended to reveal the extent of this mismatch through quantification of water loss through interstate movement of food grains.

From the VW-flows assessment it can be inferred that there were net WS of 207.54 PL (1PL = 10^{15}L) during 1996–2014 due to the inter-state movement of food grains in India (Table 4). These WS are an outcome VW-flows from high to a low water productivity zones [*Novo et al*., 2009; *Yang and Zehnder*, 2007]. Higher water productivity (ton/m^3) is reflected in lower WF. Average WS increased from 11.157 TL/yr in the postreforms period (1996–2005) to 25931.673 TL/yr in period of recovery (2005–2014). Highest WS were through VW-flows embedded in rice not in the husk, i.e.,109.5PL in 2011–2012, followed by wheat, 97.8PL in 2012–2013. In fact, highest production of food grains was recorded in the year 2011–2012. It was equivalent to 259.32 million tonnes, 242.23 million tonnes of it was cereals, and 17.09 million tonnes was pulses [*Government of India*, 2014b]. Rice and wheat have relatively lower WF in comparison to other food grains considered (Table 3), therefore, it can be inferred that large amount of interstateVW-flows is due to movement of large volumes of rice and wheat which are staples in India.

It is interesting to note that highest water losses were also through VW-flows embedded in rice not in the husk. The quantum of highest water losses through rice not in the husk was −4485 GL in 2007–2008, followed by maize and millets, −954 GL in 2010–2011. 2007–2008 is the year when the need to enhance agriculture productivity, and farm incomes was recognized and major central government schemes, like National Food Security Mission, Rashtriya Krishi Vikas Yojana, Macro Management of Agriculture, National Mission for Sustainable Agriculture were introduced. Central government's role in decision-making has

Table 4. VW-Flows Crop-Wise and Year-Wise for the Period of 1996–2014

		Crop-Wise and Year-Wise VW-flows (Giga Litres = GL = $\times 10^9$ L)									
	Year	Rice in the Husk	Rice not in the Husk	Wheat	Wheat Flour	Gram and Gram Products	Pulses Other Than Gram	Sorghum and Millet	Maize and Millet	Other Sorts of Grains	Total
Postreform Period	1996–1997	34	2	975	11	−2	94	0	0	−3	1111
	1997–1998	3	−55	854	111	−15	152	0	0	1	1050
	1998–1999	10	1	−5	56	−107	24	0	−2	−2	[−]25
	1999–2000	0	−4	−3	11,998	−2	3142	0	0	0	15,131
	2000–01	1	−1185	6561	16	−46	−43	−7	−201	−208	4888
	2001–02	0	−1429	14,610	83	−6	−146	46	808	10,955	24922
	2002–03	−482	−1387	4998	1	−18	−172	1962	−124	−173	4606
	2003–04	49	−2992	18,555	6	−10	−68	26	−33	−313	15,222
	2004–05	50	−2251	24,734	7	155	−196	48	8	−224	22,330
Period of Recovery	2005–06	219	2248	12,871	−5	−11	−49	22	−209	150	15,237
	2006–07	16	−332	6609	5	164	52	24	−35	158	6660
	2007–08	46	−4485	4566	1	142	−106	30	−680	−17	[−]504
	2008–09	19	−4325	10,504	1	83	−58	53	97	0	6372
	2009–10	17	1943	10,175	−3	49	−153	102	−383	595	12,343
	2010–11	28	673	3501	2	13	−227	65	−954	0	3102
	2011–12	−1	105,811,625	9816	2	28	3688770	82	−715	35	109,509,642
	2012–13	44	1950	97,885,464	−2	64	−296	26	−307	83	97,887,026
	2013–14	27	2090	11,297	0	6	−122	12	−593	286	13,004
	Total	79	105,802,087	98,026,081	12,289	490	3,690,599	2492	[−]3324	11325	207,542,117
	Water loss (Max)	−482	−4485	−5	−5	−107	−227	−7	−954	−313	
	WS (Max)	219	105,811,625	97,885,464	11,998	164	3,688,770	1962	808	10,955	

been considered crucial for achieving self-sufficiency and self reliance in food grains production, even though agriculture is a state subject in India [*Government of India*, 2012a].

Maize is the third most important food grain in India after rice and wheat and contributes about 9% to the national food grain production [*Government of India*, 2013b]. The VW-flows assessment reveals that maize and millets was the only category associated with water loss throughout the two periods, with a net water loss of −3324 GL from 1996 to 2014 (Table 4). Further, there were two years with net water losses, 1998–1999 with −25 GL, and 2007–2008 with −504 GL of water losses. Although at the national level net water losses were reflected in only 2 years, larger unsustainable VW-flows are visible at the subnational scale. Identifying these unsustainable VW-flows at subnational scale are crucial for effective state water and agriculture policy decisions. These are discussed for postreforms period and period of recovery in the next section.

4.2. VW-Flows of Food Grains at Subnational Level

VW-flows is discussed first zone-wise and state-wise, second of states with highest WS and water losses in the two periods.

4.2.1. VW-Flows: Zone-Wise and State-Wise

Among the zones of India, North has the highest water losses (−19.8 TL/yr), while West has highest WS (11.1 TL/yr), and South zone had the second highest WS (9.7 TL/yr). Major VW inflows in West and South are from North (Figure 2). It is important to emphasize here that, VW-flows are also from relatively water plenty East and North-East zones, to water-scarce South and North zones, respectively (for relative water scarcity in India please refer to *Katyaini and Barua* [2016]).

North zone continues to have the highest water losses in the period of recovery. The water losses increased from −19.8 TL/yr in the postreforms period to −16.2 PL/yr in the period of recovery (Figures 2 and 3). While Central zone had WS in postreforms period; it has water losses in the period of recovery, i.e., −11.7 PL/yr.

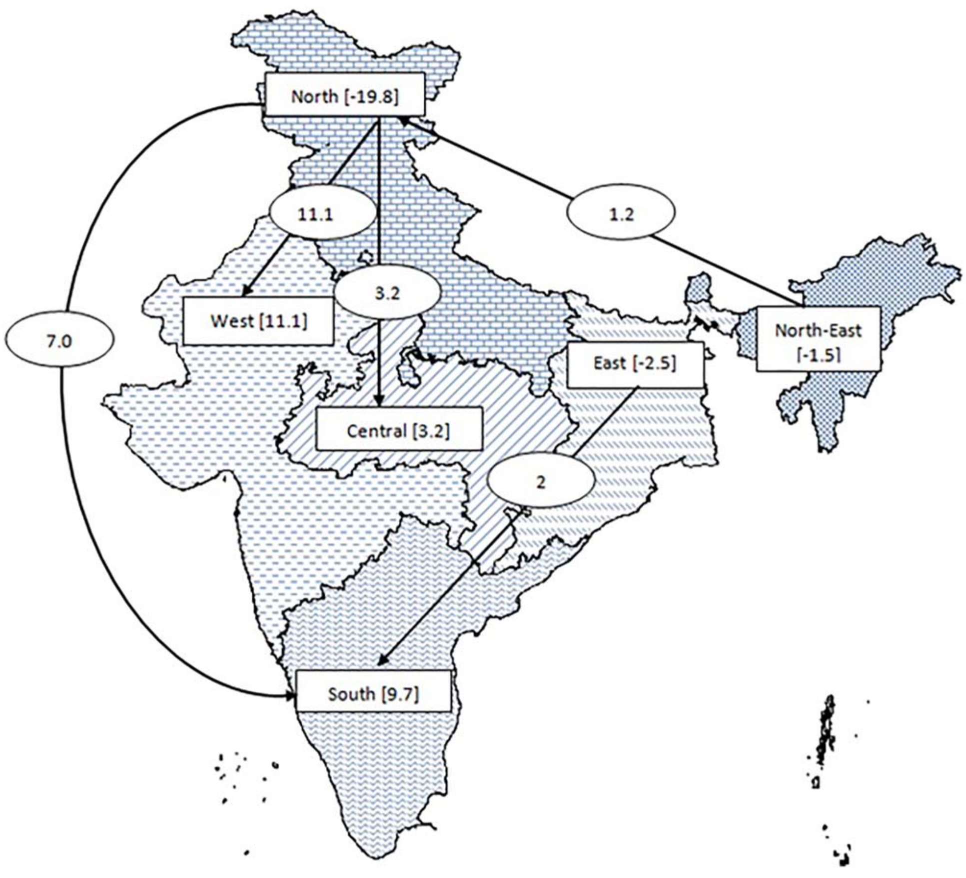

Figure 2. Zone-wise VW-flows (TL/yr) during 1996–2005. (Values in boxes are net VW exports or imports. Values in circles indicate major flows between zones.)

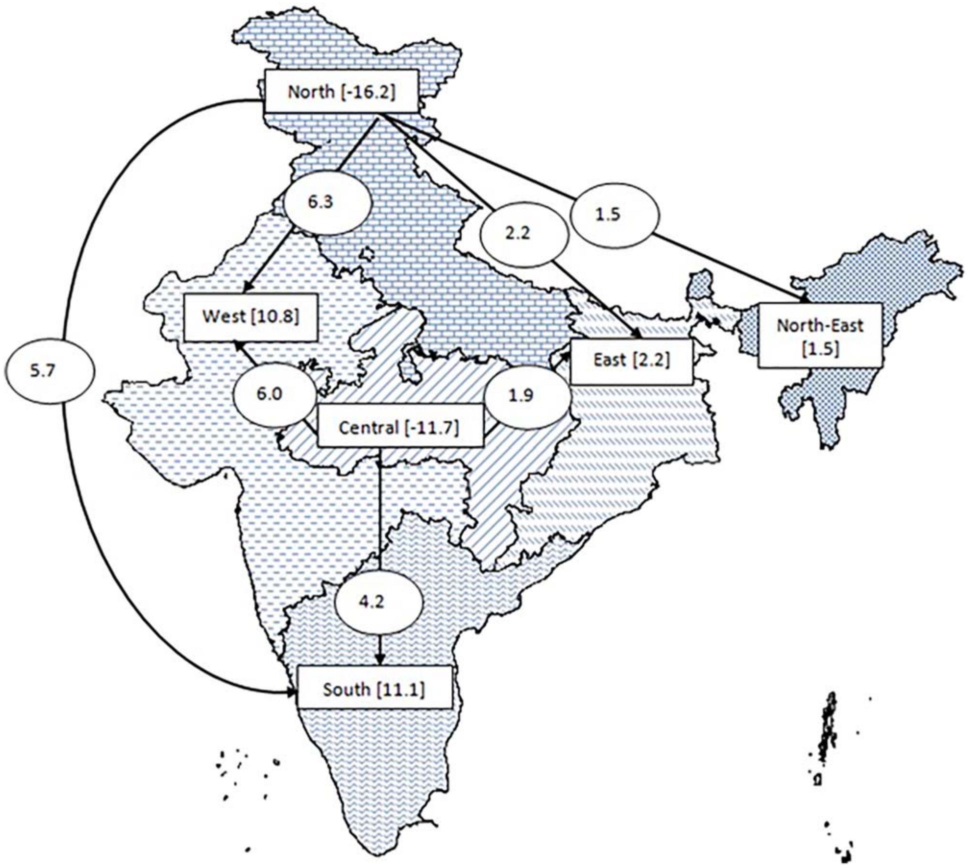

Figure 3. Zone-wise VW-flows (PL/yr) during 2005–2014. (Values in boxes are net VW exports or imports. Values in circles indicate major flows between zones.)

The water losses are because Central zone has become VW exporter. South and West zones continue to have highest WS 11.1PL/yr and 10.8PL/yr, respectively. In comparison to the postreforms period, WS of South zone has surpassed that of West. It is important to emphasize here that the quantum of WS and losses during 2005–2014 are much higher than the 1996–2005 because of increase in interstate movement of food grains.

Interstate VW-flows during 1996–2005 resulted in water saving in Gujarat, Maharashtra, and Rajasthan states of West zone, and Andhra Pradesh, Karnataka, Kerala, and Tamil Nadu states of South zone (Figure 4). In contrast, VW-flows led to water loss in Delhi, Haryana, Himachal Pradesh, Punjab, and Uttar Pradesh. While Maharashtra had highest WS (3.724 TL/yr), Punjab had highest water losses (−4.589 TL/yr). The concern here is that Punjab is a highly water-scarce state [*Katyaini and Barua*, 2016]. It is crucial to emphasize here that, among the states with WS only Karnataka and Maharashtra have implemented a state water policy (SWP) during the postreforms period,in 2002 and 2003, respectively. These states are at the forefront of institutional reforms for sustainable water use. It is evident from their water policies that they aim to enhance agriculture productivity and WUE through an integrated approach to land and water use policies [*Government of Karnataka*, 2002; *Government of Maharashtra*, 2003]. These aspects are crucial from the viewpoint of VW research. In addition to prioritizing WUE, Maharashtra is saving scarce water resources through VW-imports embedded in interstate movement of food grains. It would be important to know which are these states from the perspective of alleviation of water scarcity, this is discussed in section 4.2.2.

Among the states with water losses, only Uttar Pradesh had implemented SWP, 1999. The SWP acknowledges water as a scarce resource, and considers it necessary to minimize water loss in crop production [*Government of Uttar Pradesh*, 1999]. Even though, Punjab has the highest water losses, there is no state-specific water policy in the postreforms period. Green Revolution for intensive foodgrains production in Punjab was intiated in 1960s to meet national food requirements of India, and prevent famines. The intervention did

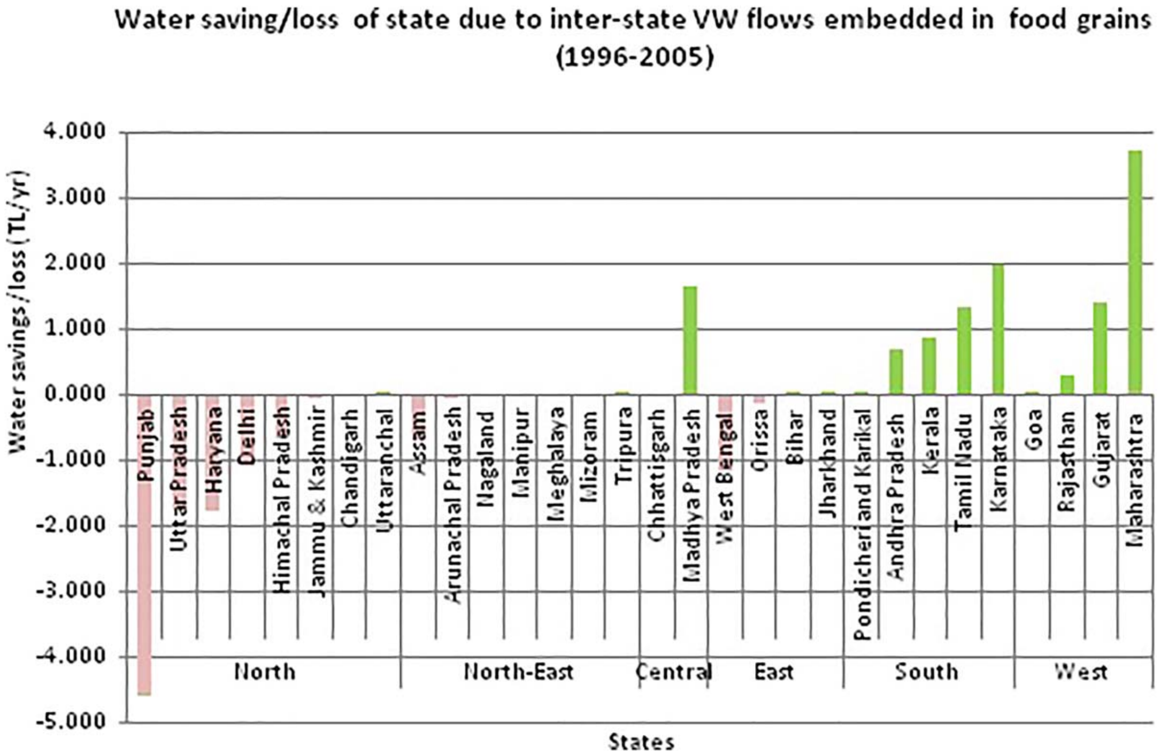

Figure 4. Water saving/loss of state due to interstate VW-flows embedded in food grains (1996–2005).

not pay adequate attention to the impacts on water scarcity situation in the state. As a result of lack of attention, and water governance in absence of SWP, there was high water scarcity in Punjab [*Katyaini and Barua*, 2016].

Meeting agriculture water requirements for food security has always been a priority in the NWP of India. During postreforms period, NWPs (1987, 2002) emphasized more on irrigation. In fact, first NAP came into existence much later, i.e., in 2000 than the first NWP of 1987 [*Government of India*, 2000b]. Although both agriculture and water are state subjects in India, none of the states forumlated or implemented agriculture policy based on NAP to address state-specific issues, concerns, and challenges during postreforms period.

Punjab state continues to face highest water losses in the period of recovery, quantum of water losses increased from −4.589 TL/yr in 1996–2005 to −5.982 PL/yr in 2005–2014. Despite highest water losses Punjab did not have a state-specific water policy. A draft SWP was formulated in 2008 but has not been accepted yet. Absence of a SWP for Punjab has crippled water resources management and governance in Punjab. WS in Maharashtra have increased from 3.724 TL/yr in 1996 − 2005 to 3.694PL/yr in 2005 − 2014. However, Tamil Nadu is the state with highest WS during 2005–2014, i.e., 4.398 PL/yr (Figure 5). Both Maharashtra and Tamil Nadu are at the forefront of water resources management. Revision of their SWP was being considered during 2005–2014 [*Government of Tamil Nadu*, 2013; *Press Trust of India*, 2013]. Periodic revision of SWP reflects a strong institutional arrangement to regulate and manage access and use of water. This is crucial for adapting to the changing patterns.

4.2.2. VW-Flows: State With Highest Water Saving/Loss

This section examines the major inflows to highest WS states (Maharashtra in 1996–2005 and Tamil Nadu in 2005–2014) and outflows from highest water losing state (Punjab in both the periods). Maharashtra is a net VW importer embedded in food grains despite being a major producer of food grains (Table 1 and Figure 4). This is primarily because Maharashtra is the second most populous state of India [*Government of India*, 2012b]. This reflects that high VW imports are driven by food requirements of large population. Among the states from which Maharashtra received VW inflows are highly water-scarce Punjab and Haryana (Figures 6 and Figure 7). Relatively, Maharashtra is moderate to highly water scarce [*Katyaini and Barua*, 2016]. Therefore, water security in Punjab and Haryana is a concern.

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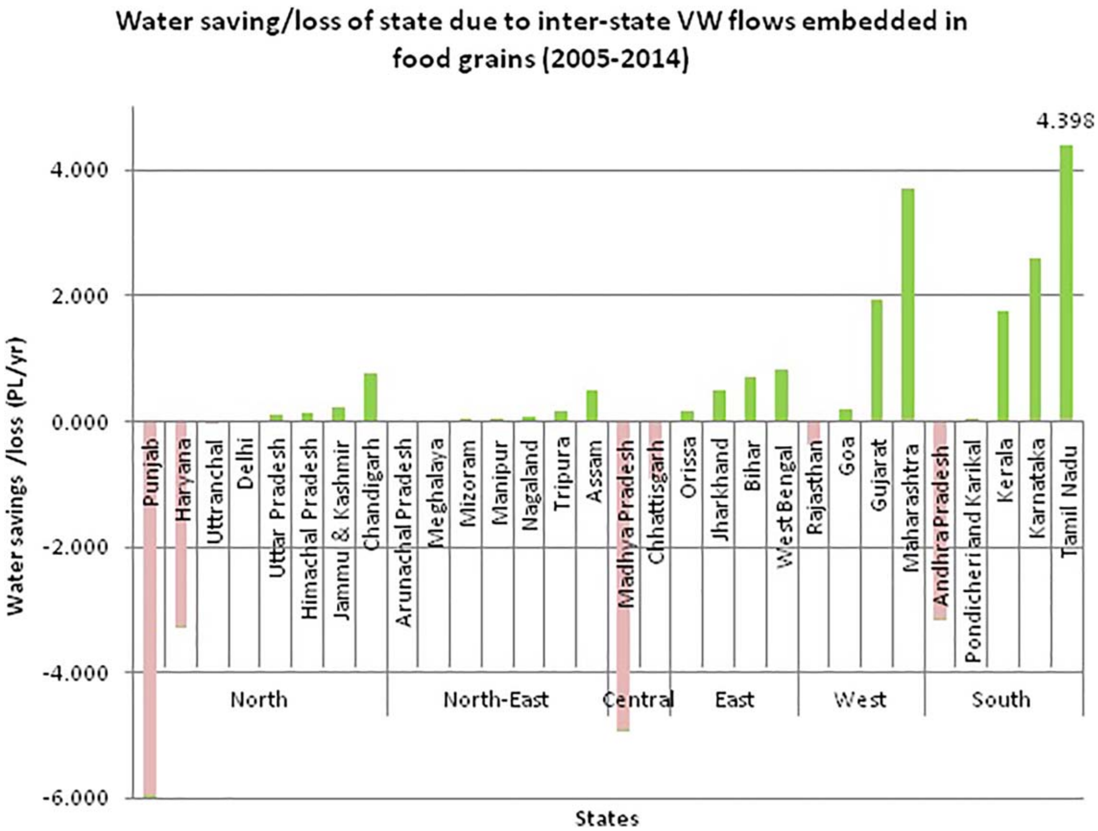

Figure 5. Water saving/loss of state due to interstate VW-flows embedded in food grains (2005–2014).

Punjab was the largest VW exporter because North-West zone comprising Punjab was considered as highly productive for food grains production according to the regionally differentiated strategy of IX FYP (1997–2002) [*Government of India*, 2008a]. The strategy classified Punjab as high irrigation-low rainfall zone for increasing agriculture production. However, the strategy did not forsee sustainability of water use for increased agriculture production. Inspite of the scientific knowledge on sustainability of water resources, the economic planning continued to consider the states in North zone as granary of India rather than realizing the agriculture potential of states in North-East and East zones. VW outflows from Punjab are to highly populous states of India such as Maharashtra and Gujarat in the West, Madhya Pradesh in the Central, and Karnataka, and Andhra Pradesh in the South zones (Figure 7) [*Government of India*, 2012b]. Therefore, it can be inferred that Punjab is supporting the food security of highly populous states at the expense of its scarce water resources. Further, VW-flows from Punjab to Gujarat and Andhra Pradesh reflect VW-flows from a highly water-scarce state to other highly water-scarce states [*Katyaini and Barua*, 2016]. Therefore, it can be inferred that interstate movement of foodgrains is not aligned with water endowments.

Tamil Nadu, the state with highest WS during 2005–2014, received highest VW inflows from Andhra Pradesh, Madhya Pradesh, Punjab, Rajasthan, and Kerala (Figure 8). Among them Rajasthan, Punjab, and Andhra Pradesh are major producers of food grains despite high water scarcity (Table 1) [*Government of India*, 2015b; *Katyaini and Barua*, 2016]. This is because these states have large arable land. In India, arable land and yield are the main criteria for decisions on agriculture production [*Government of India*, 1997]. Although water scarcity was recognized as a challenge, and water was considered important for development planning since the first NWP (1987), they are being considered for the first time in economic planning through the current FYP (2012–2017) [*Government of India*, 2013a; *Katyaini and Barua*, 2016].

Among the five states from where major VW inflows to Tamil Nadu, only Punjab does not have a SWP. Absence of a SWP reflects weak governance of water resources in Punjab leading to highest water losses in both postreforms period and period of recovery. VW outflows are from highly water-scarce Punjab to relatively water plenty state, like Assam. Besides Assam and Tamil Nadu, major VW outflows from Punjab are to

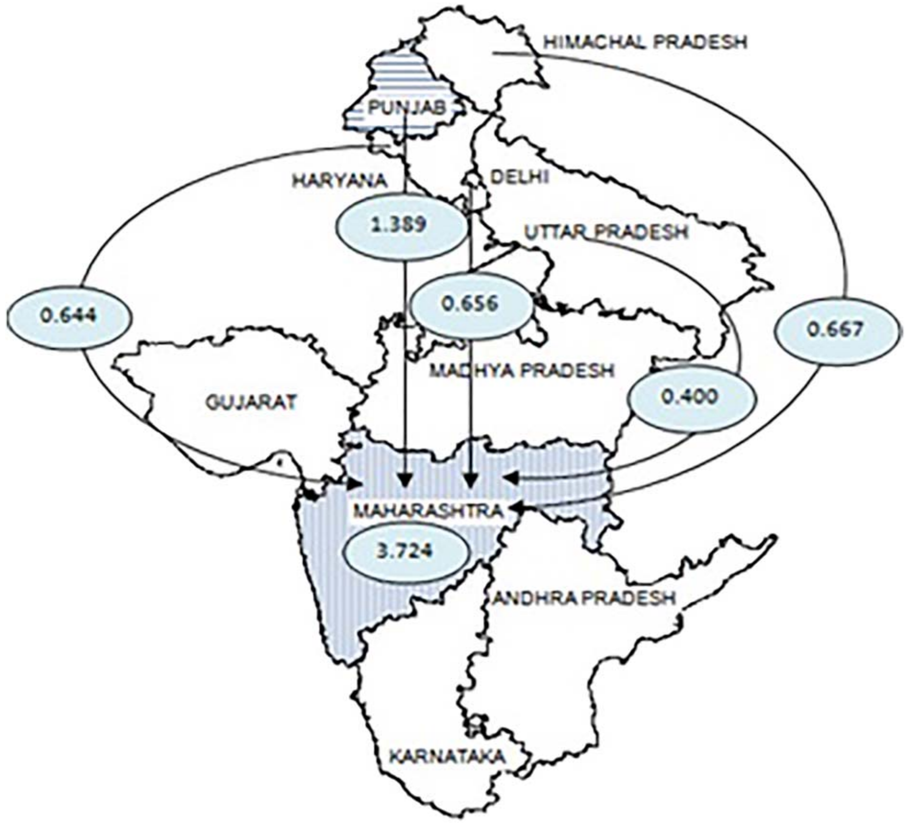

Figure 6. Five major VW inflows to Maharashtra, state with highest WS during 1996–2005 (in TL/yr).

moderately to highly water-scarce Karnataka and Maharashtra, and highly water-scarce Gujarat (Figure 9) [*Katyaini and Barua*, 2016]. This reflects that VW-flows are not leading to distribution of water scarcity, hence are unsustainable.

All the five states, Tamil Nadu, Assam, Karnataka, Maharashtra, and Gujarat, to which there are VW outflows from Punjab have relatively larger population than Punjab. Therefore, it can be inferred that food demand for larger population is the driver of VW outflows from Punjab [*Government of India*, 2012b].

5. Conclusion and Scope for Future Research

Among the economic sectors, agriculture has the largest direct water consumption in India; hence water scarcity can have an adverse effect on agriculture production. Therefore, sustainable agricultural water use is crucial for water, food, and livelihood security in India. Assessment of VW-flows embedded in interstate movement of agricultural products in India provides policy direction toward sustainable agricultural water use and is significant for comanagement of water and land at various governance scales. This study is unique as VW-flows are assessed in the context of subnational water scarcity and policies to determine whether VW-flows in the postreforms period and period of recovery were sustainable. It also examines the cause of unsustainability. It contributes to the VW research pool as it demonstrates the policy relevance of VW-flows assessment at subnational scale to distribute water scarcity in an emerging economy like India.

Our findings indicate that WS through interstate movement of food grains in India increased from postreforms period, 1996–2005, to period of recovery, 2005–2014 at national scale primarily through rice and wheat. This can be attributed to improvement in yields and in turn reduction in WF. However, sustainability of water use in highly water-scarce states in North, West and South India is emerging as a challenge. From the water conservation and sustainability perspective, agriculture production should be aligned with water endowments, i.e., relatively well endowed zone/state should produce and export water-intense products. Our analysis reflects that although North zone is highly water scarce it is a net VW exporter to highly water

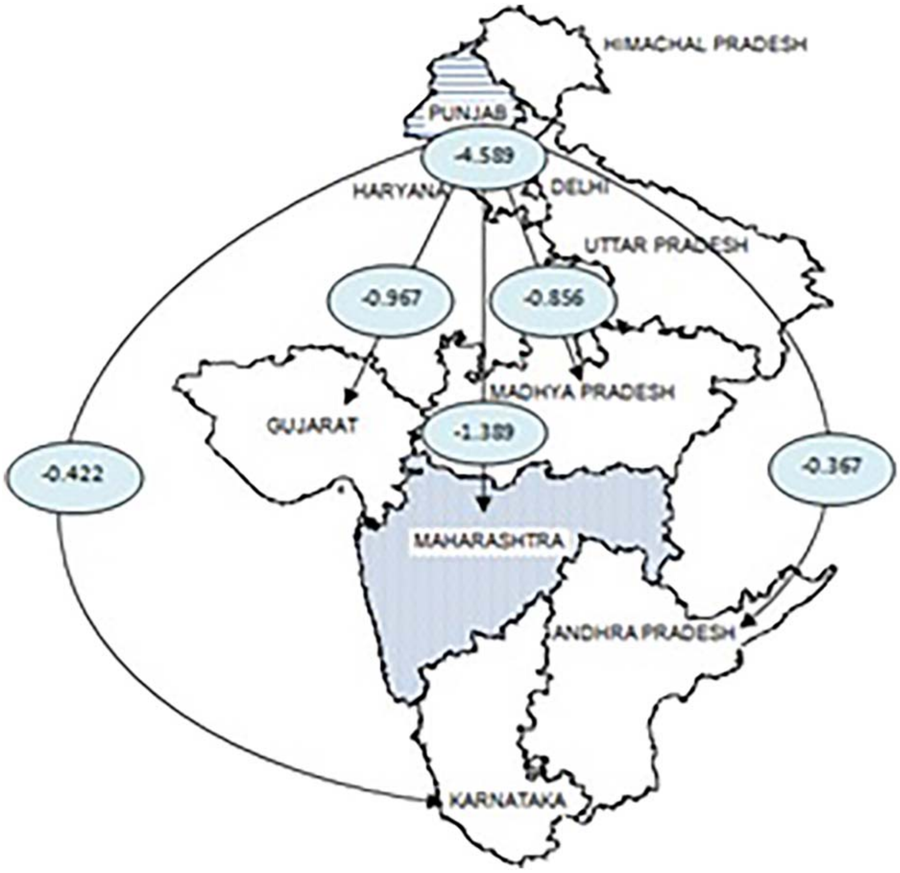

Figure 7. Five major VW outflows from Punjab, state with highest water losses during 1996–2005 (in TL/yr).

scarce, West and South, which are net VW importers. Among the states of North zone, Punjab has highest water losses, while Maharashtra from West and Tamil Nadu from South have the highest WS in 1996–2005 and 2005–2014, respectively. As these VW-flows are from highly water-scarce zone to highly water-scarce zone therefore at subnational scale VW-flows are not consistent with relative water scarcity and are not leading to distribution of water scarcity. This finding is also crucial as it emphasizes on the need to carry out a subnational VW-flows assessment.

Our analysis shows that food grains production and VW-flows is driven by agriculture productivity, and population size. Major VW-flows are from zones/states of higher to lower land productivity and from lower to higher population. Both Maharashtra and Tamil Nadu have lower land productivity than Punjab for producing food grains but are relatively highly populated. Punjab as the granary of India was institutionalized through public intervention, Green Revolution, based on the criteria of high agriculture productivity of the state. This has led to dominance of Punjab in food grain production. While lack as well as lag in policy emphasis for agriculture growth in relatively water plenty states in East and North-East zone due to lack of water infrastructure led to continued dependence on food import from North zone. The analysis indicates that absence of a state water policy for Punjab has crippled the water resources governance and management in the state. In contrast, state water policies of Maharashtra and Tamil Nadu have facilitated WS. Therefore, it is crucial to recognize the significance of water policies at national and subnational scales for planning favorable agricultural growth and assessing ecological impacts to promote sustainable water use, as there is diversity in water endowments and agro-climatic conditions in India.

VW-flows assessment provides policy direction toward WS strategies through identifying unsustainably high VW-flows. VW concept supports the idea of decentralized decision-making and coordination among trading partners to enhance sustainable VW-flows. It is needed to make a conscious decision on agriculture production and export backed by knowledge on whether it is using its scarce water resources to meet the

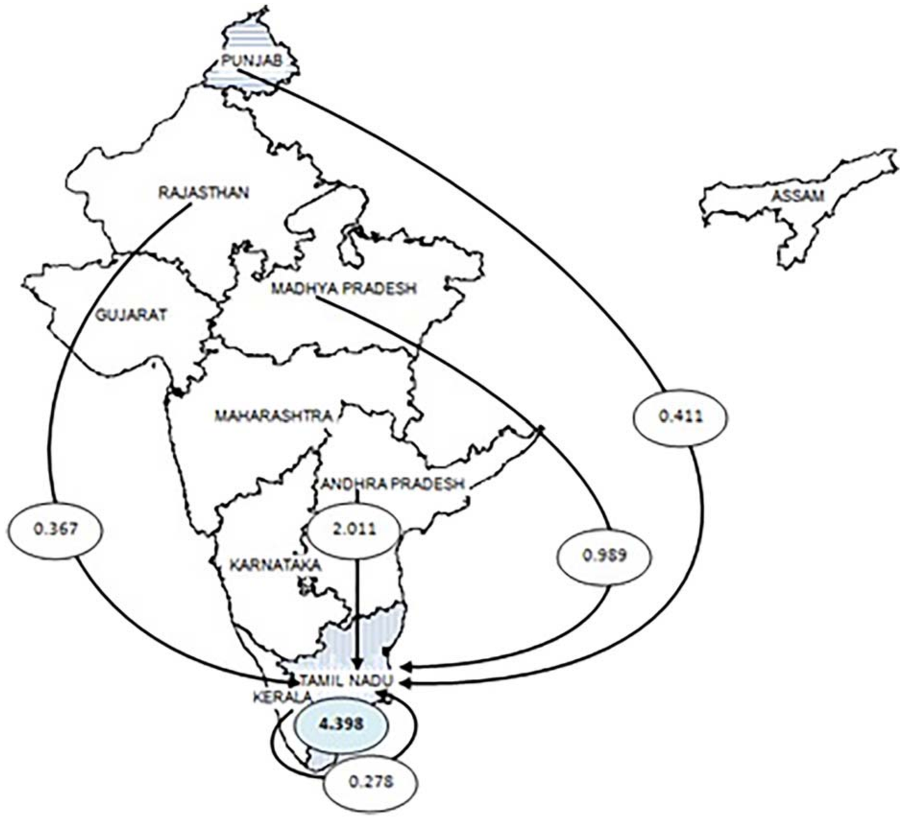

Figure 8. Five major VW inflows to Tamil Nadu which contributes to highest WS during 2005–2014 (in PL/yr).

Figure 9. Five major VW outflows from Punjab which contributes to highest water losses during 2005–2014 (in PL/yr).

food requirements of a relatively water rich or scarce state. This knowledge creation is important to give visibility to the virtual or embedded water flows to distribute water scarcity. A paradigm shift toward integration of water in economic planning and crucial policy decisions of India is seen. The present study on assessment of VW-flows intends to strengthen this transition for sustainable water use. The research argues that emerging economy like India must make conscious decision considering environmental constraints, like water scarcity, as water is an indispensable factor of agricultural production. Inadequate attention to water among other factors in decision-making on agriculture production has resulted from undervaluation of environmental resources and has led to alteration of water and ecological systems to suit agricultural water needs. This has resulted in unsustainable VW-flows which concentrates and intensifies water scarcity rather than distribute it. To ensure sustainable water use, VW-flows assessment needs to be taken into account while formulating and implementing water and agriculture policy decisions apart from other factors. NWP is a guideline for the SWP. Although water footprint was integrated in the National Water Policy 2012, states have yet not revised and implemented their water policies based on NWP 2012. This research demonstrates the significance of interstate VW-flows assessment for water policies to adequately address water scarcity. Consideration of latest scientific knowledge in water policy formulation remains a challenge in translating research into policy action due to weak science-policy interface. Another challenge is the complexity in adjusting production system to water scarcity to make it sustainable. Therefore, institutional arrangements which enhance water use efficiency using best production methods, and water literacy among user on sustainability of rainfed systems, wastewater generation, and improvements in water accounting at various governance scales are essential for bringing about the translation into policy actions. Further, long-term assessment of subnational VW-flows is crucial to have a comprehensive understanding of sustainable water use and flows as well as minimizing shifting of environmental burden of water-intensive production, and water pollution to relatively water-scarce areas. Our research is a primer for research on policy relevant VW-flows assessment to strengthen the science-policy interface for distribution and mitigation of water scarcity. Therefore, future scope of research on VW-flows in India can be enhanced through integration of the following concerns. First, uncertainties associated with the use of WF, and trade data. *Hoekstra et al*. [2011] emphasized on the significance of examining uncertainties associated with the assumptions in WF assessment in the context of assumptions made. In this research, it was assumed that WF is a function of yield and researchers have identified changes in factors like future climatic changes (measured through precipitation, temperature, carbon dioxide levels), reference evapotranspiration, crop calendar, soil water content at field capacity, yield response factor, and maximum yield as sources of uncertainties [*Bocchiola et al*., 2013; *Guieysse et al*., 2013; *Zhuo et al*., 2014; *Duarte et al*., 2014]. In addition, there are uncertainties in predictions made through global climate models, especially regarding climate variability [*Saravanakumar*, 2015; *Senapati et al*., 2013; *Narain et al*., 2009]. Although an improvement in the yield of all the food grain categories considered was recorded from1996–2005 to 2005–2014 (Figure 1), there is a concern of decrease in the yield due to these uncertainties [*Saravanakumar*, 2015; *Senapati et al*., 2013; *UNDP*, 2009]. Decline in the yield in the future would be a concern for achieving water and food security. Further, within the agriculture sector rainfed agriculture (represented by green WF) is more sensitive to climatic changes [*Astha Latha et al*., 2012]. This would also result in a change in the share of blue and green WF of the food grains. Hence, it is important to adequately address these issues through policy measures to avoid short-term effects such as decline in the yield, and associated loss of income, and long-term effects like farmers moving away from rainfed agriculture which contributes significantly to food grain production. It is crucial to integrate these uncertainties on impacts of climate change on agriculture in future research on VW-flows to enhance precision of assessments to support policy decisions on mitigation of water scarcity.

Second, inclusion of interstate movements of food grains by modes other than rail would be important as they are also transported by road and river. Although significant, the data are not collected by DGCIS. Ministry of Road Transport and Highways collects data on goods transported by road, however there is no official record on origin or destination, which is crucial for assessing sustainability of VW-flows. This necessitates recording of data on these aspects for enhancing the precision of VW-flows assessment.

Third, as the economy of India is diversifying with the emphasis being laid on manufacturing and services sectors, water use of these sectorsis becoming important. Inclusion of these sectors along with agriculture provides a holistic view of VW-flows within and between these sectors [*Guan and Hubacek*, 2007; *Lenzen and Foran*, 2001; *Serrano et al*., 2016]. This calls for developing the input-output analysis at subnational scale in India to extend it with addition of dimension of VW-flows.

Lastly, to gain a holistic understanding of implications of policy choices based on VW-flows assessment, there is need to look at the impacts on natural resources, socio-economic aspects like food security and livelihood security, and political situation [*Serrano et al.*, 2016; *Wichelns*, 2015; *Witmer and Cleij*, 2012; *Yang and Zehnder*, 2007]. It is crucial to communicate the research finding on WF and VW-flows assessments with policy-makers in India to contribute to the transformation toward well-informed policies which has initiated in China, Spain, and Netherlands and other EU nations [*Lenzen*, 2009; *Aldaya et al.*, 2010; *Hoekstra and Mekonnen*, 2012]. This would further strengthen the policy relevance of the VW-flows concept to adequately address water scarcity.

Acknowledgments
The author would like to thank the anonymous reviewers for their insightful comments and suggestions that have contributed to improve this paper. We express gratitude to Directorate General of Commercial Intelligence and Statistics, Ministry of Commerce and Industry, Government of India for sharing data with us for academic purpose. Data of Ministry of Agriculture is available on indiastat portal (http://www.indiastat.com/agriculture/2/stats.aspx). We would like to acknowledge the timely guidance of Mesfin Mekonnen, postdoctoral researcher at the University of Twente. All data for this paper are properly cited and referred to in the reference list. The authors would also like to acknowledge doctoral research fellowship of Indian Institute of Technology Guwahati for this research.

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