Virtual water trade and its implications on water sustainability

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ABSTRACT

Limited and declining water resources, increasing demand of water resources from different sectors, has posed a major challenge for maintaining water sustainability and thus overall sustainability for a populous and water-scarce country like India. Over extraction and changing climate have put additional pressure to maintain water sustainability. Therefore, there is a need for proper planning of utilization and management of water resources. Recently, virtual water trade has received much attention and become an important tool for balancing the water budget. On the other hand, virtual water trade may also adversely affect the water balance of the exporter’s country as well as the economy. Analysis of the virtual water trade with its implications for water resources is missing; hence, there is a need for such analysis that will help in management of water resources. In this study an attempt is made to present a quantitative analysis of the virtual water trade and its implications for water sustainability. For this study, the rice crop is considered only due to its characteristics as rice is a major water consumer crop and water exporter crop from India.

Key words: virtual water export, virtual water import, virtual water trade, water footprint, water sustainability

HIGHLIGHTS

- Total water required for production of rice is 318 billion m³, 16.67% of total water available.
- Virtual water export is about 32 billion m³, while the virtual water import is negligible.
- The net virtual water content export is about 4.8 billion m³ which is irreversible in the system and leads to loss of water sustainability.
- The net export of virtual water is about 32 billion m³, a large volume of water export.

INTRODUCTION

With declining water resources and increasing demand for water in different sectors of the economy, there is a challenge to provide the basic necessities of the increasing population and to maintain the water sustainability for the long term (Fallenmark 2013; Grey et al. 2013; Mekonnen & Hoekstra 2016; Goswami & Nishad 2018). Population growth and changing consumption patterns have affected the demand, supply and trade of food (Liu & Savnije 2008; Liu et al. 2009). These factors are strongly related to water resource management for food sustainability and sustainable water availability for agricultural production. Freshwater availability has become a major global concern, various sectors competing for scarce water resources. There is an alarming situation in fresh water availability from regional to global scale. Even water-rich countries are also struggling to cope with growing fresh water scarcity to fulfill the minimum demand (Kummu et al. 2016). Several studies have highlighted the challenges and the impact of water scarcity in India as well as other countries in meeting their water demand (Saleth 2010; Goswami & Nishad 2015; Mancosu et al. 2015; Goswami & Nishad 2018; Graham et al. 2020; Rosa et al. 2020; Oki & Quincho 2020). Water sustainability has become a major global concern due to increasing demand, unsustainable consumption, over extraction, declining water resources with added vulnerabilities due to changing climate (Qureshi & Hanjra 2010). Many countries of the world are facing the danger of very high water stress and rising demand that has pushed countries into extreme stress (Mohammed & Darwish 2017). Increasing food demand affects the supply, availability and trade of food; these are strongly related to available water resources for long term sustainability; any significant changes may affect the sustainability of water resource and thus food sustainability. Thus, there has emerged a major challenge to maintain the water sustainability and to provide the sustainable supply of basic necessities of the increasing population (Goswami & Nishad 2017, 2018). This necessitates the water resources management for food security and...
food production. Therefore, there is a need for proper planning of utilization and management of water resources to maintain water sustainability. The virtual water trade has emerged as an important concept and is getting attention in context of food and water sustainability in recent years (Wichelns 2001; Yang et al. 2006; Goswami & Nishad 2015; Chittaranjan et al. 2018). The virtual water trade has been used as a tool for globalization of fresh water resources, sharing of fresh water resources and better management of water resources (Oki & Kanae 2003; Hoekstra & Hung 2005; Yang & Zehnder 2007; Chapagain & Hoekstra 2008; Konar et al. 2011; Sadek 2011; Dalin et al. 2012; Chen & Chen 2013).

Virtual water provides a better approach for water management and utilization of water resources (Allan 1998; Hoekstra & Hung 2002). However, there are some disadvantages; for example, export of virtual water may harm the water sustainability of a nation and net export of virtual water may influence sustainability through irreversible losses. Therefore, there is need to rethink or sustainability policies on virtual water export as there are not many effective policies for virtual water export. The estimates shows that the exports of virtual water alone can lead to loss of water sustainability and may affect food sustainability from regional to global scale (Kumar & Singh 2005; Wichelns 2010; Goswami & Nishad 2015). Several studies have emphasized the importance of the virtual water trade and its impact on water and food sustainability from regional to global scale (Goswami & Nishad 2018). Assessment of water footprint and virtual water trade are relevant for national policy planning for resource management and sustainable supply of food and water (Hoekstra & Mekonnen 2012).

Virtual water can be defined in terms of minimum water required to produce the crop and water content. The water requirement of production is the volume of water used to produce the crop in the production cycle. While the virtual water in terms of water content is defined as the water available in the end product of the crop as a percentage of the weight, which is irreversible in the hydrological cycle. In general, the water content available in food grains, vegetables and fruits is about 15, 85 and 75% of their weight respectively (Goswami & Nishad 2015). Thus assessment of the virtual water trade in terms of water content is important for analysis of virtual water exports.

Recently, water footprint has been acknowledged as a strong tool for sustainable water management and policy planning at the national, regional and even product level (Hoekstra & Mekonnen 2012). The water footprint of a crop is defined as the total volume of fresh water consumed during the production. The water footprint of a region or crop provides the information about the quantity of total water consumed in the region or by a particular crop. While traditional methods only provide the information about the direct water withdrawals, the water footprint method provide the accurate volume of water used to produce the crop. Water footprint methods also delineate the type of water consumed, which are named as blue, green and grey water footprint. The water footprint depends on agricultural practices, water use efficiency, time, place and local climatic conditions. For an example, virtual water for producing 1 ton of crop in the arid region is higher than the wet region or semi-arid region. Virtual water, from the consumption perspective, is defined as the amount of water to produce the minimum food requirement of a person for healthy life.

In the present study, rice crop is considered as it is one of the major crops that feeds more than 60% of the population of India and is exported world-wide. India is also the second largest producer of rice in the world, accounting for 22% of world’s rice production. Currently, India has produced 172 million tons of rice in the year 2018 and occupies about 45 million ha harvested area, equivalent to 16% of total harvested area in India; this is the largest harvested area in the world for rice cultivation. Along with these, rice is a major water intensive crop that consumes 318 billion m³ water (16.6% of total available water) to produce rice for meeting demand. On the other hand, India has only 3.83% of total world’s fresh water resource to feed the second largest population in the world (about 1,500 million population). It is observed over the year an increasing trend in water demand for production of rice to meet increasing demand. While per capita water availability has reached a critical level of 1,486 m³, less than 1,700 m³ (standard per capita water requirement), there is a declining trend in per capita water availability. Due to poor management and inadequate infrastructure, India faces a persistent water shortage and has become a water-stressed country. As per International norms, a country is classified as water stressed and water scarce if per capita water availability goes below 1,700 m³ and 1,000 m³. India is already a water-stressed country (1,486 m³) and is moving towards turning into water scarce. Over-extraction of groundwater for irrigation, declining water resource with changing rainfall pattern and climate has become a major concern for its availability for production.

A quantitative analysis of the virtual water trade combining with constraints like declining water resource can provide a significant insight and its implications for water sustainability and results may provide the inputs to the policymakers for better management of water resources. The current study is focused on the virtual water trade for the rice crop and its implication on water sustainability for India. It is also analyzed the virtual water trade in terms of water content. Virtual water...
export, virtual water import, net virtual water export, virtual water content export/import and net virtual water content exports are investigated in the present study.

FORMULATION AND METHODOLOGY

Total water available
The total available water depends upon annual rainfall and it is defined as the sum of groundwater and surface water. For India, the average annual precipitation in about 4,000 billion m$^3$ (BCM), natural runoff is about 1,911 billion m$^3$ (AQUASTAT, n.d.) and the total utilisable water is about 1,123 billion m$^3$ that is sum of surface water and groundwater, respectively 690 billion m$^3$ and 433 billion m$^3$ (Central Water Commission, Govt. of India (Water Information, n.d.)). For quantitative assessment of total water available, the total water available is defined as:

$$W_{A}(t) = \alpha \cdot R(t) \cdot A + W_{G}(t)$$  \hspace{1cm} (1)

Here, $R(t)$ represents the area-average annual rainfall at the year $t$ and $A$ represents the total land area. $W_{G}(t)$ represents the available groundwater resource in the year $t$. A fixed value of groundwater is considered for analysis, although there is inter-annual variability and declining trend in the water table. The depletion of groundwater resource is not considered for this study. Generally, only a fraction of rainfall is available for utilization, which is about 28% of total water precipitation for India. Thus, the value of $\alpha$ depends on surface characteristics of the country. The total water available, surface water and the groundwater available for utilization is adopted from AQUASTAT and Central water Commission, Govt. of India (Water Information, n.d.).

Water requirement for production of rice
The total water required for the production of crops is calculated as multiplying the total production of the crop to the water footprint (sum of green water footprint and blue water footprint).

The total water required, $W_{RP}(i, t)$, for production of the crop may be defined as

$$W_{RP}(i, t) = F_P(i, t)W_F(i)$$  \hspace{1cm} (2)

Here $F_P(i, t)$ represents the production of the crop $i$ in the year $t$. $W_F(i)$ represents the water footprint of the crop $i$ used to produce crop given as m$^3$/ton.

In terms of water content available in the end products of total production of rice

$$W_{CP}(i, t) = \alpha_C W_{RP}(i, t)$$  \hspace{1cm} (3)

here $\alpha_C$ represents the water content available in the end products as percentage of the weight of the crop. The value of $\alpha_C$ is 0.15.

Similarly, total water required, $W_{RC}(i, t)$, in terms of food consumption, is calculated as

$$W_{RC}(i, t) = F_C(i, t)W_F(i)$$  \hspace{1cm} (4)

Here $F_C(i, t)$ represents the total consumption of the crop $i$ in the year $t$.

Virtual water export
The virtual water export can be calculated by multiplication of trade volume of the crop to the water footprint of the crops. The virtual water export is calculated as

$$W_E(i, t) = F_E(i, t)W_F(i)$$  \hspace{1cm} (5)

Here $W_E(i, t)$ represents the virtual water export in the year $t$.

Virtual water content export is calculated as

$$W_{CE}(i, t) = \alpha_C W_E(i, t)$$  \hspace{1cm} (6)
Here $W_{CE}(i, t)$ represents the virtual water export in terms of water content available in the end product in the year $t$.

**Virtual water import**

The green virtual water import can be calculated as

$$W_I(i, t) = \sum_{j=1}^{N} F_t(i, t, j) W_F(i, j)$$  \hspace{1cm} (7)

Here $F_t(i, t, j)$ represents the import of the crop $i$, in the year $t$ from the country $j$. $W_F(i, j)$ is the water footprint of crop $i$ of the country $j$.

Virtual water content import is calculated as

$$W_{IC}(i, t) = \alpha_C W_I(i, t)$$  \hspace{1cm} (8)

$W_{IC}(i, t)$ represents the virtual water import in terms of water content available in the end product $i$ in the year $t$.

**Net virtual water export (Trade balance)**

The net virtual water export is defined as

$$W_{NE}(i, t) = W_E(i, t) - W_I(i, t)$$  \hspace{1cm} (9)

Here $W_{NE}(t)$ represents the virtual water trade balance for of the crop $i$ in the year $t$.

The present study analyzes virtual water trade of India along with comparative analysis with other parts of the world. Production, consumption, yield, harvested area and data of trade of rice for India and other countries have adopted from FAOSTAT for the period 1961–2018. Harvested area and the yield of rice has adopted from FAOSTAT for the period 1961–2018.

The total water footprint of rice is considered as the sum of the blue water footprint and green water footprint. The grey water footprint is not taken account for the present study due to not being used in the production process. The blue and green water footprints of rice are adopted from the Water Footprint Network proposed by Mekonnen & Hoekstra (2010). The green water footprint is the volume of water required to produce 1 ton of the crop from rainfall, while total green water footprint of rice is multiplied by total production and per unit water requirement (green water footprint). While, the blue water footprint is the volume of fresh water required to produce 1 ton of the crop from surface water and groundwater, while the total blue water footprint of rice is multiplied by total production and per unit water requirement (blue water footprint). Similarly, grey water footprint represents the amount of water required to dilute the pollutants to produce 1 ton of the crop. In the presents study, only blue and green water footprint is considered while grey water footprint is not considered. Current blue and green water footprint is measured for the study calculated by Mekonnen & Hoekstra (2010) for India and the states. An 1,846 m³/ton water footprint of rice is used. The water content available in the end product is considered from Agriculture Research Service (Agriculture Research Service, n.d.), USDA and Transport Information Service (Transport Information Service, n.d.).

**RESULTS**

**Assessment of production, demand and trade of rice**

Rice is a major crop that is produced and consumed in India; production of rice has increased threefold from 50 million tons to 172 million tons in the period 1961–2018. Similarly, the consumption of rice has increased in the same trend (Figure 1, top panel). On the other hand, the export of rice was very low until 1990 and started increasing and reached about 17 million tons in 2018, which is about 10% of total production (Figure 1, bottom panel). While the import of rice was higher than exports until 1990 and then became negligible (Figure 1). The net export of rice is about 17 million tons (Figure 1).

**Assessment of water required for production of rice**

The total water required for production has increased in the period 1961–2018. Currently, 318 billion m³, water is required to produce 172 million tons of rice in the year 2018, which is approximately 16% of total water available (Figure 2, solid line) for India in the year 2018. The total water requirement for production of rice has risen from 98 billion m³ to 318 billion m³ from
**Figure 1** | Production (solid line, top panel) and consumption of rice (dashed line, top panel), export (solid line, bottom panel), import (dashed line, bottom panel) and export as % of total production of rice (long dashed line, right y axis, bottom panel) for India for the period 1961–2018. The data is adopted from FAOSTAT.

**Figure 2** | Total water requirement for production of rice in quantity (solid line, left y axis, top panel) and as percentage of total water availability (dashed line, right y axis, top panel). In term of water content available in the end product, the total water is given in quantity (solid line, left y axis, bottom panel) and as percentage of total water available (dashed line, right y axis, bottom panel) for the period 1961–2018.
1961 to 2018. In terms of water content available in the end product, the total water demand is about 50 billion m$^3$, which is about 2% of total water available (Figure 2). The global analysis of water required for the production of rice shows that India is a major country that uses a huge amount of water (Figure 3).

**Virtual water trade network of rice**

India is one of the major virtual water exporters in terms of rice export of the world in which virtual water export is around 18 billion m$^3$ and exported to 199 countries and territories. The major countries are namely African countries, Europe and the USA which are importing virtual water embedded in rice from India (Figure 4(a)). On the other hand, the global analysis import of rice shows that India is importing virtual water in terms of rice from only some countries like the USA, Spain, Malaysia, Russia, Thailand and Australia, which is less than 0.004 billion m$^3$, which is approximately negligible value in comparison with the virtual water export (Figure 4(b)).

**Virtual water export**

From a negligible value of virtual water export until 1990, India’s virtual water export has risen to 32 billion m$^3$ in the period 1990–2018 (Figure 5(a), solid line) which is about 1.6% of total available water. Similarly, virtual water export, in terms of water required for production, is about 10% in the year 2018. In contrast, the virtual water import of India was about 1.5 billion m$^3$ in 1970, which then fell to negligible values from 1990 onwards. In terms of water required for consumption, the virtual water import was about 3% in 1960–70, which then fell to negligible values from 1990 onwards. India has moved from an import-intensive paradigm to an export-intensive regime in virtual water trade (Figure 5). Similar results also hold for other crops (Supplementary Figures 1 and 2).

Similarly, virtual water export, in terms of water content, is about 4.8 billion m$^3$ in the year 2018, while the virtual water import is about negligible from 1990 onwards. In terms of total water available, the virtual water content export is about 10% of total water content (Figure 6).

The global analysis gives the more insightful picture of virtual water export. In terms of total water required for production of rice, India, Thailand, Pakistan and Vietnam are the major virtual water exporter countries, which is about 76% of total virtual water export across the world. Of these, India contributes about 24% of the total virtual water trade across the world (Figure 7).
Virtual water trade balance

India’s trade balance has turned positive in recent years (export > import). The trade balance (export-import) was negative until 1990, and turned positive since 1990. In terms of quantity, the net virtual water export was –1.0 billion m³ in 1960–70 and then it has become around 32 billion m³ in the year 2018, equivalent to about 10 million population water demand (Figure 8). In terms of percentage of total available water, net virtual water export was negative until 1980 and then turned positive by about 1.6 percent (Figure 8). In terms of net virtual water content export, the volume of water that is exported is 4.8 billion m³ which is about 0.25% of total water available (Figure 8). The current deficit of water is about 32 billion m³.

CONCLUSIONS

Overall food sustainability depends upon primary resources like arable land, water, and any changes may pose a significant impact on the sustainable availability. The arable land is immobile while the other primary resource, water, can be transported across countries through export of agricultural commodities. A long-term perspective is needed for assessment and policy design for sustainability of water resource; even small but persistent effects like net exports of water may influence sustainability through irreversible losses. The estimates show that export of water embedded in the end product alone can lead to loss of water sustainability; with the current rate of net export of water, India may lose its entire available water in less than 300 years (Goswami & Nishad 2015). Increase in food demand and reduction in water resource due to climate change will further exacerbate the issue.
change may reduce the timescale. This export of agricultural commodities is indirectly accompanied with virtual water that is exported. Rice is a major food product that is consumed in large scale in India and across the world. Along with these, rice is a major crop that consumes a large volume of water for its production and exported across the world from India. The virtual water export through rice is about 32 billion m$^3$ and the virtual water content export is about 4.8 billion m$^3$, which is irreversible, that indicates the water loss. Irreversible loss of water resource of a populous and water stressed country like India will have large impacts on the water sustainability and thus on the global economy and food sustainability. Improved and efficient water management can help to delay the inevitable if net virtual water export continues. India is among the major water scarce countries and exporting of such huge amount of water may increase the level of water scarcity. Along with these, there are evidences of potential impact of changing climate on water availability, quality and accessibility that may affect the water sustainability.

**Figure 5** | Virtual water export (solid line, top panel) and virtual water import (dashed line, right y axis) are given in quantity (top panel), as percentage of total water available (middle panel) and as percentage of total water required for production (bottom panel).
Figure 6 | Virtual water content export (left y axis, solid line), virtual water import (right y axis, top panel) and virtual water content export as percentage of total water content in the end product (dashed line, bottom panel).

Figure 7 | Global analysis of virtual water export.
The purpose of this analysis is to draw the attention of policy makers to the virtual water trade policy. The results show that the total virtual water required for production of rice is about 320 billion m\(^3\); this is about 16% of total water available. While dependency on irrigation for production of rice has accelerated the over extraction of groundwater for irrigation, resulting in water scarcity in many regions of India and these regions have reached the red zone. Water sustainability has become a major concern and challenge in these regions.

A global analysis of virtual water export reveals that India is a major water exporter country, which exports around 32 billion m\(^3\) of water or 1.6% of total available water and contributes a 24% share in the global virtual water export while virtual water import is almost negligible. Our analysis shows that India has become the major virtual water exporter in terms of export of rice across the world. Such magnitude of virtual water trade may affect the water sustainability and thus food sustainability. The present analysis shows that the export of virtual water is much higher than the import of virtual water as a result; India has become a major water exporter from 1990 onwards. Such an increasing trend in virtual water trade may have significant impact on overall sustainability of a nation like India, in which per-capita water availability is less than the standard minimum water requirement. In contrast, the virtual water import of India is negligible from 1990 onwards. Therefore, the net virtual export of water through export of rice only can lead to irreversible loss of water sustainability.

Shrinking of rainfall, declining trend in rainfall, and a changing rainfall pattern with potential climate change may reduce the water availability for production of rice that will affect the overall food sustainability. Thus, virtual water export in this trend may affect the overall water sustainability of India. There is need of water balance in the virtual water trade of a water-scarce country like India. While dependency on blue water for rice production has accelerated over extraction of groundwater in India resulting in groundwater scarcity. Therefore, there is need for interventions for better management of virtual water export. It is found that there are clear indications of significant impacts of virtual water export on water sustainability. Inclusion of other crops like grain, fruit, vegetables etc.) may affect the water sustainability.

Figure 8 | Net virtual water export in terms of water requirement for production (top panel) and water content (bottom panel) is given as quantity (left y axis, solid line) and percentage of total water available (right y axis, dashed line).
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AUTHOR CONTRIBUTION

The contributions of S.N. are in conceptualization, methodology, formal analysis, writing, review and editing of manuscript, visualization, validation. The contributions of N.K. are investigation, analysis, review, writing, and editing the manuscript.

DECLARATION OF CONFLICT INTEREST

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories. The crop production data is adopted from http://www.fao.org/faostat/en/#data. Water footprint data is adopted from https://waterfootprint.org/en/resources/waterstat/. Water availability data is adopted from http://www.fao.org/aquastat/en/index.html.

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