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Virtual water trade and time scales for loss of water sustainability: A comparative regional analysis

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Assessment and policy design for sustainability in primary resources like arable land and water need to adopt long-term perspective; even small but persistent effects like net export of water may influence sustainability through irreversible losses. With growing consumption, this virtual water trade has become an important element in the water sustainability of a nation. We estimate and contrast the virtual (embedded) water trades of two populous nations, India and China, to present certain quantitative measures and time scales. Estimates show that export of embedded water alone can lead to loss of water sustainability. With the current rate of net export of water (embedded) in the end products, India is poised to lose its entire available water in less than 1000 years; much shorter time scales are implied in terms of water for production. The two cases contrast and exemplify sustainable and non-sustainable virtual water trade in long term perspective.

Water availability, quality, management and distribution have emerged as critical issues at regional scales for populous countries like China and India¹. Several studies have highlighted the challenges faced by both China and India in meeting their water demands²⁻⁵. In general, water sustainability has emerged as a major global concern⁶⁻⁸, with uncertainties and added vulnerability due to climate change^{9,10}. An emerging issue of growing importance and debate in the context of water and food sustainability is the virtual water trade^{11,12}. Virtual trade of water has become an important component of global fresh water demand and supply¹³ and has resulted in globalization of water resource¹⁴⁻¹⁷. It has also become a medium of the global fresh water sharing¹⁵⁻¹⁸. It needs to be further emphasized that the demands of virtual trade of water also need to take into account the trade requirement of food, and hence the potential production¹⁹⁻²¹. The role of virtual water in the overall resource management has been recognized early²¹⁻²³. Several studies have emphasized the role of virtual water trade in globalization of water resource and in the overall food requirement. Several studies have emphasized the emerging but critical roles of network of virtual water trade in water management²¹⁻²³ and regional water systems²².

While virtual water can provide a more integrated approach to water management²³, it can also affect regional food sustainability²⁴ and other processes²⁵. Importance and impacts of virtual water trade on food and water sustainability have been discussed at the global^{26,27} as well as regional scale²⁸⁻³⁰. An index for water scarcity based on virtual water has been also proposed²⁵, highlighting the importance of water use efficiency; however, such an index is focused on usage and influence of virtual water and not on implications for water sustainability due to trade of virtual (embedded) water. Analysis of virtual water profiles at global and regional scales using input-output model for 112 nation-level regions revealed India, USA, and China as the world's leading virtual water consumers^{16,17}.

In terms of agriculture and food, virtual water can be defined both in terms of water required for the production, and as water content embedded in the end products^{24,27}. In production perspective, the volume of water used to produce an agricultural product is considered; this volume of water depends on the agricultural practices, water use efficiency, place and time of production^{31,32}. Water footprint of a crop also strongly depends on local climate conditions; for example, water required for producing 1 kg of a crop in an arid region is two or three times more than that in a humid region^{31,32}. Thus assessment of water sustainability in terms of agricultural production needs to adopt a regional perspective. The issue of virtual water is a particularly important concept for water scarce countries¹⁹⁻²⁸ with large demands. India and China are the two most populous countries with limited arable land³³ and fresh water resources. Similarly, fresh water resources of India and China are, respectively, 3.83 percent and 6 percent of the world's fresh water resources³⁴. A large fraction of the total annual rainfall is



precipitated in the monsoon season from June to September in India and China; thus decrease in monsoon rainfall can strongly impact water availability³⁵.

It is, however, important to elaborate the usage of the term virtual water in our study. The water content available in the crop is defined as the water content embedded in the crop at the time of trade as percentage of weight of the crop, which differs from the virtual water content or water footprint of the crop. For example, the amount of water content in cereals at the time of trade is around 9–15% of its weight while in vegetables and fruits it is around 70–96 per cent of their weight. Therefore, the fraction and the amount of water content embedded in the end-products are not negligible. While several approaches and frameworks for assessing virtual water are available, an important but less explored question is the long-term effect of export of embedded water through water content in exported food. It is worth emphasizing that while the water footprint of a crop depends on many variables and varies with time and location (country), the water content (embedded) in a the food grains (end product) is essentially constant. A comparative and quantitative analysis of virtual (embedded) water trade and its effects, combining constraints due to limits on primary resource (arable land), can provide significant insights into the dynamics and the implications on water sustainability. The main objective of the present study is an assessment and analysis of the dynamics of virtual (embedded) water trade for India and China. A primary focus is the implications, and time scales, for loss of water sustainability through export of virtual (embedded) water alone.

Methodology. The focus of our work is on net water exported (embedded water) through trade, as the embedded water in exported/imported food goes outside the usage (production) cycle. The water used in production of crops, of course, (~1000 L/Kg) is much larger than the content (~1 L/Kg); however, water used during a process is recoverable and recyclable. Thus the virtual water in our case refers to water embedded (water content) in the food or agricultural product either at the time of production or at the time of export. However, we shall also consider water used in production and overall water demand to compare the embedded water.

We have calculated virtual water export or import for both scenarios water footprint and water content available in the end-product for all crops and food grains. The water content in the end products

of the agricultural commodities has been taken from Transport Information Services³⁶ and Agricultural Research Service, United States Department of Agriculture³⁷ (Supplementary Table 1a–1f).

Formulation: Total water available and demand. The total available water for a country in a year is taken as the sum of ground water and surface water available through annual rainfall; for quantitative assessment, we define the total water available in a year n , $W_A(n)$, as

$$W_A(i,n) = \alpha(i) * R(i,n) * Area(i) + W_G(i) \quad (1)$$

Where $R(i,n)$, $Area(i)$ and $W_G(i)$, respectively, represent area-averaged annual rainfall (precipitation depth) for the year n , total land area and ground water (Table 1) of the country i . In general, only a fraction of the annual rainfall will be available for utilization; the rest is lost through evaporation, runoff and ground water recharge. Thus, α represents the fraction of total surface water available for utilization; the value of α depends on surface characteristics of a country (Table 2). Approximately 90 percent of this water is used for agricultural purposes while the rest is used for domestic, industrial and other usage. The potential water available as surface water and ground water for India and China has been adopted from AQUASTAT³⁴ (Table 1). We have considered the ground water available as its current value, although it has its inter-annual variability. Similarly, depletion of ground water due to other withdrawal processes is not considered at this stage; thus time scales are considered in terms of $W_A(i,n)$.

The water demand is calculated based on water required for production of food to meet the demand. The total agricultural production is defined as the sum of production of all crops (or food grains); consumption is defined as the product of per capita consumption of all crops (or food grains) and population. From the consumption perspective, the total water required, $W_D(i,n)$, to produce the total food demand is estimated as

$$W_D(i,n) = \sum_{j=1}^{N_c(i)} P_T(i,n) * F_{CP}(i,j,n) * W_{FP}(i,j) \quad (2)$$

$P_T(i,n)$ and $F_{CP}(i,j,n)$, respectively, represent the total population and per capita consumption of food grains or all crops for the country i

Table 1 | Water and land data for India and China are based on averages during 1961–2009 available from different sources. The signs '+', '*', '#', respectively, represent the observed data adopted from NCEP⁴⁰, FAOSTAT³³, AQUASTAT³⁴T

Sl. No.	Parameters (units)	Symbol	Current value (2009/2010)		Data period
			India	China	
1	Area-average annual rainfall (mm)	$R(i)$	1148	755	1961–2010 ⁺
2	Total land (10^{10} m ²)	Area	297	932.7	1961–2010 [#]
3	Arable land (10^{10} m ²)	A_g	157.8	111.3	1961–2010 [*]
4	Population (10^6)	P_T	1210	1320	1961–2010 [*]
5	Total export of food products (10^9 Kg)	F_{ET}	12.5	28.65	1961–2010 [*]
6	Total import of food products (10^9 Kg)	F_{IT}	13.83	109	1961–2010 [*]
7	Per capita consumption of all crops (Kg)	F_{CP}	350	650	1961–2010 [*]
8	Per capita consumption of food grains (Kg)	F_{CP}	150	146	1961–2010 [*]
9	Total food consumption (10^9 Kg)	F_D	413	911	1961–2010 [*]
10	Water footprint (m ³ /kg)	W_{FP}	---	---	1996–2005
4	Total water available (surface and ground water) (10^9 m ³ /year)	W_A	1911	2840	1961–2010 [#]
5	Total water demand for production for food grains (10^9 m ³ /year)	W_P	579.6	593	1961–2010 [#]
6	Total water demand for production for all crops (10^9 m ³ /year)	W_P	1139.6	1133	1961–2010 [#]
7	Total water demand for consumption for food grains (10^9 m ³ /year)	W_D	536.9	227	1961–2010 [#]
8	Total water demand for consumption for all crops (10^9 m ³ /year)	W_D	1111.8	876	1961–2010 [#]
9	Total water Export (10^9 m ³ /year)	W_{ET}	44	10.1	1961–2010 [*]
10	Total water Import (10^9 m ³ /year)	W_{IT}	5.9	27.5	1961–2010 [*]
11	Cumulative water import (10^9 m ³ /year)	---	290	1042.3	1961–2010 [*]
12	Cumulative water export (10^9 m ³ /year)	---	263	339.8	1961–2010 [*]
13	Ratio of export/import (all crops)	---	3.9	0.36	1961–2010 [*]
14	Ratio of export/import (food grains)	---	25.2	0.17	1961–2010 [*]



Table 2 | Description of model parameters

Sl. No.	Parameters	Description	India	China
1	P_s	Saturation value of population (million)	1700	1500
2	β	Population growth rate (million/year)	0.038	0.05
3	α	Fraction of total water available for utilization	0.35	0.47
4	W_{PO}	Water required to produce food (m^3/ton) demand for food grains	2934	1097
5	W_{PO}	Water required to produce food (m^3/ton) demand for all crops	2605	1160
6	N_C	Number of total crops produced in a country for food grains	6	8
7	N_C	Number of total crops produced in a country for all crops	55	63
8	N_{CE}	Number of crops involved in export for food grains	8	7
9	N_{CE}	Number of crops involved in export for all crops	32	32
10	N_{CI}	Number of crops involved in import for food grains	8	8
11	N_{CI}	Number of crops involved in import for all crops	33	34

for the year n . The values of $W_{FP}(i,j)$ represent the water footprint of crop j for the country i based on the available literature for the period 1996–2005^{31,32}. The total number of all crops and food grains, $N_C(i)$, varies with the country due to agricultural practices and climatic conditions (Table 2). Similarly, the values of parameters like $N_C(i)$ and $P_T(i, n)$ have been adopted from available data for India and China (Table 2). The surplus water, $W_S(i,n)$, for the year n is defined as

$$W_S(i,n) = W_A(i,n) - W_D(i,n) \quad (3)$$

From the production perspective, the total water required for production of food is defined as

$$W_P(i,n) = \sum_{j=1}^{N_C(i)} F_D(i,j,n) * W_{FP}(i,j) \quad (4)$$

Where $F_D(i,j,n) = P_T(n) * F_{CP}(i,j,n) + F_{ET}(i,j,n) - F_{IT}(i,j,n)$

The quantity $W_P(i,n)$ is the total water required to produce all crops (or food grains); $F_D(i,j,n)$ represents the demand for all crop (or food grains) in the year n . Here $F_{ET}(i, j, n)$ and $F_{IT}(i, j, n)$, respectively, represent the total export and import for the country i , crop j and the year n .

Trade of virtual (embedded) water. The virtual export in terms of water content available in the end-product, $W_{ECT}(i,n)$, is calculated as

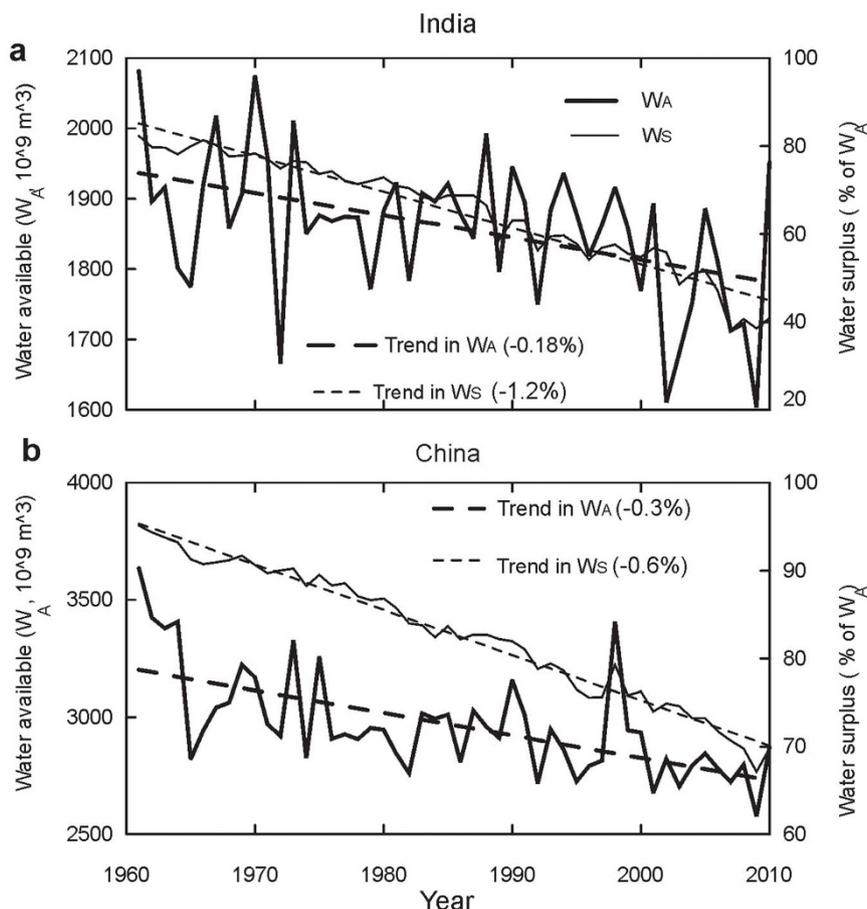


Figure 1 | Water availability, W_A , (left y axis, thick solid line) and water surplus (W_S) (right y axis, thin line) for India (a) and China (b). The thick and thin dash line, respectively, represents the linear trend for water available and water surplus for the respective case. The coefficients of linear trend are given in the brackets as percentage of respective mean in the corresponding panel.

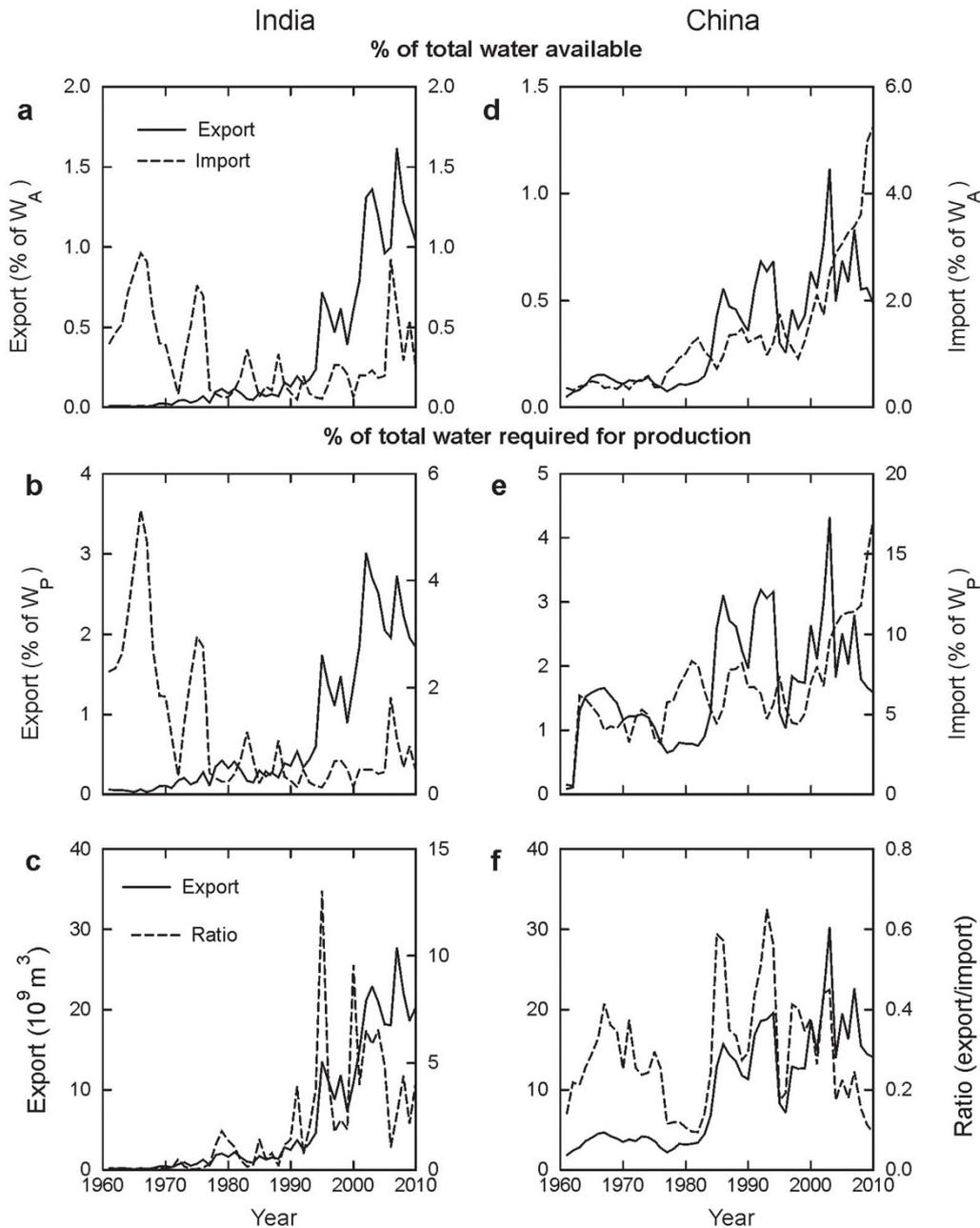


Figure 2 | Export (left y axis, solid line) and import (right y axis, dash line) in terms of water involved in production for all crops. (a, d): As percentage of total water available for India (a) and China (d), respectively. (b, e): As percentage of total water required for production for all crops for India (b) and China (e), respectively. (c, f): Export (10^9 m^3 , left y axis) and ratio of export to the import (right y axis, dash line) for India (c) and China (f), respectively.

$$W_{ECT}(i,n) = \sum_{j=1}^{N_{CE}(i)} W_C(j) * F_{ET}(i,j,n) * W_{FP}(i,j) \quad (5)$$

Here $W_C(j)$ represents the fraction of water content available in the crop j (Supplementary Table 1a–1f) and $F_{ET}(i,j,n)$ represents export of the j^{th} crop for the year n of the country i ; $W_{FP}(i,j)$ represents water footprint of the j^{th} crop for the country i .

The virtual water export in terms of total water required for production of the exported items, $W_{ET}(i,n)$, is calculated as

$$W_{ET}(i,n) = \sum_{j=1}^{N_{CE}(i)} F_{ET}(i,j,n) * W_{FP}(i,j) \quad (6)$$

$N_{CE}(i)$ represents the number of exported crops (or food grains). The value of $N_{CE}(i)$ for all crops and food grains is given in Table 2.

Similarly, the virtual water import, $W_{ICT}(i,n)$, in terms of water content available in the end-product for the year n , is calculated as

$$W_{ICT}(i,n) = \sum_{i=1}^{N_{CI}(i)} W_C(j) * F_{IT}(i,j,n) * W_{FP}(i,j) \quad (7)$$

$F_{IT}(i,j,n)$ represents the import of j^{th} crop in the year n for the country i and $N_{CI}(i)$ represents the number of imported all crops (or food grains) (Table 2).

The virtual water import, in terms of water involved in production, $W_{IT}(i,n)$, is calculated as

$$W_{IT}(i,n) = \sum_{j=1}^{N_{CI}(i)} F_{IT}(i,j,n) * W_{FP}(i,j) \quad (8)$$

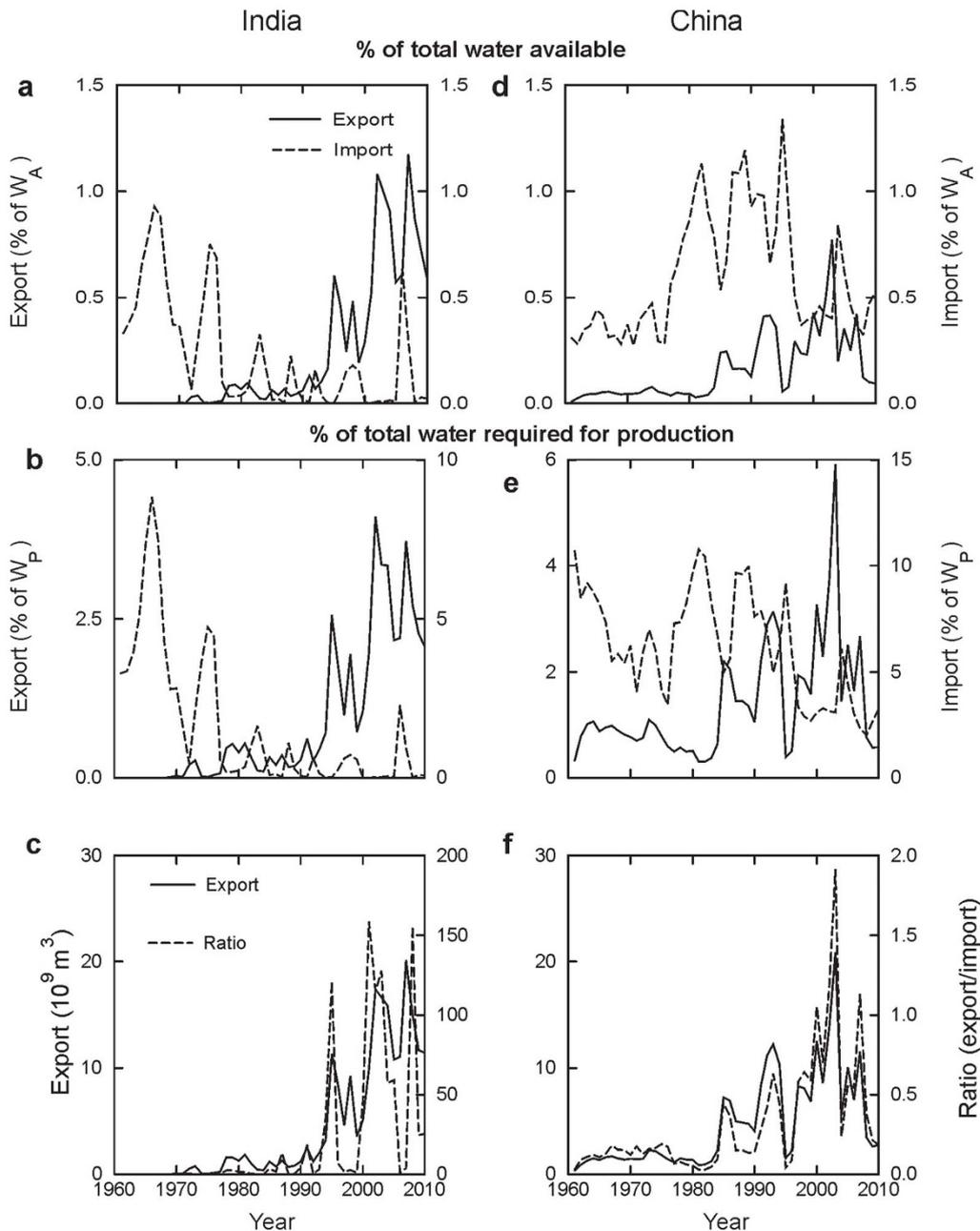


Figure 3 | Export (left y axis, solid line) and import (right y axis, dash line) of total water export for food grains (W_{ET}) as percentage of total water availability (top panel) and total water requirement for production of crops (middle panel) for India and China. The bottom panel represents export (left y axis; solid line) in terms of actual quantity (10^9 m^3) and ratio of export-import (dash line, right y axis) for India and China.

Trade balance in virtual water, in terms of water content in end-product of food and total water involved in production, is calculated as

$$W_{TBC}(i,n) = W_{ECT}(i,n) - W_{ICT}(i,n) \quad (9)$$

$$W_{TBT}(i,n) = W_{ET}(i,n) - W_{IT}(i,n) \quad (10)$$

Where $W_{TBC}(i,n)$ represents the trade balance ($W_{ECT} - W_{ICT}$) in terms of water content embedded in the end-product for the year n and $W_{TBT}(i,n)$ represents the net export in terms of water involved in production.

Projections and time scales of water sustainability due to virtual (embedded) water trade. For projection of water demand and sustainability, we have considered demand in terms of projection

of population. We represent the population of either India or China as

$$\frac{dP_T}{dt} = \beta \left(1 - \frac{P_T(t)}{P_S} \right) P_T(t) \quad (11)$$

Where $P_T(t)$ is the population of the country at time t (year n). β and P_S , respectively, are the rate of population growth and carrying capacity for India and China (Table 2), adopted based on observed trends and UN projections^{38,39}.

The export is projected by taking three different values of export: Average (year 1961–2009), maximum (year 1990–2009) and current (average, year 2005–2009). For long-term projection of water demand, we have assumed the average value of water footprints of all crops and food grains for the projection of water demand in terms of food demand, $W_{PO}(i)$, as given below

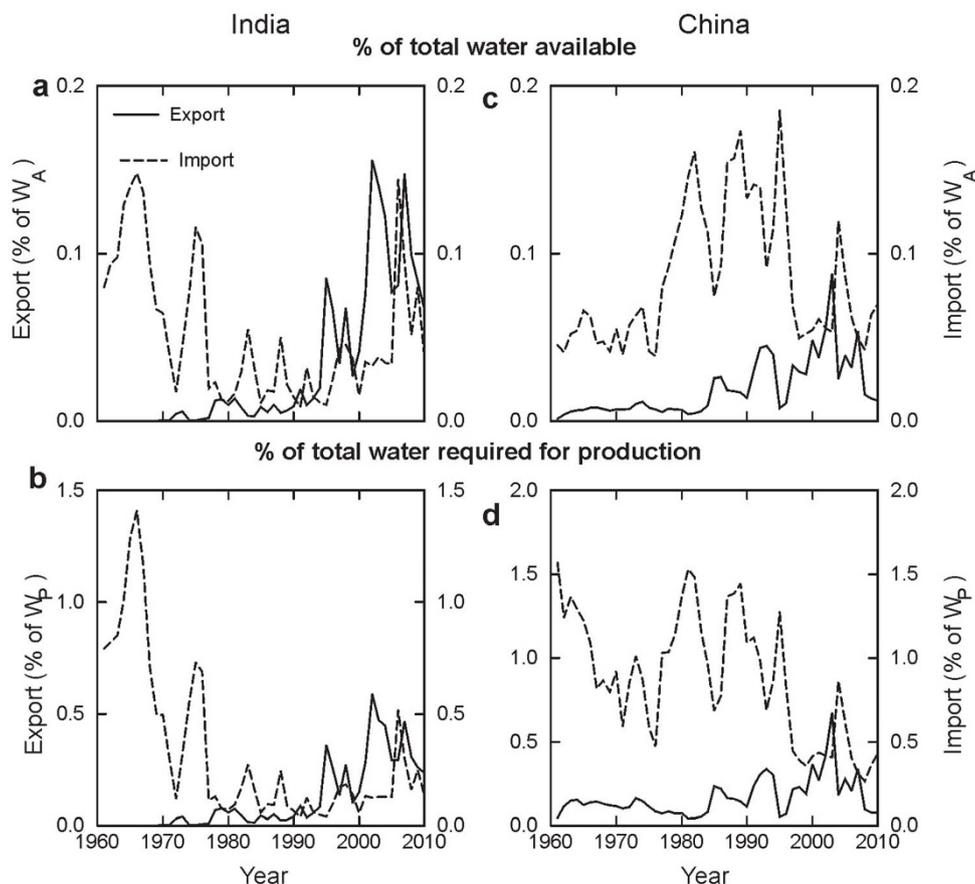


Figure 4 | Export (solid line) and import (dash line) of actual water through export and import of food grains (as available in end-products of crops) for India and China as percentage of available water (top panel) and percentage of total water used for production (bottom panel).

$$W_{PO}(i) = \frac{1}{N_C(i)} \sum_{j=1}^{N_C(i)} W_{FP}(i,j) \quad (12)$$

By using average value of water footprints for all crops (or food grains), equation (2) can be written as

$$W_D(i,n) = P_T(i,n) * F_C(i,n) * W_{PO}(i) \quad (13)$$

$$\text{Where } F_C(i,n) = \sum_{j=1}^{N_C(i)} F_{CP}(i,j,n)$$

Here $F_C(i,n)$ is the total food consumption per capita of all crops (or food grains), the current per capita consumption of all crops for India and China, respectively, are 350 kg/capita/year and 650 kg/capita/year for the year 2009. Similarly, current per capita consumption of food grains for India and China, respectively, are 152 kg/capita/year and 151 kg/capita/year³³.

The virtual trade of water implies certain time scales, including extreme cases where water sustainability is lost through virtual trade. We therefore define a number of time scales based on scenarios of virtual water export through food and other agricultural products for both cases water footprint and water content. The number of years in which the total water export in terms of water footprint and water content embedded in the end-product will equal the total water available ($W_A(i)$), current water required for production ($W_P(i,n)$, year 2009) and water surplus ($W_S(i,n)$, year 2009) is defined as

$N_{TA}(i)$: Time scale (years) for total virtual water export in terms of water footprint equal to total renewable water available

$$W_E(i) * N_{TA}(i) = W_A \quad (14a)$$

$N_{CA}(i)$: Time scale (years) for total virtual water export in terms of water content equal to total renewable water available for all crops (or food grains)

$$W_{EC}(i) * N_{CA}(i) = W_A \quad (14b)$$

$N_{TP}(i)$: Time scale (years) for total virtual water export in terms of water footprint equal to current water used for production ($W_P(i)$, year 2009) for all crops (or food grains)

$$W_E(i) * N_{TP}(i) = W_P \quad (14c)$$

$N_{CP}(i)$: Time scale (years) for total virtual water export in terms of water content equal to current water used for production ($W_P(i)$, year 2009) for all crops (or food grains)

$$W_{EC}(i) * N_{CP}(i) = W_P \quad (14d)$$

$N_{TS}(i)$: Time scale (years) for total virtual water export in terms of water footprint equal to water surplus for all crops (or food grains)

$$W_E(i) * N_{TS}(i) = W_S \quad (14e)$$

$N_{CS}(i)$: Time scale (years) for total virtual water export in terms of water content equal to water surplus for all crops (or food grains)

$$W_{EC}(i) * N_{CS}(i) = W_S \quad (14f)$$

Here $W_E(i)$ and $W_{EC}(i)$, respectively, are the rate of total water export through exports of all crops (or food grains) in terms of water footprint and water content available for the country I for three scenarios of export current, average and maximum.

Where $W_{EC}(i)$ is the rate (average, maximum or current) of the water content export through exports of all crops or food grains for

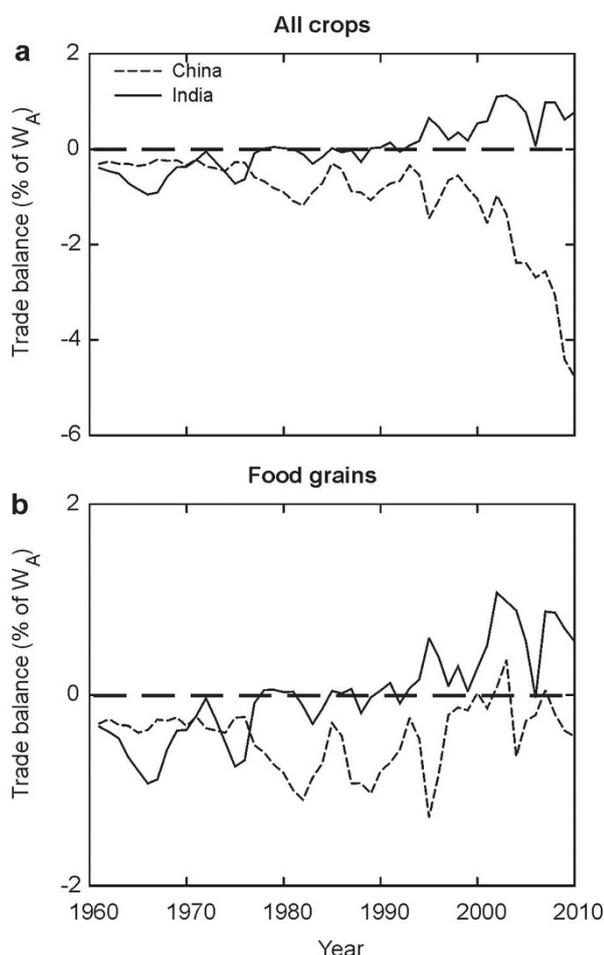


Figure 5 | Trade balance in terms of total water involved in production as percentage of water available for all crops (a) and food grains (b) for India (solid line) and China (dash line).

the country *i*. The average export is calculated from the total export of the period 1990–2010. Similarly, maximum export is taken from the total export of the period 1990–2010 and the current export is taken for the year 2010. While many other time scales can be defined, we shall consider time scales implied by virtual export of water as this is an irreversible loss of water.

Methods

The observed data for production, consumption, export and import of food grains and all crops has been adopted from public domain data portal (Table 1) like Food and Agriculture Statistics Division³¹. The observed data for arable land and population, for India and China, is available at Food and Agriculture Statistics Division³¹. The observed data for total water available, surface water, ground water and per capita water available is adopted from AQUASTAT³⁴. We have considered virtual water trade for two categories: all crops and food grains. We have included cereals, vegetable, fruits, pulses, roots and tubers and oil crops in the category of all crops; the category of food grains includes only cereals (wheat, rice, barley, maize, millet, rye, oats and sorghum) are included in the category of food grains. Except for water footprint, the data is available at yearly time scale for the period 1961–2009/10 from FAOSTAT³³ or AQUASTAT³⁴; for water footprint average data for the period 1996–2005 has been used^{31,32} (supplementary table 1(a–f)).

The virtual water footprints of primary and processed crop products, livestock products and industrial products of many countries is based on analysis given by Chapagain and Hoekstra³¹. While computing virtual water export and import, we have considered primary food crops in two groups all crops and food grains. The virtual water footprints of livestock products and industrial products have not considered in the present study. The data for water footprints for all crops has been adopted from Water Stat; Water Footprint Network, Netherlands^{31,32}. The water footprints are changing with location, time and due to climatic conditions and agricultural practices. The water required to produce 1 ton of food (m^3/ton) of food is calculated as the average value of the water footprints of all crops for India, China and the world (Supplementary Table 1a–1f) based on data available in literature³¹. The

total water footprint of a crop is divided into three components: the blue, the green and the grey water footprint. The blue water footprint of a crop is the amount of freshwater water evaporated from the surface water and ground water resources to produce 1 ton of the crop. Similarly, green water footprint of crop is the amount of water evaporated from rainwater stored in soil to produce a 1 ton of the crop. The grey water footprint is the amount of polluted water that is required to dilute pollutants. We are not considering grey water here due to not usage for food production, we have considered the sum of blue and green water footprint of an individual crop for both groups all crops and food grains (Supplementary Table 1a–1f).

The water content in the end products of the agricultural commodities has been taken from Transport Information Services³⁶ and Agricultural Research Service, United States Department of Agriculture³⁷ (Supplementary Table 1a–1f).

The rainfall data has been extracted from NCEP daily reanalysis on a global grid⁴⁰.

Results

Water availability and vulnerability to virtual trade. A comparison of water resource and water budget for India and China (Table 1) shows that while India receives about 50 percent more annual rainfall than China, the total water available for India is only about 67 percent of that of China. For India, the available water varies between $1600\text{--}2100 \times 10^9 m^3$ during 1960–2010 (Fig. 1a); for China, the corresponding range is $2500\text{--}3600 \times 10^9 m^3$ (Fig. 1b). Both countries are characterized by declining trends in available and surplus; the per capita water availability for India has decreased $4098 m^3/capita/year$ in 1961 to $1519 m^3/capita/year$ in 2010. Similar decline is also seen for China: from $4113 m^3/capita/year$ in 1961 to $2051 m^3/capita/year$ in 2010³⁴. However, although trend in water available for India (-0.18 percent) is much smaller than that for China (-0.3 percent) (Fig. 1). At the same time, India requires much larger amount ($537 \times 10^9 m^3$) of water for production of its food grains than the corresponding requirement ($537 \times 10^9 m^3$) for China (Table 1); similar conclusion also holds for water requirement for all crops (Table 1). As a result, the water required for production of food grains has reached almost the same level ($\sim 500 \times 10^9 m^3$) for both countries. Thus water sustainability for both India and China can be affected by virtual trade of water.

Virtual export and import of water. From a negligible value until about 1990, India's virtual export of water for all crops has risen to about 1.5 percent of the available water (Fig. 2a), or about 4 percent of annual water involved in production (Fig. 2b). In terms of actual quantity, this export is about $25 \times 10^9 m^3$ for India; which is equivalent to the annual water demand of nearly 13 million people (Fig. 2c). On the other hand, India's virtual water import was about 3 percent of its total water involved in production during 1960–1970, which then fell to negligible values during 1980–2000; the current value is once again about 1 percent. As percentage of water available, China has virtual import of water higher than its virtual export of water throughout the period 1960–2010 (Fig. 2d); its virtual import of water (as percentage of water required for food production) is nearly three times of its virtual export, essentially throughout the period of 1960–2010 (Fig. 2e). Thus the ratio of export to import of virtual water has (non-linearity but) steadily grown for India, with some decline in the recent years (Fig. 2c, dash line); this ratio has been much less than 1 for China, with marked decline in the recent years (Fig. 2f, dash line). In terms of virtual export only in food grains (Fig. 3), the patterns for all crops for India (Fig. 3a, 3b, 3c) and China (Fig. 3d, 3e, 3f), are very similar to those for food grains for the respective country (Fig. 2). Once again, the export of water for China for all crops (Fig. 3d, 3e, 3f) is less than its corresponding import.

India was strongly dependent on food import until about 1970; this is reflected in India's virtual water trade. From an import-intensive paradigm during 1960–1970, India has moved to an export-intensive regime in virtual water trade (Fig. 2); currently, India's water import for food grains is virtually nill (Fig. 3a, 3b, 3c). In contrast, China has maintained essentially an import-intensive virtual water trade since 1960, although the export-import ratio is close to 1 in the recent years (Fig. 2f). This shift in export of food has considerable impact on water sustainability.

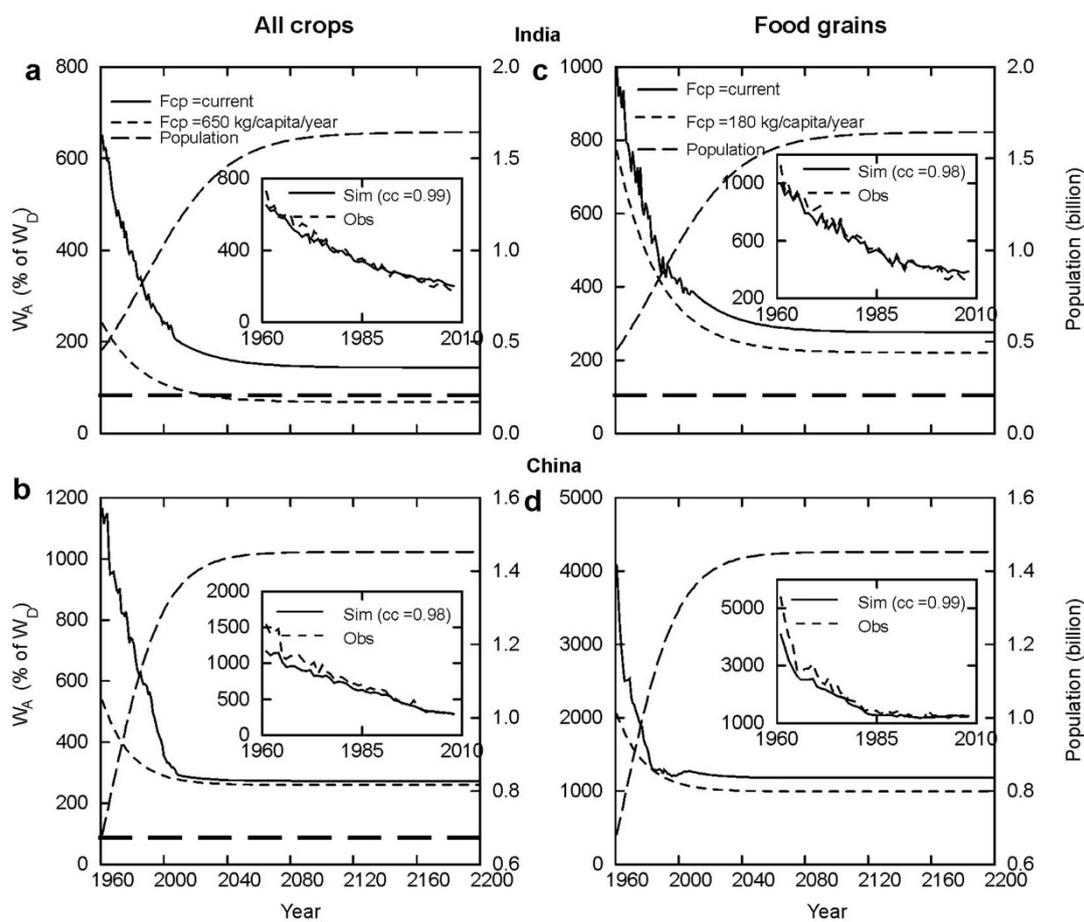


Figure 6 | Simulation (1960–2010) and projection of water availability (2010–2200) (as percentage of water demand) for all crops (left panels) and food grains (right panels) for two values of per capita food consumption. (a, b): current and 650 kg/capita/year of all crops for India (a) and China (b). (c, d): current and 180 kg/capita/year of food grains for India (c) and China (d). The horizontal long dash line represents the level at which the water demand equals the total water available. The inset figure in each panel shows the simulation (solid line) and observation of the water availability as percentage of water demand for the annual per capita food consumption of all crops and food grains for the respective country; the correlation coefficient between simulation and observation is given in the bracket.

Considered in terms of water content available in food grains, India's current water export is much higher than its corresponding import. Compared to nearly 0.2 percent of total water available involved in export, India imports less than 0.1 percent of its total water available (Fig. 4a). In terms of total water involved in production, India's export is now close to 0.5 percent, while its import is generally less than 0.1 percent (Fig. 4b). In contrast, China imports more than 0.1 percent of its total water available through virtual water trade, while its corresponding export is less than 0.1 percent (Fig. 4c). In terms of total water required for production, China's virtual import has been several times higher than its corresponding virtual export throughout the period 1960–2010 (Fig. 4d). Thus, while India's trade balance in virtual water has turned positive (export > import) in the recent years, China's has shown a negative balance essentially for the entire period 1960–2010. This holds for all crops (Fig. 5a, dash line) as well as food grains (Fig. 5b, dash line). For India (solid line, Fig. 5), total trade balance (export–import), as percentage of available water (Fig. 5), has been negative until around 1980; however, it has turned increasingly positive (export > import) since 1990 for all crops (Fig. 5a, solid line) as well as food grains (Fig. 5b, solid line); the current deficit amounts to about 1 percent of total water available ($\sim 3 \times 10^9 \text{ m}^3$).

Projections and time scales for sustainability. The virtual export of water, especially in terms of water content in end products, implies certain time scales. For example, India's water availability is likely to

equal its water demand around the year 2100 (Fig. 6a); for China, the water availability is expected to remain more than 200 percent of the water demand even beyond 2200 and even for a per capita consumption of 650 kg/year (Fig. 6b). Although the projections have their inherent uncertainties, they validate well against observations during 1960–2010 (insets), with correlation coefficients above 99 percent significance level (Fig. 6). Considered only in terms of food grains, the water availability for India can saturate above the critical value for the population scenario considered (Fig. 6c); a similar conclusion holds for China (Fig. 6d). However, these conclusions critically depend on the population growth scenarios considered (equation 11). Expectedly, the saturation in decline of water availability is around the point where the population saturates (Fig. 6, right axis). Because of the inherent uncertainties in projections, the time scales are essentially indicative.

For average (1990–2010) net export of virtual (embedded) water in all crops in terms of water involved in production, the time scale (years) in which the net export equals water surplus can be as short as 120 years for a population of 1700 million (Fig. 7a); for the current or the maximum values of net export, these time scales are even shorter. Expectedly, the time scales are longer in terms of water involved in production of either all crops (Fig. 7c) or food grains (Fig. 7d).

The time scales for loss of water sustainability for average rate of export of total virtual (embedded) water are expectedly shorter than those for average net export. However, even if water involved in production is not all lost (unlike in export in food grains), conditions

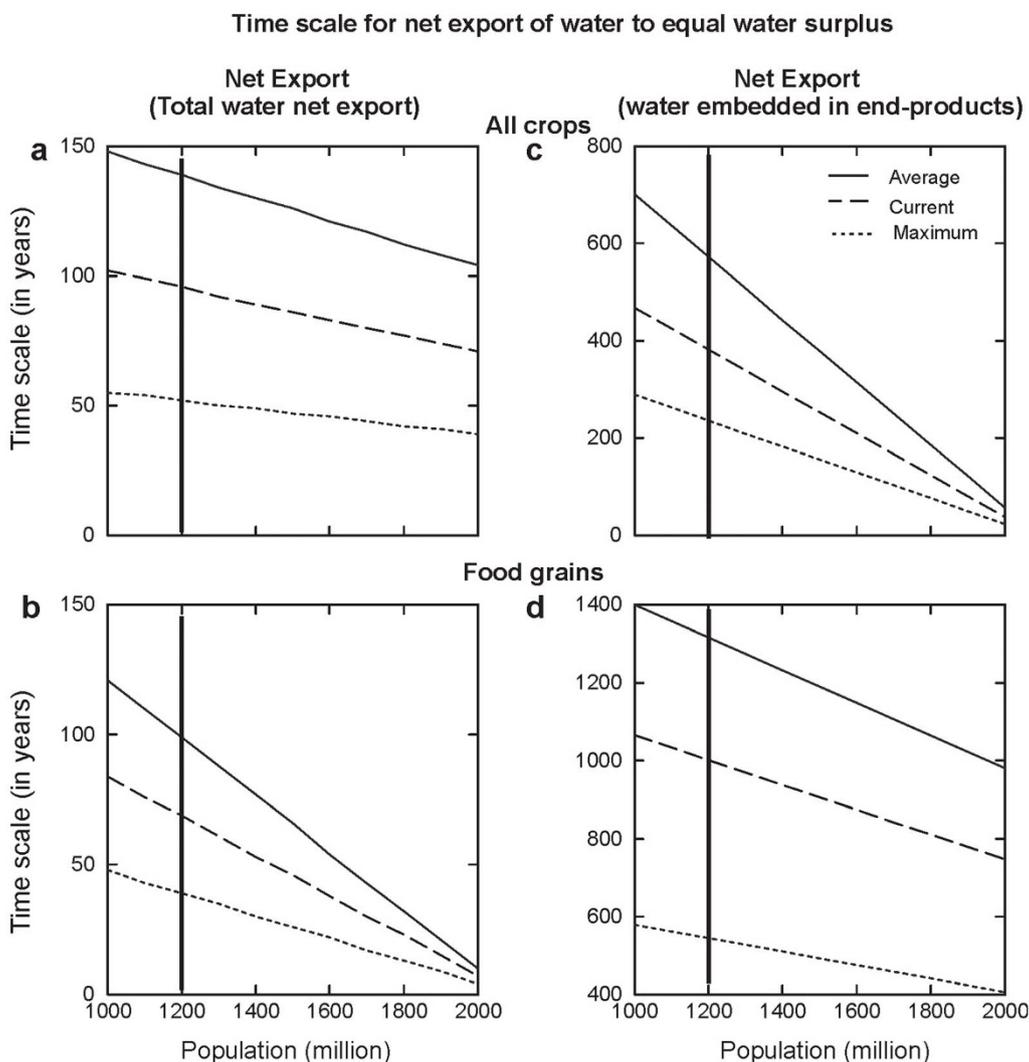


Figure 7 | Time scales for India for loss of water sustainability through virtual net export in terms of water involved in production for all crops (a) and food grains (b), and in terms of water content in end-products for all crops (c) and food grains (d) equals to water surplus for all food crops (top panels) and food grains (bottom panels). The net export is projected by taking three different values of net export: Average (1990–2009, solid line), maximum (1990–2009, dotted line) and current (2005–2009; average, long dash line). We have taken 350 kg/capita and 150 kg/capita/year, respectively, per capita consumption of all crops and food grains. The vertical dash line represents the current population.

where water requirement in production equals water availability can create appreciable stress. The time scale for average export in all food crops and food grains, respectively, are about 70 years and 160 years in terms of water involved in production (Fig. 8a, 8b). These time scales are higher in water export in terms of water content available in end-product; the time scales for average export for all crops and food grains are 400 years and 1000 years, respectively (Fig. 8c, 8d). The time scales (in years), for average, maximum and current export scenarios equal to the water available, water required for production and water surplus (Table 3) vary between 1500 years to a few decades.

Discussion and Conclusions

Overall sustainability of a nation depends on two major primary resources: arable land and water; while the former is essentially immobile, water can be, and is, transported across countries through water (embedded) in agricultural items. Thus a trade network of food or agricultural products is accompanied by a network of virtual trading of water. Our analysis shows that the magnitude and the impact of such a virtual trade of water can affect overall sustainability of a nation. In particular, a net export of water through export of

agricultural products, as in the case of India, can lead to slow but irreversible loss of water sustainability.

An important conclusion of our study is that the net virtual water export alone can lead to loss of water sustainability of a nation in time scales that cannot be considered too long for a nation. For India, the time scales for loss of water sustainability through virtual export is less than 300 years for water requirement and less than 500 years for water available. Since we are considering actual water content available in food grains, the loss is irreversible. Increase in food demand⁴¹, and reduction in surface water due to climate change^{9,10} can further reduce these time scales. Our analysis thus suggests that sustainable food or agricultural policy must be based on zero trade deficit in virtual water. While it is possible to meet these conditions, and are met for China, they are grossly off for India. Even a partial but irreversible loss of water resource of a populous country like India, on the other hand, will have large impacts on the global economy and sustainability. While improved and efficient water management can help, such measures can only delay the inevitable if net virtual export continues. Additional constraints on water sustainability are expected as water demands in other sectors like manufacturing, services and construction increase.



Time scale for export of water to equal water surplus

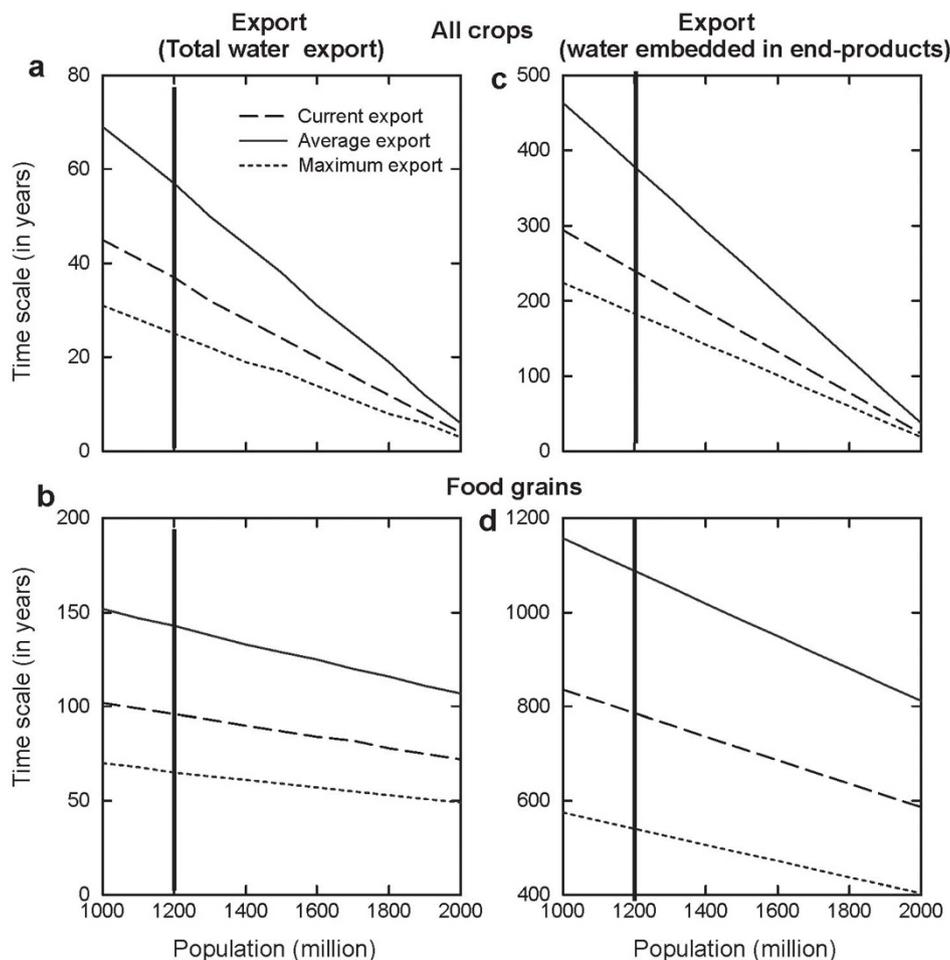


Figure 8 | Time scales for India for loss of water sustainability through virtual export in terms of water involved in production for all crops (a) and food grains (b), and in terms of water content in end-products for all crops (c) and food grains (d) equals to water surplus for all food crops (top panels) and food grains (bottom panels). The export is projected by taking three different values of export: Average (1990–2009, solid line), maximum (1990–2009, dotted line) and current (2009; long dash line). We have taken 350 kg/capita and 150 kg/capita/year, respectively, per capita consumption of all crops and food grains. The vertical dash line represents the current population.

It needs to be emphasized that the time scales estimated here are time scales of onset of criticality; the projections of water availability themselves are affected by many uncertainties. At the same time, these estimates of time scales or water sustainability are only likely to be optimistic; increase of use of water in other sectors like manufacture, service and others are likely to introduce further constraints

and reduce these time scales of onset of criticality. On the other hand, improvements in water use efficiency through improved technology like laser land leveling and better agronomical practices can reduce water demand for production. However, as water content in a given crop is essentially constant, the conclusions and the estimates of embedded water are unlikely to change substantially. Indeed, while

Table 3 | Time scales for water export in terms of water content in end-product (W_{EC}) and total water involved in production of exports (W_{ET}) to equal total water available (W_A) and current water required for production (W_{PF}) and the water surplus (W_S) for India for three different scenarios of export of agricultural products (all crops and food grains): average (1990–2009), maximum (1990–2009) and current (2005–2009, average) of export

Time scale	Sustainability water export scenarios	Time (in years) for export scenario					
		Average export (1995–2010)		Maximum export (1961–2010)		Current export (Average 2005–2010)	
		Food grains	All crops	Food grains	All crops	Food grains	All crops
N_{CA}	$W_{EC} \sim W_A$	1505	889	747	431	1086	564
N_{CP}	$W_{EC} \sim W_P$	467	527	232	255	337	335
N_{CS}	$W_{EC} \sim W_S$	1089	378	540	183	786	240
N_{TA}	$W_E \sim W_A$	197	133	91	59	132	85
N_{TP}	$W_E \sim W_P$	62	79	28	35	41	51
N_{TS}	$W_E \sim W_S$	143	57	66	25	96	37



improved water use efficiency, and export-import policy can delay the times of onset, increase on food demand due to increase in population as well as consumption can hasten these onsets.

The present analysis has been carried out based on current annual rainfall for the respective country. However, changes in temporal and spatial distributions of rainfall can introduce additional factors. There are indications that the spatio-temporal extent of India's rainy season (summer monsoon) is reducing³⁵. Similarly, while global or oceanic monsoon rainfall may be increasing⁴², the continental rainfall over India may decrease in a changed climate⁴³. Mitigative measures to reduce virtual water export will have to take into account the role of agricultural export in the overall economy. Similar considerations, although of less serious implications, also apply for regional (domestic) virtual water export. It is clear that the effects of virtual export of water will emerge long before the criticality condition is reached.

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Author contributions

All authors discussed the results and commented on the manuscript. P.G. formulated the algorithm, carried out literature review, interpreted the results and prepared the manuscript. S.N. performed the experiment, carried out literature survey, contributed to analysis, interpretation and writing manuscript.

Additional information

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