Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Global Environmental Change 15 (2005) 45–56
GLOBAL ENVIRONMENTAL CHANGE
www.elsevier.com/locate/gloenvcha

Globalisation of water resources: international virtual water flows in relation to crop trade

A.Y. Hoekstra*, P.Q. Hung

UNESCO-IHE Institute for Water Education, P.O. Box 3015, 2601 DA Delft, The Netherlands

Received 3 September 2003; received in revised form 12 June 2004; accepted 29 June 2004

Abstract

The water that is used in the production process of a commodity is called the 'virtual water' contained in the commodity. International trade of commodities brings along international flows of virtual water. The objective of this paper is to quantify the volumes of virtual water flows between nations in the period 1995–1999 insofar related to international crop trade and to analyse national virtual water balances in relation to national water needs and water availability. The basic approach is to multiply international crop trade flows (ton/yr) by their associated virtual water content ($m^3\,ton^{-1}$). The calculations show that the global volume of crop-related international virtual water flows between nations was 695 $Gm^3\,yr^{-1}$ in average over the period 1995–1999. For comparison: the total water use by crops in the world has been estimated at 5400 $Gm^3\,yr^{-1}$. This means that 13% of the water used for crop production in the world is not used for domestic consumption but for export (in virtual form). This is a conservative estimate because only a limited number of crops—although the most important ones—have been taken into account and because crop products (such as cotton clothes) have been excluded from the study. The countries with the largest net virtual water export are United States, Canada, Thailand, Argentina and India. The largest net import appears to be in Japan, the Netherlands, the Republic of Korea, China and Indonesia.

Keywords: Globalisation; Virtual water; Water use efficiency

1. Introduction

Water should be considered an economic good. Ten years after the Dublin conference this sounds like a mantra for water policy makers. The sentence is repeated again and again, conference after conference. It is suggested that problems of water scarcity, water excess and deterioration of water quality would be solved if the resource 'water' were properly treated as an economic good. The logic is clear: clean fresh water is a scarce good and thus should be treated economically. There is an urgent need to develop appropriate concepts and tools to do so.

In dealing with the available water resources in an economically efficient way, there are three different levels at which decisions can be made and improvements be achieved. The first level is the user level, where price and technology play a key role. This is the level where the 'local water use efficiency' can be increased by creating awareness among the water users, charging prices based on full marginal cost and by stimulating water-saving technology. Second, at the catchment or river basin level, a choice has to be made on how to allocate the available water resources to the different sectors of economy (including public health and the environment). People allocate water to serve certain purposes, which generally implies that other, alternative

*Corresponding author. Tel.: +31 15 215 1828; fax: +31 15 212 2921.
E-mail address: a.hoekstra@unesco-ihe.org (A.Y. Hoekstra).

0959-3780/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.gloenvcha.2004.06.004

purposes are not served. Choices on the allocation of water can be more or less 'efficient', depending on the value of water in its alternative uses. At this level, we speak of 'water allocation efficiency'.

Beyond 'local water use efficiency' and 'water allocation efficiency' there is a level at which one could talk about 'global water use efficiency'. It is a fact that some regions of the world are water scarce and other regions are water abundant. It is also a fact that in some regions there is a low demand for water and in other regions a high demand. Unfortunately, there is no general positive relation between water demand and availability. Until recently, people have focused very much on considering how to meet demand based on the available water resources at national or river basin scale. The issue is then how to most efficiently allocate and use the available water. There is no reason to restrict the analysis to that. In a protected economy, a nation will have to achieve its development goals with its own resources. In an open economy, however, a nation can import products that are produced from resources that are scarcely available within the country and export products that are produced with resources that are abundantly available within the country. A water-scarce country can thus aim at importing products that require a lot of water in their production (water-intensive products) and exporting products or services that require less water (water-extensive products). This is called *import of virtual water* (as opposed to import of real water, which is generally too expensive) and will relieve the pressure on the nation's own water resources. For water-abundant countries an argumentation can be made for *export of virtual water*. Import of water-intensive products by some nations and export of these products by others results in international 'virtual water flows'.

The overall efficiency in the appropriation of the global water resources can be defined as the 'sum' of local water use efficiencies, meso-scale water allocation efficiencies and global water use efficiency. So far, most attention of scientists and politicians has gone to local water use efficiency. There is quite some knowledge available and improvements have actually been achieved already. More efficient allocation of water as a means to improved water management has got quite same attention as well, but if it comes to the implementation of improved allocation schemes there is still a long way to go. At the global level, it is even more severe, since basic data on virtual water flows and water dependency of nations are generally even lacking.

The volume of virtual water 'hidden' or 'embodied' in a particular product is defined as the volume of water used in the production process of that product (Allan, 1997; Hoekstra, 1998). Not only agricultural products contain virtual water—most studies to date have been limited to the study of virtual water in crops—but also industrial products and services contain virtual water. As an example of virtual water content, one often refers to the virtual water content of grains. It is estimated that for producing one kilogram of grain, grown under rain-fed and favourable climatic conditions, we need about one to two cubic metres of water, which is 1000–2000 kg of water. For the same amount of grain, but growing in an arid country, where the climatic conditions are not favourable (high temperature, high evapotranspiration) we need up to 3000–5000 kg of water.

If one country exports a water-intensive product to another country, it exports water in virtual form. In this way, some countries support other countries in their water needs. For water-scarce countries, it could be attractive to achieve water security by importing water-intensive products instead of producing all water-demanding products domestically. Reversibly, water-rich countries could profit from their abundance of water resources by producing water-intensive products for export. Trade of real water between water-rich and water-poor regions is generally impossible due to the large distances and associated costs, but trade in water-intensive products (virtual water trade) is realistic. Virtual water trade between nations and even continents could thus be used as an instrument to improve global water use efficiency and to achieve water security in water-poor regions of the world.

World wide, both politicians and the general public increasingly show interest in the pros and cons of 'globalisation' of trade. This can be understood from the fact that increasing global trade implies increased interdependence of nations. The tension in the debate relates to the fact that the game of global competition is played with rules that many see as unfair. Knowing that economically sound water pricing is poorly developed in many regions of the world, this means that many products are put on the world market at a price that does not properly include the cost of the water contained in the product. This leads to situations in which some regions in fact subsidise export of scarce water.

The objectives of this paper are to estimate the amount of water needed to produce crops in different countries of the world, to quantify the volume of virtual water flows between nations in the period 1995–1999, and to analyse national virtual water balances in relation to national water needs and water availability. This paper is primarily meant as a data report. We do not pretend to give an in-depth interpretation of the results. Besides, we limit ourselves to virtual water flows in relation to international crop trade, thus excluding virtual water flows related to international trade of livestock products and industrial products. International virtual water flows in relation to trade in livestock and livestock products have been analysed in an accompanying study (Chapagain and Hoekstra, 2003).

2. Method

2.1. Calculation of specific water demand per crop type

Per crop type, average specific water demand has been calculated separately for each relevant nation on the basis of FAO data on crop water requirements and crop yields:

$$SWD[n,c] = \frac{CWR[n,c]}{CY[n,c]}. \tag{1}$$

Here, SWD denotes the specific water demand ($m^3\,ton^{-1}$) of crop c in country n, CWR the crop water requirement ($m^3\,ha^{-1}$) and CY the crop yield ($ton\,ha^{-1}$).

The crop water requirement CWR (in $m^3\,ha^{-1}$) is calculated from the accumulated crop evapotranspiration ET_c (in $mm\,day^{-1}$) over the complete growing period. The crop evapotranspiration ET_c follows from multiplying the 'reference crop evapotranspiration' ET_0 with the crop coefficient K_c:

$$ET_c = K_c \times ET_0. \tag{2}$$

The concept of 'reference crop evapotranspiration' was introduced by FAO to study the evaporative demand of the atmosphere, independently of crop type, crop development and management practices. The only factors affecting ET_0 are climatic parameters. The reference crop evapotranspiration ET_0 is defined as the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 12 cm, a fixed crop surface resistance of $70\,s\,m^{-1}$ and an albedo of 0.23. This reference crop evapotranspiration closely resembles the evapotranspiration from an extensive surface of green grass cover of uniform height, actively growing, completely shading the ground and with adequate water (Smith et al., 1992). Reference crop evapotranspiration is calculated on the basis of the FAO Penman–Monteith equation (Smith et al., 1992; Allen et al., 1994a, b, 1998):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma 900/(T+273)U_2(e_a - e_d)}{\Delta + \gamma(1 + 0.34U_2)}, \tag{3}$$

in which ET_0 is the reference crop evapotranspiration ($mm\,day^{-1}$), R_n the net radiation at the crop surface ($MJ\,m^{-2}\,day^{-1}$), G the soil heat flux ($MJ\,m^{-2}\,day^{-1}$), T the average air temperature (°C), U_2 the wind speed measured at 2 m height ($m\,s^{-1}$); e_a the saturation vapour pressure (kPa), e_d the actual vapour pressure (kPa), $e_a - e_d$ the vapour pressure deficit (kPa), Δ the slope of the vapour pressure curve ($kPa\,°C^{-1}$), and γ the psychrometric constant ($kPa\,°C^{-1}$).

The crop coefficient accounts for the actual crop canopy and aerodynamic resistance relative to the hypothetical reference crop. The crop coefficient serves as an aggregation of the physical and physiological differences between a certain crop and the reference crop.

The overall scheme for the calculation of specific water demand is drawn in Fig. 1. This figure also shows the next step: the calculation of the virtual water flows between nations.

2.2. Calculation of virtual water flows and the national virtual water balance

Virtual water flows between nations have been calculated by multiplying the international crop trade flows by their associated virtual water content. The latter depends on the specific water demand of the crop in the exporting country where the crop is produced. Virtual water trade is thus calculated by

$$VWT[n_e, n_i, c, t] = CT[n_e, n_i, c, t] \times SWD[n_e, c], \tag{4}$$

in which VWT denotes the virtual water trade ($m^3\,yr^{-1}$) from exporting country n_e to importing country n_i in year t as a result of trade in crop c. CT represents the crop trade ($ton\,yr^{-1}$) from exporting country n_e to importing country n_i in year t for crop c. SWD represents the specific water demand ($m^3\,ton^{-1}$) of crop c in the exporting country. Above equation assumes that if a certain crop is exported from a certain country, this crop is actually grown in this country (and not in another country from which the crop was just imported for further export). Although a certain error will be made in this way, it is estimated that this error will not substantially influence the overall virtual water balance of a country. Besides, it is practically impossible to track the sources of all exported products.

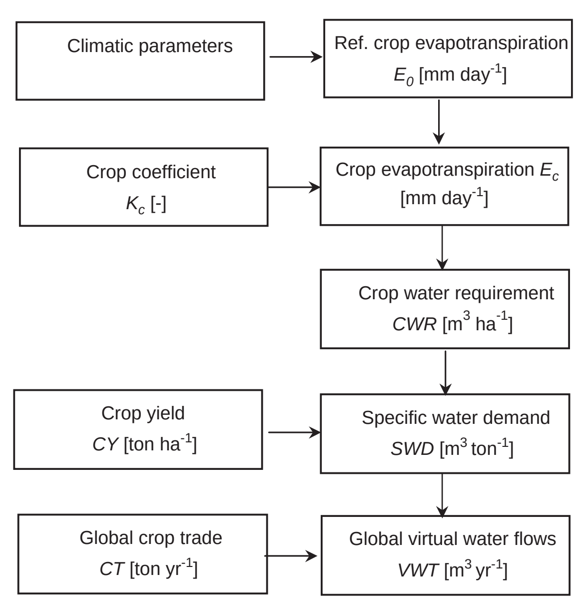

Fig. 1. Steps in the calculation of global virtual water flows.

The gross virtual water import to a country n_i is the sum of all imports:

$$GVWI[n_i, t] = \sum_{n_e, c} VWT[n_e, n_i, c, t]. \quad (5)$$

The gross virtual water export from a country n_e is the sum of all exports:

$$GVWE[n_e, t] = \sum_{n_i, c} VWT[n_e, n_i, c, t]. \quad (6)$$

The net virtual water import of a country is equal to the gross virtual water import minus the gross virtual water export. The virtual water balance of country x for year t can thus be written as

$$NVWI[x, t] = GVWI[x, t] - GVWE[x, t], \quad (7)$$

where $NVWI$ stands for the net virtual water import ($m^3\,yr^{-1}$) to the country. Net virtual water import to a country has either a positive or a negative sign. The latter indicates that there is net virtual water *export* from the country.

2.3. Calculation of national water scarcity, water dependency and water self-sufficiency

One would logically assume that a country with high water scarcity would seek to profit from net virtual water import. On the other hand, countries with abundant water resources could make profit by exporting water in virtual form. In order to check this hypothesis, we need indices of both water scarcity and virtual water import dependency. Plotting countries in a graph with water scarcity on the x-axis and virtual water import dependency on the y-axis, would expectedly result in some positive relation.

As an index of national water scarcity, we use the ratio of total water use to water availability:

$$WS = \frac{WU}{WA} \times 100. \quad (8)$$

In this equation, WS denotes the national water scarcity (%), WU the total water use in the country ($m^3\,yr^{-1}$) and WA the national water availability ($m^3\,yr^{-1}$). Defined in this way, water scarcity will generally range between 0% and 100%, but can in exceptional cases (e.g. groundwater mining) be above 100%. As a measure of the national water availability WA, we take the annual internal renewable water resources that are the average fresh water resources renewably available over a year from precipitation falling within a country's borders (see for instance Gleick, 1993). Total water use WU should ideally refer to the sum of 'blue' and 'green' water use, but for practical reasons we have provisionally chosen in this paper to define water scarcity as the ratio of blue water use to water availability, which is generally done by others as well.

Next, we have looked for a proper indicator of 'virtual water import dependency' or 'water dependency' in brief. The indicator should reflect the level to which a nation relies on foreign water resources (through import of water in virtual form). The water dependency WD of a nation is in this paper calculated as the ratio of the net virtual water import into a country to the total national water appropriation:

$$WD = \begin{cases} \dfrac{NVWI}{WU + NVWI} \times 100 & \text{if } NVWI \geqslant 0, \\ 0 & \text{if } NVWI < 0. \end{cases} \quad (9)$$

The value of the water dependency index will per definition vary between 0% and 100%. A value of zero means that gross virtual water import and export are in balance or that there is net virtual water export. If on the other extreme the water dependency of a nation approaches hundred percent, the nation nearly completely relies on virtual water import.

As the counterpart of the water dependency index, the water self-sufficiency index is defined as follows:

$$WSS = \begin{cases} \dfrac{WU}{WU + NVWI} \times 100 & \text{if } NVWI \geqslant 0, \\ 100 & \text{if } NVWI < 0. \end{cases} \quad (10)$$

The water self-sufficiency of a nation relates to the water dependency of a nation in the following simple way:

$$WSS = 100 - WD. \quad (11)$$

The level of water self-sufficiency WSS denotes the national capability of supplying the water needed for the production of the domestic demand for goods and services. Self-sufficiency is 100% if all the water needed is available and indeed taken from within the own territory. Water self-sufficiency approaches zero if a country heavily relies on virtual water imports.

3. Data sources

Data on crop water requirements are calculated with FAO's CropWat model for Windows, which is available through the website of FAO (www.fao.org). The CropWat model uses the FAO Penman–Monteith equation for calculating reference crop evapotranspiration, as described in the previous section (Clarke et al., 1998). The CropWat model calculates crop water requirement of different crop types on the basis of the following assumptions:

(1) Crops are planted under optimum soil water conditions without any effective rainfall during their life; the crop is developed under irrigation conditions.

(2) Crop evapotranspiration under standard conditions (ET_c) is the evapotranspiration from disease-free, well-fertilised crops, grown in large fields with 100% coverage.
(3) Crop coefficients are selected depending on the single crop coefficient approach, that means single cropping pattern, not dual or triple cropping pattern.

3.1. Climatic data

The climatic data needed as input to CropWat have been taken from FAO's climatic database ClimWat, which is also available through FAO's website. The ClimWat database contains climatic data for more than 100 countries. For many countries climatic data are available for different climatic stations. As a crude approach, the capital climatic station data have been taken as the country representative. For the countries, where the required climatic input data are not available in ClimWat, the crop water requirement is taken from the guideline of FAO as reported by Gleick (1993). Depending on the country, the authors made an estimate somewhere between the minimum and maximum estimate given in the FAO guideline. If still data were lacking, data were taken from a neighbouring country.

3.2. Crop parameters

In the crop directory of the CropWat package, sets of crop parameters are available for 24 different crops (Table 1). The crop parameters used as input data to CropWat are the crop coefficients in different crop development stages (initial, middle and late stage), the length of each crop in each development stage, the root depth and the planting date. For the 14 crops where crop parameters are not available in the CropWat package, crop parameters have been based on Allen et al. (1998).

3.3. Crop yields

Data on crop yields have been taken from the FAOSTAT database, again available through FAO's website.

3.4. Global trade in crops

As a source for the global trade in crops, we have used the 1995–1999 data contained in the Personal Computer Trade Analysis System (PC-TAS), a cd-rom produced by the United Nations Statistics Division (UNSD) in New York in collaboration with the International Trade Centre (ITC) in Geneva. These data are based on the Commodity Trade Statistics Data Base (COMTRADE) of the UNSD. Every year individual countries supply the UNSD with their annual international trade statistics, detailed by commodity and partner country. These data are processed into a standard format with consistent coding and valuation. Commodities are classified according the Harmonised System (HS) classification of the World Customs Organization.

3.5. Link between two crop classifications

Specific water demand is calculated for 38 crop types as distinguished by the FAO in CropWat. The HS classification used in the COMTRADE database is a much more detailed classification. For our purpose, we therefore had to group the commodity classes of the HS classification in order to link to the FAO crop types.

4. Specific water demand per crop type per country

For the calculated crop water requirements for different crops in different countries that are used in this paper, the reader is referred to the full report of this study (Hoekstra and Hung, 2002). The calculated crop water requirements refer to the evapotranspiration under optimal growth conditions. This means that the calculated values are overestimates, because in reality there are often water shortage conditions. On the other

Table 1
Availability of crop parameters

Crops for which crop parameters have been taken from FAO's CropWat package			Crops for which crop parameters have been taken from Allen et al. (1998)	
Banana	Maize	Sugar beet	Artichoke	Onion dry
Barley	Mango	Sugar cane	Carrots	Peas
Bean dry	Millet	Sunflower	Cauliflower	Rice
Bean green	Oil palm fruit	Tobacco	Citrus	Safflower
Cabbage	Pepper	Tomato	Cucumber	Spinach
Cotton seeds	Potato	Vegetable	Lettuce	Sweet potato
Grape	Sorghum	Watermelon	Oats	
Groundnut	Soybean	Wheat	Onion green	

hand, the calculated values can also be seen as conservative, because they exclude inevitable losses (e.g. during transport and application of water) and required losses such as drainage. The calculated crop water requirements differ considerably over countries, which is mainly due to the differences in climatic conditions.

Data on country-average actual crop yields in the year 1999 have been retrieved from the FAOSTAT database. Where country-specific crop yield data are lacking in FAOSTAT, regional averages have been taken. The differences between countries are here even larger than in the case of the crop water requirements. This is due to the impact of the human factor on the actual crop yields.

Specific water demand ($m^3\,ton^{-1}$) per crop type has been calculated for different countries by dividing the crop water requirement ($m^3\,ha^{-1}$) by the crop yield ($ton\,ha^{-1}$). Because both crop water requirements and crop yields strongly vary between countries, specific water demands vary as well.

It is noted here that the specific water demand data for 1999 have been used in this study to calculate the virtual water flows in the whole period 1995–1999 (see next section). This is acceptable because country crop yield data appear not to vary considerably over years.

5. Global virtual water flows

5.1. Virtual water flows between nations

The calculation results show that the global volume of crop-related international virtual water flows was $695\,Gm^3\,yr^{-1}$ in average over the period 1995–1999. For comparison: the global water withdrawal for agriculture (water use for irrigation) was about $2500\,Gm^3\,yr^{-1}$ in 1995 and $2600\,Gm^3\,yr^{-1}$ in 2000 (Shiklomanov, 1997, p.61). Taking into account the use of rainwater by crops as well, the total water use by crops in the world has been estimated at $5400\,Gm^3\,yr^{-1}$ (Rockström and Gordon, 2001). This means that 13% of the water used for crop production in the world is not used for domestic consumption but for export (in virtual form). This is the global percentage; the situation strongly varies between countries.

Considering the period 1995–1999, the top-five list of countries with net virtual water export is United States, Canada, Thailand, Argentina and India. The top-five list of countries in terms of net virtual water import for the same period is Japan, Netherlands, Republic of Korea, China and Indonesia. Top-ten lists are given in Table 2.

National virtual water balances over the period 1995–1999 are shown in Fig. 2. Countries with net virtual water export are shown in green colour and countries with net virtual water import in red colour. It should be noted that some countries, such as Brazil, Syria, Pakistan, Tajikistan and Uganda have net export of virtual water over the period 1995–1999, but net import of virtual water in one or more particular years in this period. There are also countries that show the reverse, such as the Philippines, the Russian Federation, Uzbekistan, Kyrgyztan, Mongolia, Nicaragua and Mexico.

Table 2
Top-ten of virtual water export countries and top-ten of virtual water import countries (period 1995–1999)

Country	Net export volume ($10^9\,m^3\,yr^{-1}$)	Ranking	Country	Net import volume ($10^9\,m^3\,yr^{-1}$)
United States	152	1	Japan	59
Canada	55	2	Netherlands	30
Thailand	47	3	Korea Rep.	23
Argentina	45	4	China	20
India	32	5	Indonesia	20
Australia	29	6	Spain	17
Vietnam	18	7	Egypt	16
France	18	8	Germany	14
Guatemala	14	9	Italy	13
Brazil	9	10	Belgium	12

The calculations show that developed countries generally have a more stable virtual water balance than the developing countries. Peak years in virtual water export were for instance found for Thailand, India, Vietnam, Guatemala and Syria. The opposite, the occurrence of peak years with relatively high virtual water import, was found for Jordan.

Countries that are relatively close to each other in terms of geography and development level can have a rather different virtual water balance. While European countries such as the Netherlands, Belgium, Germany, Spain and Italy import virtual water in the form of crops, France exports a large amount of virtual water. In the Middle East, we see that Syria has net export of virtual water related to crop trade, but Jordan and Israel have net import. In Southern Africa, Zimbabwe and Zambia had net export in the period 1995–1999, but South Africa had net import. (It should be noted that the balance of Zimbabwe has recently turned due to the recent political and economic developments.) In the regions of the Former Soviet Union, countries such as Kazakhstan and the Ukraine have net export of virtual water, but the Russian Federation has net import.

It is hard to put the data calculated in this study in the context of earlier studies, for the simple reason that few quantitative studies into virtual water flows between nations have been carried out. A few interesting studies have been done for the Middle East and Africa (Allan, 1997, 2001; Wichelns, 2001; Nyagwambo,

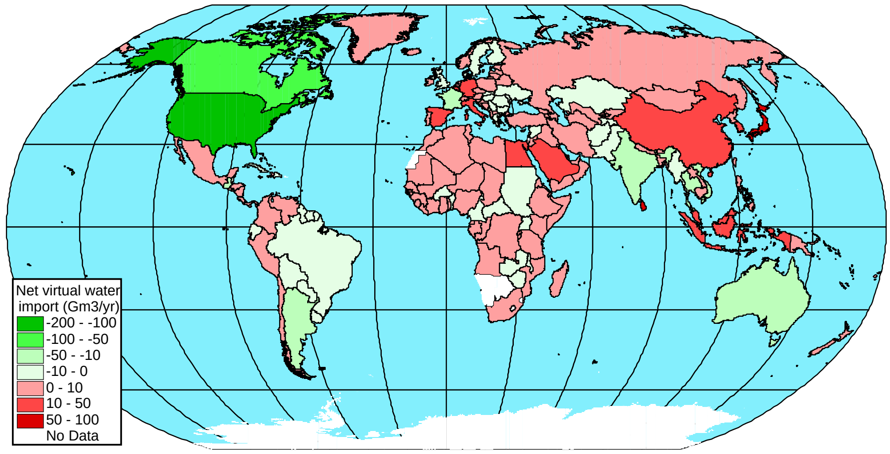

Fig. 2. National virtual water balances over the period 1995–1999. Green coloured countries have net virtual water export; red coloured countries have net virtual water import.

Table 3
Global virtual water flows between nations by product (Gm^3)

Product	1995	%	1996	%	1997	%	1998	%	1999	%	Total	%
Wheat	181	32.35	215	26.49	254	32.01	203	29.00	197	32.73	1049	30.20
Soybean	103	18.37	108	13.28	125	15.79	122	17.47	135	22.45	593	17.07
Rice	81	14.57	198	24.35	71	8.95	119	16.95	65	10.78	534	15.36
Maize	58	10.40	56	6.93	67	8.51	65	9.22	61	10.14	307	8.85
Raw sugar	9	1.60	68	8.35	119	14.99	42	5.99	13	2.09	250	7.20
Barley	36	6.41	30	3.67	35	4.41	29	4.15	30	5.05	170	4.88
Sunflower	12	2.17	24	2.97	20	2.50	20	2.92	18	2.94	94	2.71
Sorghum	12	2.14	26	3.21	12	1.49	10	1.39	10	1.73	70	2.01
Bananas	11	1.88	16	2.00	15	1.95	15	2.15	11	1.83	68	1.97
Grapes	12	2.07	13	1.64	13	1.65	13	1.87	13	2.24	65	1.86
Oats	9	1.67	10	1.25	11	1.41	9	1.34	10	1.61	50	1.43
Tobacco	5	0.98	10	1.19	11	1.33	13	1.90	7	1.10	46	1.31
Groundnuts	6	1.10	7	0.84	8	1.02	6	0.90	4	0.70	32	0.91
Peppers	4	0.80	5	0.62	9	1.12	6	0.84	6	1.02	30	0.87
Cotton seeds	5	0.83	5	0.56	5	0.64	6	0.92	7	1.24	28	0.81
Peas	3	0.46	4	0.48	4	0.57	5	0.67	2	0.31	18	0.50
Beans	3	0.47	6	0.68	3	0.35	2	0.36	2	0.38	16	0.45
Potatoes	2	0.40	2	0.26	2	0.31	2	0.33	2	0.37	11	0.33
Onions	2	0.28	3	0.33	2	0.19	2	0.35	1	0.25	10	0.28
Vegetables	1	0.14	1	0.10	1	0.12	4	0.50	1	0.17	7	0.20
Millet	1	0.23	1	0.14	1	0.16	1	0.17	1	0.22	6	0.18
Tomatoes	1	0.14	1	0.12	1	0.13	1	0.17	1	0.19	5	0.15
Palm nuts	1	0.12	1	0.12	1	0.07	1	0.08	0	0.08	3	0.09
Safflower	1	0.12	1	0.09	1	0.08	1	0.09	1	0.09	3	0.09
Cucumbers	0	0.06	1	0.12	1	0.07	0	0.06	0	0.07	3	0.08
Cauliflower	0	0.06	0	0.05	0	0.05	0	0.06	0	0.07	2	0.06
Cabbages	0	0.05	0	0.04	0	0.04	0	0.05	0	0.06	2	0.05
Carrots	0	0.04	0	0.03	0	0.03	0	0.04	0	0.05	1	0.04
Citrus	0	0.04	0	0.03	0	0.02	0	0.01	0	0.01	1	0.02
Artichokes	0	0.02	0	0.01	0	0.01	0	0.01	0	0.02	1	0.01
Lettuce	0	0.01	0	0.01	0	0.01	0	0.01	0	0.02	0	0.01
Sweet potato	0	0.02	0	0.01	0	0.01	0	0.01	0	0.01	0	0.01
Spinach	0	0.00	0	0.00	0	0.00	0	0.00	0	0.01	0	0.00
Grand total	559	100.00	813	100.00	793	100.00	700	100.00	601	100.00	3475	100.00

1998; Earle, 2001). One study was done by Buchvald for Israel and is available in Hebrew only. The main results of this study are cited in Yegnes-Botzer (2001). According to Buchvald's estimation, Israel exported 377 million m^3 of virtual water in 1999 and imported more than 6900 million m^3. The current paper calculates for Israel an export of 700 million m^3 of virtual water in 1999 and an import of 7400 million m^3.

The total volume of crop-related international virtual water flows in the period 1995–1999 can for 30% be explained by trade in wheat (Table 3). Next come soybeans and rice, which account, respectively, for 17% and 15% of global crop-related virtual water flows.

5.2. Virtual water flows between 13 world regions

In order to show virtual water flows between major world regions, the world has been classified into 13 regions: North America, Central America, South America, Eastern Europe, Western Europe, Central and South Asia, the Middle East, South-east Asia, North Africa, Central Africa, Southern Africa, the Former Soviet Union and Oceania. Gross virtual water flows between and within regions in the period 1995–1999 are presented in Table 4. Net virtual water flows between regions in the same period are shown in Fig. 3. The largest virtual water flows have been indicated with arrows. Table 5 presents, for each world region, the most important regions for gross import and gross export of virtual water.

Regions with a significant net virtual water import are Central and South Asia, Western Europe, North Africa and the Middle East. Two other regions with net virtual water import, but less substantial, are Southern Africa and Central Africa. Regions with substantial net virtual water export are North America, South America, Oceania and South-east Asia. Three other regions with net virtual water export, but less substantial, are the FSU, Central America and Eastern Europe. North America is by far the biggest virtual water exporter in the world, while Central and South Asia is by far the biggest virtual water importer. A full ranking of the world regions is given in Table 6.

The gross virtual water flows between countries *within* a region have been calculated by summing up all virtual water imports of the countries of the region that originate from other countries in the same region. (This yields the same result as if we would have added all virtual water exports of the countries in a region that go to other countries in the same region.) The results are shown in the italicised cells of Table 4. Western Europe is the region with the biggest volume of internal virtual water flows. Besides, the volume appears to be rather stable over the years. South America is second in the ranking of internal virtual water flow volume. Central and South Asia is a rather unstable region if we look at the annual virtual water flows between the countries of the region. Central and South Asia is the largest region in terms of population, so food demand is higher than in the other regions. This explains why the region is the biggest virtual water importer. The virtual water flows between countries within the region are also high; thus, the countries within the region highly depend on both countries outside and countries within the region.

Table 4
Average annual gross virtual water flows between world regions in the period 1995–1999 (Gm^3/yr)

Exporter	Importer													
	Central Africa	Central America	Central & South Asia	Eastern Europe	Middle East	North Africa	North America	Oceania	FSU	Southern Africa	South America	South-east Asia	Western Europe	Total gross export
Central Africa	*0.33*	0.00	0.02	0.02	0.01	0.01	0.01	0.00	0.00	0.13	0.00	0.01	0.40	0.6
Central America	0.05	*0.92*	24.90	0.16	0.09	0.31	8.07	0.00	0.86	0.03	0.49	0.08	2.87	37.9
Central and South Asia	0.71	0.13	*20.08*	0.61	4.33	2.75	0.66	0.08	1.98	1.89	0.17	12.98	3.55	29.8
Eastern Europe	0.00	0.03	0.56	*4.08*	2.07	1.51	0.11	0.04	1.05	0.02	0.02	0.11	7.48	13.0
Middle East	0.16	0.03	2.31	0.51	*5.13*	2.64	0.47	0.16	0.24	0.01	0.10	0.54	3.67	10.8
North Africa	0.03	0.03	0.49	0.23	0.75	*0.55*	0.84	0.00	0.04	0.09	0.92	0.03	2.76	6.2
North America	0.57	30.65	79.04	1.90	12.75	25.70	*16.56*	0.80	1.93	1.97	17.73	16.56	34.05	223.7
Oceania	0.16	0.08	16.65	0.01	1.89	1.86	0.54	*0.56*	0.01	0.57	0.73	6.31	0.88	29.7
FSU	0.00	0.07	1.60	2.61	5.85	0.61	0.19	0.00	*9.74*	0.00	0.01	0.08	7.00	18.0
Southern Africa	0.15	0.14	1.08	0.10	0.07	0.08	0.35	0.02	0.05	*0.56*	0.26	0.24	1.53	4.1
South America	0.33	1.43	12.46	1.57	4.05	3.73	2.67	0.07	0.97	0.55	*29.35*	3.30	38.24	69.4
South-east Asia	0.36	0.43	45.33	0.51	5.15	6.31	2.59	0.53	1.20	2.36	0.69	*17.44*	2.22	67.7
Western Europe	0.40	0.45	11.91	3.79	4.04	5.09	1.02	0.03	0.78	0.41	0.32	0.36	*50.09*	28.6
Total gross import	2.9	33.5	196.4	12.0	41.1	50.6	17.5	1.7	9.1	8.0	21.4	40.6	104.7	539.5

The italicised cells refer to gross flows between countries within the regions.

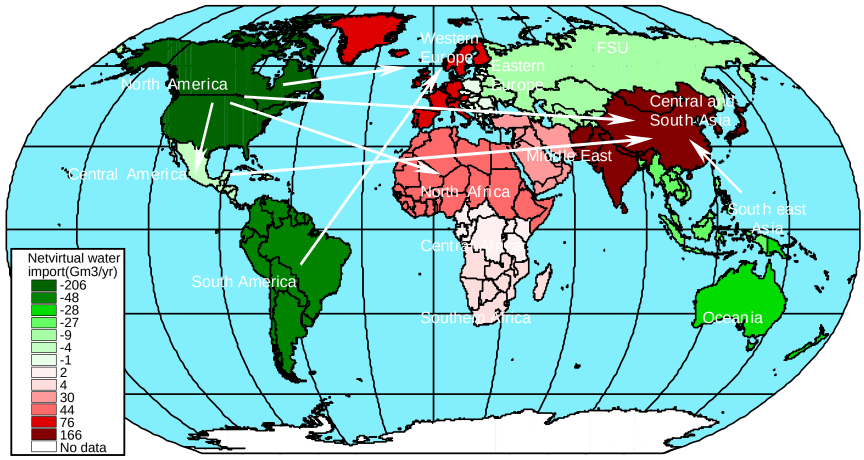

Fig. 3. Virtual water balances of 13 world regions over the period 1995–1999. Green coloured regions have net virtual water export; red coloured regions have net virtual water import. The arrows show the largest net virtual water flows between regions ($>20\,\mathrm{Gm^3\,yr^{-1}}$).

Table 5
Ranking of gross import and gross export regions for each of the 13 world regions

Region	Gross import from				Gross export to			
	First	Second	Third	Fourth	First	Second	Third	Fourth
Central Africa	Central and South Asia	North America	Western Europe	South-east Asia	Western Europe	Southern Africa	Eastern Europe	Central and South Asia
North Africa	North America	South-east Asia	Western Europe	South America	Western Europe	South America	North America	Middle East
Southern Africa	South-east Asia	North America	Central and South Asia	Oceania	Western Europe	South and Central Asia	North America	South America
South America	North America	North Africa	South-east Asia	Oceania	Western Europe	Central and South Asia	Middle East	North Africa
Central America	North America	South America	Western Europe	South-east Asia	Central and South Asia	North America	Western Europe	Russian Fed
North America	Central America	Southern Africa	South-east Asia	Western Europe	Central and South Asia	Western Europe	Central America	North Africa
Central Asia	North America	South-east Asia	Central America	Oceania	South-east Asia	Middle East	Western Europe	North Africa
Middle East	North America	Russian Fed	South-east Asia	Central and South Asia	Western Europe	North Africa	Central and South Asia	South-east Asia
South-east Asia	North America	Central and South Asia	Oceania	Southern Africa	Central and South Asia	North Africa	Middle East	North America
Eastern Europe	Western Europe	Russian Fed	North America	South America	Western Europe	Middle East	North Africa	Russian Fed
Western Europe	South America	North America	Eastern Europe	Middle East	Central and South Asia	North Africa	Middle East	Eastern Europe
Oceania	North America	South-east Asia	Middle East	Central and South Asia	Central and South Asia	South-east Asia	Middle East	North Africa
Russian Fed	Central and South Asia	North America	South-east Asia	Eastern Europe	Western Europe	Middle East	Eastern Europe	Central and South Asia

6. The national virtual water balance in relation to national water needs and availability

Using the definitions provided in Section 2.3, indicators of national water scarcity, water self-sufficiency and water dependency have been calculated. The basic data on national water withdrawal and water availability have been taken from FAO (2004). The water availability data refer to the sum of internal and external water resources. The data on net virtual water import per country are taken from this study. The results for a number of selected countries (averages for the period 1995–1999) are shown in Table 7. As always with this kind of statistics, the data

Table 6
Ranking of regions in terms of gross virtual water import and gross virtual water export

Gross virtual water import (1995–1999)		Ranking	Gross virtual water export (1995–1999)	
Region	$Gm^3 yr^{-1}$		Region	$Gm^3 yr^{-1}$
Central and South Asia	196	1	North America	224
Western Europe	105	2	South America	69
North Africa	51	3	South-east Asia	68
Middle East	41	4	Central America	38
South-east Asia	41	5	Central and South Asia	30
Central America	33	6	Oceania	30
South America	21	7	Western Europe	29
North America	18	8	FSU	18
Eastern Europe	12	9	Eastern Europe	13
FSU	9	10	Middle East	11
Southern Africa	8	11	North Africa	6
Central Africa	3	12	Southern Africa	4
Oceania	2	13	Central Africa	1

Table 7
Water withdrawals, virtual water import and export, water scarcity, water self-sufficiency and water dependency for a few selected nations (1995–1999)

Country	Population	Water availability ($10^6 m^3 yr^{-1}$)	Water withdrawal ($10^6 m^3 yr^{-1}$)	Gross virtual water import ($10^6 m^3 yr^{-1}$)	Gross virtual water export ($10^6 m^3 yr^{-1}$)	Net virtual water import ($10^6 m^3 yr^{-1}$)	Water scarcity (%)	Water self-sufficiency (%)	Water dependency (%)
Bangladesh	128,837,760	1,210,644	79,394	8304.6	2562.6	5742	7	93	7
Brazil	168,220,660	8,233,000	59,298	23,161.6	32,161.8	−9000.2	1	100	0
China	1,252,042,000	2,896,569	630,289	30,550.4	10,114.9	20,435.6	22	97	3
Egypt	62,782,964	86,800	68,653	16,937.1	901.6	16,035.5	79	81	19
France	58,656,600	203,700	39,959	9376.3	27,051.4	−17,675.1	20	100	0
Germany	82,109,980	154,000	47,052	23,260.4	9671.3	13,589.1	31	78	22
India	997,775,760	1,907,760	645,837	2413	34,612.3	−32,199.3	34	100	0
Indonesia	207,029,780	2,838,000	82,773	21,366.2	1139.2	20,227	3	80	20
Japan	126,624,200	430,000	88,432	59,632	188.4	59,443.6	21	60	40
Jordan	4,742,815	880	1016	4536	55	4481	115	18	82
Pakistan	134,871,900	233,770	169,384	2547.1	2556.8	−9.8	72	100	0
Russian Fed	146,180,880	4,507,250	76,686	14,534.5	12,079.6	2454.9	2	97	3
South Africa	42,043,988	50,000	15,306	6927.6	2558.3	4369.3	31	78	22
USA	278,035,840	3,069,400	479,293	29,264.3	180,924.3	−151,660	16	100	0

should be taken with extreme caution, because of the quality of the underlying source data and the assumptions that had to be made.

From a water resources point of view, one would expect a positive relationship between water scarcity and water dependency, because high water scarcity will make it attractive to import virtual water and thus become water dependent. One would logically suppose: the higher the scarcity within a country, the more dependency on water in other countries. To test this hypothesis, the countries of the world have been plotted in a scarcity-dependency graph. Fig. 4 shows that there is no simple relation. The reason is that water scarcity is a driver of international food trade to a limited extent only. Other determinants, such as available land, labour and technology, national food policies and international trade regulations are often more important. Besides, the world food market is to a significant extent driven by supply (countries exporting their food surpluses) rather than by demand. Yang et al. (2003) have studied the relation between per capita water availability in a country and the net cereal import into the country in order to see when international virtual water trade is actually water-scarcity induced. They find a threshold at a water availability of approximately 1500 $m^3 yr^{-1}$ per capita. Below this threshold, the demand for cereal import and thus the virtual water import increases exponentially with decreasing water resources. Above the threshold, there is no relationship discernable.

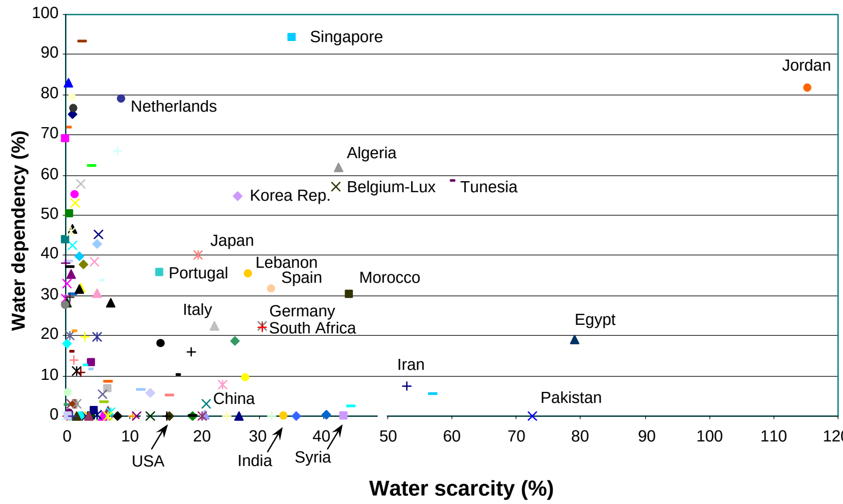

Fig. 4. Water dependency versus water scarcity for all countries of the world (1995–1999).

7. Concluding remarks

This paper is limited to an assessment of virtual water flows in relation to *crop* trade between nations. Also other goods contain virtual water, for instance meat, diary products, cotton, paper, etc. In order to get a complete picture of the global virtual water flows, also other products than crops have to be taken into account. In another paper, Chapagain and Hoekstra (2003) estimate that global international virtual water flows in relation to trade in *livestock and livestock products* have an average volume of 336 $Gm^3 yr^{-1}$ over the period 1995–1999.

As stated in the introduction, this paper is primarily a data report, aimed at disclosing the numbers. A next step is of course to interpret the results and ask the question why the global virtual water flows are as they are. What are the explanatory factors behind changes in national virtual water balances? What is, for instance, the relative importance of year-to-year fluctuations in agricultural yields, subsidies in agriculture, national water scarcity, the development of domestic demand for agriculture products? Another next step is to go beyond 'explanation' and to study how governments can deliberately interfere in the current national virtual water balances in order to save their domestic water resources.

Knowing the actual national virtual water balance is essential for developing a rational national policy with respect to virtual water trade. But for some large countries it might be as relevant to know the internal trade of virtual water within the country. For China, for instance, relatively dry in the north and relatively wet in the south, domestic virtual water trade is a relevant issue.

The method used for the calculation of the virtual water content of different types of crops has a few weak points. As explained, the crop water requirement estimates used in this paper are conservative on the one hand (due to the water losses that are not taken into account), but they are overestimates on the other hand (because they are based on the assumption of optimal growth conditions, an assumption which is generally not met in reality). Improvements to the calculated figures can be made if we could make better estimates of the actual specific water use per crop.

Acknowledgements

The authors are thankful to the National Institute of Public Health and the Environment (RIVM), Bilthoven, The Netherlands, which sponsored the work underlying this paper. The research is part of the research programme of Delft Cluster. We would like to thank Ton Bresser (RIVM) and Huub Savenije (UNESCO-IHE) for their valuable inputs.

References

Allan, J.A., 1997 Virtual water: a long term solution for water short Middle Eastern economies? Occasional Paper 3, School of Oriental and African Studies (SOAS), University of London.

Allan, J.A., 2001. The Middle East Water Question: Hydropolitics and the Global Economy. I.B. Tauris, London.

Allen, R.G., Smith, M., Perrier, A., Pereira, L.S., 1994a. An update for the definition of reference evapotranspiration. ICID Bulletin 43 (2), 1–34.

Allen, R.G., Smith, M., Perrier, A., Pereira, L.S., 1994b. An update for the calculation of reference evapotranspiration. ICID Bulletin 43 (2), 35–92.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration: guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56, FAO, Rome, Italy.

Chapagain, A.K., Hoekstra, A.Y., 2003. Virtual water flows between nations in relation to trade in livestock and livestock products.

Value of Water Research Report Series No.13, UNESCO-IHE, Delft, The Netherlands.

Clarke, D., Smith, M., El-Askari, K., 1998. CropWat for Windows: User guide, Version 4.2, www.fao.org.

Earle, A., 2001. The role of virtual water in food security in Southern Africa. Occasional Paper 33, School of Oriental and African Studies (SOAS), University of London.

FAO, 2004. Online AQUASTAT 2000 database.

Gleick, P.H. (Ed.), 1993, Water in Crisis: A Guide to the World's Fresh Water Resources. Oxford University Press, New York, USA.

Hoekstra, A.Y., 1998. Perspectives on Water: A Model-based Exploration of the Future. International Books, Utrecht, The Netherlands.

Hoekstra, A.Y., Hung, P.Q., 2002. Virtual water trade, a quantification of virtual water flows between nations in relation to international crop trade. Value of Water Research Report Series No.11, UNESCO-IHE, Delft, The Netherlands.

Nyagwambo, N.L., 1998. 'Virtual water' as a water demand management tool: the Mupfure river basin case. M.Sc. Thesis, DEW 045, IHE, Delft, The Netherlands.

Rockström, J., Gordon, L., 2001. Assessment of green water flows to sustain major biomes of the world: implications for future ecohydrological landscape management. Physics and Chemistry of the Earth (B) 26, 843–851.

Shiklomanov, I.A. (Ed.), 1997.Assessment of water resources and water availability in the world. Comprehensive Assessment of the Freshwater Resources of the World. World Meteorological Organisation, Geneva.

Smith, M., Allen, R.G., Monteith, J.L., Perrier, A., Pereira, L.S., Segeren, A., 1992. Report on the Expert Consultation on revision of FAO methodologies for crop water requirements. FAO, Rome, Italy 28–31 May 1990.

Wichelns, D., 2001. The role of 'virtual water' in efforts to achieve food security and other national goals, with an example from Egypt. Agricultural Water Management 49, 131–151.

Yang, H., Reichert, P., Abbaspour, K.C., Zehnder, A.J.B., 2003. A water resources threshold and its implications for food security. In: Hoekstra, A.Y. (Ed.), Virtual water trade: Proceedings of the International Expert Meeting on Virtual Water Trade. Value of Water Research Report Series No.12, UNESCO-IHE, Delft, The Netherlands.

Yegnes-Botzer, A., 2001. Virtual water export from Israel: quantities, driving forces and consequences. M.Sc. Thesis, DEW 166, IHE, Delft, The Netherlands.