

Virtual water trade: an assessment of water use efficiency in the international food trade

H. Yang¹, L. Wang¹, K. C. Abbaspour¹, and A. J. B. Zehnder²

¹Swiss Federal Institute for Environmental Science and Technology, Ueberlandstrasse 133, 8600 Duebendorf, Switzerland

²Board of Swiss Federal Institute of Technology, ETH Zentrum, 8092 Zurich, Switzerland

Received: 29 November 2005 – Published in Hydrol. Earth Syst. Sci. Discuss.: 2 January 2006

Revised: 23 March 2006 – Accepted: 25 May 2006 – Published: 30 June 2006

Abstract. Amid an increasing water scarcity in many parts of the world, virtual water trade as both a policy instrument and practical means to balance the local, national and global water budget has received much attention in recent years. Building upon the knowledge of virtual water accounting in the literature, this study assesses the efficiency of water use embodied in the international food trade from the perspectives of exporting and importing countries and at the global and country levels. The investigation reveals that the virtual water flows primarily from countries of high crop water productivity to countries of low crop water productivity, generating a global saving in water use. Meanwhile, the total virtual water trade is dominated by green virtual water, which constitutes a low opportunity cost of water use as opposed to blue virtual water. A sensitivity analysis, however, suggests high uncertainties in the virtual water accounting and the estimation of the scale of water saving. The study also raises awareness of the limited effect of water scarcity on the global virtual water trade and the negative implications of the global water saving for the water use efficiency and food security in importing countries and the environment in exporting countries. The analysis shows the complexity in evaluating the efficiency gains in the international virtual water trade. The findings of the study, nevertheless, call for a greater emphasis on rainfed agriculture to improve the global food security and environmental sustainability.

total water withdrawal, food production is directly affected by water scarcity (Cosgrove and Rijsberman, 2000; Rosegrant et al., 2002). In many water scarce countries, an increasing amount of food is being imported to meet the domestic food demand. For these countries, importing food is virtually equivalent to importing water that would otherwise be needed for producing the food locally. Allan (1993) termed the water embodied in food import as “virtual water”. In recent years, the concept of virtual water has been extended to refer to the water that is required for the production of agricultural commodities as well as industrial goods (Hoekstra and Hung, 2003). Nevertheless, discussions on virtual water issues have so far focused primarily on food commodities due to their large share in total water use. With the continuous intensification of water scarcity in many areas of the world, the role of virtual water trade in balancing local water budget is expected to increase (Yang et al., 2003).

Against this background, studies concerning water scarcity, food security and virtual water trade have flourished in recent years. The efforts have greatly enhanced the understanding of water and food challenges and provided useful information for formulating national and international policies to deal with them. In examining the role of virtual water trade in alleviating water stress, a number of studies have estimated the volumes of virtual water embodied in the international food trade (Yang and Zehnder, 2002a; Yang et al., 2003; Hoekstra and Hung, 2003, 2005; Oki and Kanae, 2004; Zimmer and Renault, 2003; Fraiture et al., 2004). The results from these studies vary partly because of the different coverage in geographical scales and the food commodities in the calculation. The variations also reflect the complexity of site specific conditions in different regions and countries.

Building upon the virtual water accounting in the literature, this study attempts to provide an assessment of water use efficiency embodied in the virtual water trade with respect to water saving, opportunity costs of the use of green and blue water, and environmental impacts. The assessment

1 Introduction

With the continuous population growth and related developments, water resources have become increasingly scarce in a growing number of countries and regions in the world. As the largest water user, accounting for over 80% of the global

Correspondence to: H. Yang
(hong.yang@eawag.ch)

is made on two dimensions: the global and country levels, and the exporting and importing countries. With the focus of this study on the water use efficiency, we would, however, like to acknowledge that the virtual water trade issue is more complicated because of the sensitive political and social conditions, which also merit careful analyses.

In the virtual water literature, the amount of water required for producing a unit of crop is termed “virtual water content” in m^3/kg . (Hoekstra and Hung, 2003; Zimmer and Renault, 2003). It is, in essence, the inverse value of crop water productivity measured in kg/m^3 (Molden et al., 1998). Globally, a water saving results when food is exported by countries whose water productivity is higher than the importing countries. Flows in an opposite direction lead to a loss of global water resources. By “water saving” we mean the amount of water that would otherwise be required if the traded food were to be grown locally. As will be discussed later, the significance of water saving may vary from country to country. This study elaborates the implications of the virtual water trade for the water resources utilization in the countries with different water endowments.

Rainwater that falls on a watershed could be partitioned into “green” and “blue” water. The concept of green water was first introduced by Falkenmark (1995) to refer to the return flow of water to the atmosphere as evapotranspiration (ET) which includes a productive part as transpiration (T) and a non-productive part as direct evaporation (E) from the surfaces of soils, lakes, ponds, and from water intercepted by canopies. Later, green water has been generally used to refer to the water stored in the unsaturated soils (Savenije, 2000). Green water is the water source of rainfed agriculture. Blue water refers to the water in rivers, lakes, reservoirs, ponds and aquifers (Rockström et al., 1999). Irrigated agriculture typically uses blue water as a supplement to rainfall. Green water and blue water have different characteristics in many aspects. The opportunity costs of the use of these waters also differ. This study conducts a partitioning to quantify the contribution of blue and green virtual water in the international food trade, and addresses the opportunity costs associated with the trade of the two types of virtual water.

Food exporting countries are the source of virtual water. They are imperative players in the international virtual water trade. However, previous studies of virtual water issues have focused overwhelmingly on food importing countries. Little attention has been paid to food exporting countries concerning their water endowments and resource use efficiency, as well as environmental impacts associated with the virtual water export. In discussions of the application of the virtual water concept, current and future food and water policies of food exporting countries have generally been neglected (Merrett, 2003). With the virtual water trade increasingly being emphasized in the global effort to combat regional water scarcity, the issues relating to exporting countries deserve much more attention.

The subsequent sections of this paper are organized as follows: Sect. 2 introduces the methodologies used for the quantification of virtual water flows and green and blue virtual water partitioning. Section 3 examines the scale of the global water saving, the virtual water flows across regions, and the shares of virtual water import in the countries of different water endowments. A sensitivity analysis of uncertainties in the virtual water accounting at the global level is also provided. Section 4 elaborates different characteristics of green and blue water use corresponding to rainfed and irrigated agriculture, and provides a partitioning of the green and blue virtual water in the international virtual water trade. The discussion in Sect. 5 addresses some important issues related to the assessment of water use efficiency in the virtual water trade. This is followed by concluding remarks in Sect. 6.

2 Methodology and data

2.1 Crop virtual water content and virtual water accounting

“Crop virtual water content” (CVWC) is the basis for examining the quantity of virtual water embodied in the international food trade. In the virtual water literature, models have been applied for estimating CVWC. CROPWAT is one of the most widely used models. The code is developed by the Food and Agricultural Organization of the United Nations (FAO) and is downloadable from the Internet. The climate parameters and crop coefficients required for estimating crop water requirements are available in the FAO databases (FAO, 1986). Applying the CROPWAT model, Hoekstra and Hung (2003, 2005) estimated CVWC for major food crops in different countries. Given the crudeness of the available data and the complexity of cropping systems in different countries, errors are inevitable in the estimation. Nevertheless, improving the estimation requires more accurate data at the country and sub-country levels, which are not currently available for all the countries. For this reason, our study uses the CVWCs estimated by Hoekstra and Hung (2003, 2005) in the calculation of the volumes of virtual water flows.

The “gross volume of virtual water import” (GVWI) to a country is the sum of “crop imports” (CI) multiplied by their associated crop virtual water content (CVWC) in that country:

$$GVWI = \sum_c (CI \times CVWC)_c \quad (1)$$

Similarly, the “gross volume of virtual water export” (GVWE) from a country is the sum of “crop exports” (CE) multiplied by their associated crop virtual water content (CVWC) in that country:

$$GVWE = \sum_c (CE \times CVWC)_c \quad (2)$$

Table 1. Major food crops included in the virtual water accounting.

Commodity groups	Specific commodities
Cereals	Wheat, rice, maize, barley, sorghum, millet, others
Starchy roots	Cassava, potatoes, sweet potatoes, other roots
Sugar crops and sugar	Sugar cane, sugar beat, sugar (raw equivalent)
Oil crops and oil	Soybeans, groundnuts, sunflower seeds, soybean oil, groundnut oil, sunflower seed oil

The “net virtual water trade” of a country (*NVWT*) can be calculated as:

$$NVWT = G VWI - G VWE \tag{3}$$

Equations for estimating the “total global virtual water import” (*TGVWI*) and “total global virtual water export” (*TGVWE*) are expressed as:

$$TGVWI = \sum_{n=1}^N \sum_{c=1}^C G VWI_{n,c} \tag{4}$$

$$TGVWE = \sum_{n=1}^N \sum_{c=1}^C G VWE_{n,c} \tag{5}$$

where *N* is the number of countries, and *C* is the number of crops considered. Water saving/loss generated from the global “total net virtual water trade” (*TNVWT*) can be calculated as:

$$TNVWT = TGVWI - TGVWE \tag{6}$$

2.2 Green and blue virtual water partitioning

In order to specifically estimate the contribution of green and blue water in virtual water trade, a virtual water partitioning is conducted using the following procedure.

Let *R* be defined as the ratio of the yield on irrigated land (*Y_{irr}*) to the yield on rainfed land (*Y_{rf}*):

$$R = \frac{Y_{irr}}{Y_{rf}} \tag{7}$$

Irrigated land also receives green water, except in desert areas. Crop production that is generated from green water on rainfed land and irrigated land can be calculated as:

$$P_{bw} = (Y_{irr} - Y_{rf})A_{irr} \tag{8}$$

$$P_{gw} = Y_{rf} (A_{irr} + A_{rf}) , \tag{9}$$

where *P_{bw}* is the production due to blue water, and *P_{gw}* is the production due to green water. The total production (*P_t*) is therefore the sum of blue water and green water productions:

$$P_t = P_{irr} + P_{rf} = Y_{rf} (RA_{irr} + A_{rf}) \tag{10}$$

The yield on rainfed land can be calculated as:

$$Y_{rf} = \frac{P_t}{RA_{irr} + A_{rf}} \tag{11}$$

Combining Eqs. (7), (8) and (11) calculates the contribution of blue water in the total production as:

$$P_{bw} = \frac{P_t A_{irr} (R - 1)}{RA_{irr} + A_{rf}} \tag{12}$$

2.3 Data

A large variety of food commodities is traded in the international market. It is difficult to include all the commodities in the calculation. In this study, the estimation is based on 20 major food crops (items) shown in Table 1. On world average, these crops account for about 70% of the total calorie intake (FAO, 2004a). The rest of the 30% is made up by animal products (dominated by meats) and other crops, mainly vegetables and fruits. For developing countries, most of which are food importers, the proportion of these 20 food crops in the total calorie intake is higher, around 80% (FAO, 2004a). In this study, we confine the scope to food crops and do not include animal products. This is mainly because of the difficulties in estimating virtual water contents in animal products in individual countries, although it is generally the case that manifold water would be used for producing per calorie dietary energy in meat production as compared to that in food crops. Even for the same kind of meat from the same country, the virtual water contents are highly variable depending on the ways the animals are raised, e.g. under stalled conditions or grazing conditions. Moreover, the water used in processing animal products also varies to a large degree and the data are not available for most of the countries. As acknowledged by Chapagain and Hoekstra (2003): “the data weakness poses a serious constraint to such efforts (determining the virtual water content in livestock and livestock products)”. The exclusion of fruits and vegetables in the discussion is because the virtual water embodied in the trade of these crops is very small in comparison to major food crops (Zimmer and Renault, 2003).

As not all the traded food crops are included, the scale of virtual water trade estimated in this study may be underestimated. Nevertheless, this will not affect the major points to

Table 2. Global virtual water import and export and the scale of water saving, average over 1997–2001.

Crops	Global gross virtual water import (km ³ /year)	Global gross virtual water export (km ³ /year)	Global water saving	
			Volume (km ³ /year)	Ratio of virtual water saving to total virtual water import
Wheat	318.8	188.4	130.3	40.9
Rice	53.5	63.2	−10.1	−18.8
Maize	97.3	39.5	57.4	59.0
Barley	55.1	31.7	20.1	36.4
Soybean	104.9	67.3	37.1	35.3
Others*	351.1	249.2	101.9	29.0
Total	980.7	644.0	336.8	34.3

* Others refer to the rest of the crops listed in Table 1. An average of 15% sugar content is used to convert sugar (raw equivalent) to sugar crop weight equivalent. An average of 30% oil content is used to convert oil to oil crop weight equivalent.

be addressed and the conclusions to be drawn. Also, the volumes of virtual water trade estimated in this study may not be compared directly with the results from other studies due to different coverage of crop commodities in the calculation, and the years of data on which the calculation is based.

In this study, unless otherwise specified, the data concerning food production, inputs, and consumption are from FAO-STAT, the database of FAO (2004a). The data concerning water resources availability and water use in individual countries are from AQUASTA, the database of the Land and Water Development Division of FAO (2004b). The data for the trade of the food commodities with indication of source and destination countries are from the Commodity Trade Statistics Database (COMTRADE) of the United Nations Statistical Division in New York in collaboration with the International Trade Centre in Geneva (UN, 2004).

3 Water saving associated with the international food trade

3.1 Virtual water accounting at the global level

In the global food trade system, the volume of total food export is approximately equal to the volume of total food import to achieve the market clearance. This is especially so when averaged over a period of time as the effect of yearly stock exchange is smoothed out. Concerning the global virtual water trade, however, this equilibrium does not apply. Water used for producing a given amount of food differs across countries. The virtual water “value” of a given amount of food may not be identical for the importing and exporting sides. When virtual water imports and exports for all the countries are summed up separately, a gap between the two volumes occurs. Depending on the sign of the gap, a global water saving or loss associated with virtual water trade can

be determined. Table 2 shows the gross virtual water import and export at the global level estimated with Eqs. (4) and (5). Total volume of virtual water export associated with the food crops considered is about 644 km³/year. The corresponding volume for import is 981 km³/year. The difference is 337 km³/year. This volume is the global water saving resulting from the food trade. In other words, this amount of additional water would otherwise be required if the imported amount of food were produced in the importing countries.

For individual crops, the scale of water saving varies. For wheat and maize, the trade has resulted in a 41% and 59% reduction in the global water use in producing the traded amounts of the respective crops. The trading of these two crops contributes greatly to the total global water saving. An exception, however, is rice where the volume of virtual water embodied in rice export is larger than that in rice import. This implies that the rice production in the exporting countries requires more water than the production in the importing countries. This may partly be explained by the relatively high crop evapotranspiration in the major rice exporting countries, such as Vietnam and Thailand (FAO, 1986).

The water saving achieved at the global level reflects a relatively high water productivity in the major exporting countries. The estimation by Hoekstra and Hung (2003, 2005) shows that the water productivity of wheat is mostly over 1 kg/m³ in the major exporting countries in North America and Western Europe in comparison to below 0.6 kg/m³ in many countries in Africa and Central Asia. For maize, the water productivity is over 1.5 kg/m³ in the USA, Australia, and the EU countries. In contrast, the figure in most countries in Africa and Central Asia is below 0.9 kg/m³. It is noticed that the low water productivities are mainly seen in poor countries. This situation is expected because the level of water productivity is closely related to the material inputs, agronomic practices and water management at both regional and farm-level. Efforts to raise water productivity are often

Table 3. Uncertainties in the virtual water accounting.

Virtual water content adjustment	Countries concerned	Export virtual water (km ³ /year)	Import virtual water (km ³ /year)	Water saving (km ³ /year)
80%	both sides**	515.3	784.8	269.5
90%	both sides	576.7	882.9	303.2
95%	both sides	611.9	932.0	320.1
Baseline*, 100%	both sides	644.1	980.7	336.6
105%	both sides	656.2	1030.1	373.8
110%	both sides	687.5	1078.4	391.0
120%	both sides	750.0	1177.2	427.3
105%	importing side	644.1	1030.1	386.0
110%	importing side	644.1	1078.4	434.3
120%	importing side	644.1	1177.2	533.1

* The baseline estimates are from Table 2. ** Importing and exporting countries.

associated with greater material inputs and improved agromonic practices and water management, which are generally lacking in poor countries.

3.2 Uncertainties in the virtual water accounting

The estimated volumes of virtual water trade are highly sensitive to the values of *CVWC* (or crop water productivity) used in the estimation. The uncertainties in the virtual water accounting have been noted by some scholars, for example, Fraiture et al. (2004) and Hoekstra and Hung (2003, 2005). However, so far, there is no attempt in the virtual water literature to quantitatively analyze the uncertainties. The complexity of the factors involved and the lack of data for individual countries have been the major constraints to such an attempt. In this study, an initial effort is made to address the uncertainties by specifying the extent to which the estimated volumes of virtual water import and export and the scale of water saving can be affected by changes in *CVWC*.

In the study by Hoekstra and Hung (2003, 2005), *CVWC* was calculated by dividing the theoretical value of crop water requirement with the actual yield. It assumes that the evaporative demand of a crop is fully met, which is not the case in many circumstances. As they pointed out, this assumption could overestimate the *CVWC*, and thus underestimate the water productivity of a crop. However, they did not provide any sensitivity analysis of the uncertainties in their estimation of virtual water content of different crops.

On the other hand, the estimation of crop virtual water contents by Hoekstra and Hung (2003, 2005) did not take into account the losses of water during the irrigation. In reality, much more water is supplied to the irrigated field than that required for crop evapotranspiration. In most develop-

ing countries the amount of water supplied to irrigated field is typically 2–3 times that of actual irrigation requirement by crops (FAO, 2004b). Over 50–80% of the water supplied is lost through evaporation from soil surface and during the conveyance, leakage during storage and transport to the fields, runoff and uncontrolled drainage (Postel, 1999; Qadir et al., 2003). At the basin level, although part of the losses on specific irrigation sites can recharge the aquifers or can be used by downstream users and ecosystems, the real losses are nevertheless significant. Some studies have suggested that the losses to non-beneficial evapotranspiration at the river basin level are between 10–20% of the total supply (Seckler et al., 1998; Molden and Bos, 2005). This means that the real water productivity could be lower than that estimated with the crop model. The discount would be larger in developing countries where the non-beneficial losses are generally greater (FAO, 2004b).

A precise quantification of the uncertainties in *CVWC* caused by the above factors is both highly complicated and is constrained by the lack of data. For example, the information on the degree of water deficit in fulfilling the evaporative demand is generally not available at the country level. Meanwhile, the extent of water losses in irrigation varies significantly across countries and among different crops. The sensitivity analysis in this study, therefore, examines the uncertainties in the estimation of virtual water import and export and the scale of water saving based on a given set of percentage adjustments to *CVWC*. In accounting for the effect of the unsatisfied evaporative demand, a downward adjustment of virtual water contents by 5%, 10% and 20%, respectively, is made for all the crops and in all the countries concerned. In accounting for the effect of water losses in irrigation, an upward adjustment of virtual water contents by 5%, 10% and

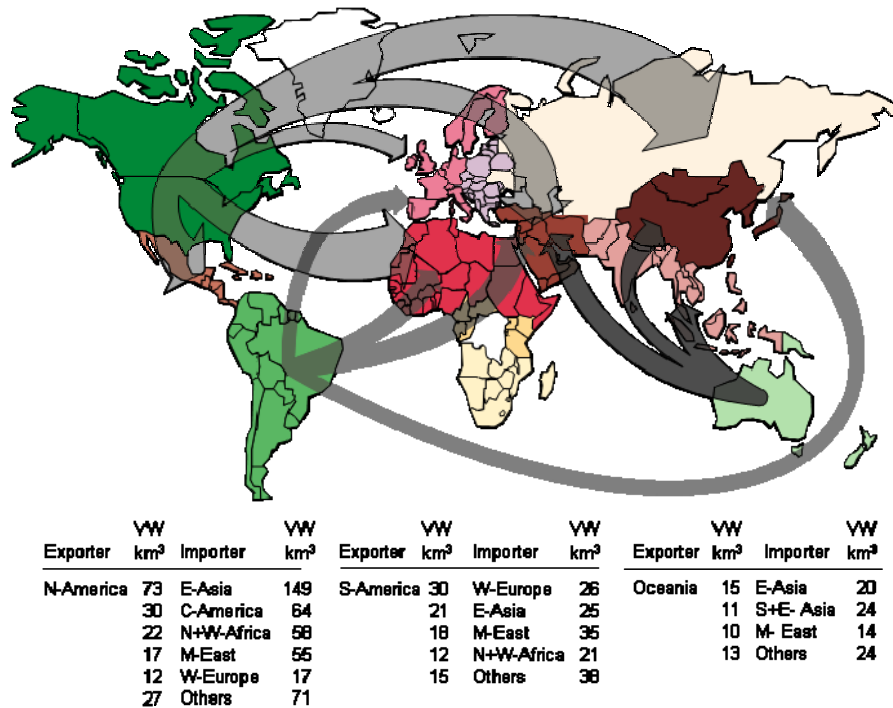


Fig. 1. Virtual Water Flows by Regions, average over 1997–2001.

20%, respectively, is made for all the crops considered. Two situations are accounted, adjustment on both the exporting and importing sides, and adjustment on the importing countries only. The latter is based on the consideration that irrigated area accounts for a small share of the total crop area in the major exporting countries, as to be addressed in detail in Sect. 4. Meanwhile, it is generally the case that poor countries, many of whom are food importing countries, have larger water losses in irrigation than that in the major food exporting developed countries (FAO, 2004b).

The uncertainties in the virtual water accounting are calculated for the proposed adjustments on *CVWC*. The results are shown in Table 3. The figures above the baseline estimates are the results of the downward adjustment of *CVWC*. It can be seen that the volumes of virtual water export and import decrease with the extent of the downward adjustment of *CVWC*. However, the degree of the decrease is greater on the importing side than the exporting side, resulting in a reduced scale of water saving in the global food trade in comparison to the baseline estimation. The larger degree of the decrease in the importing side is due to the generally higher *CVWC* in many importing countries than in the major exporting countries. A same percentage decrease in *CVWC* leads to a larger absolute reduction in the values on the importing side than on the exporting side.

The figures below the baseline estimates are the results of the upward adjustment of *CVWC*. The volumes of virtual water export and import and water saving increase with the ex-

tent of the upward adjustment of *CVWC*. The scale of the water saving is greater when the adjustment is made on the importing side only.

It should be pointed out that the above sensitivity analysis of uncertainties is rather rudimentary. The figures in Table 3 should be viewed as approximations. Nevertheless, the results show clearly the trend and the extent of the changes in the volumes of virtual water import and export and the scale of water saving with the up and downward adjustment of *CVWC*.

3.3 Global virtual water flows across regions

As water productivity is generally lower in importing countries than in exporting countries, a given amount of food commodities is worth more virtual water in the former than in the latter. This leads to an amplification of virtual water flows from source to destination. Figure 1 illustrates the amplification visually. The net virtual water flows are viewed from the exporting and importing sides, respectively, for the 14 regions of the world. The net volume of virtual water export is the net export quantities multiplied by *CVWC* in the corresponding exporting countries. The net volume of virtual water import is the net import quantities multiplied by *CVWC* in the corresponding importing countries. The two volumes represent the virtual water “values” of a given amount of food commodity measured at source and destination. Each individual country’s net virtual water export/import at source

Table 4. Net virtual water imports by country groups, average of 1997–2001.

	Total	Countries with water availability below 1700 m ³ /capita	Countries with water availability between 1700 and 2500 m ³ /capita	Countries with water availability larger than 2500 m ³ /capita
Total net virtual water import (km ³ /year)*	715.5	145.8	82.1	487.1
Percentage of total net virtual water import	100	20.4	11.5	68.1
Large importing countries		Egypt, Cyprus, Kuwait, Singapore, Poland, Syria, Lebanon, Kenya, South Africa, Jordan, United Arab Emirates, Libya, Tunisia, Yemen, Israel, Morocco, Saudi Arabia, Algeria, South Korea, Kenya, Oman...	Iran, Poland, Germany, China, Uzbekistan, Sudan, Ethiopia, Belgium, Eritrea, Somalia, Mauritius, Haiti,...	Japan, Spain, Italy, Portugal, Netherlands, Switzerland, Norway, New Zealand, Ireland, Austria, Russia, Slovenia, Sri Lanka, Indonesia, Malaysia, Mexico, Chile Colombia, Bangladesh, Peru, Venezuela, Nigeria, Senegal, Turkey, , Costa Rica, Belarus, Iraq, El Salvador, Azerbaijan, Philippines, Tanzania, North Korea, Togo, Estonia, Honduras...

* Calculated using Eq. (3) and summed for all net importing countries. As only the net importing countries are included in Table 4, the virtual water figures here may not be compared directly with those in Table 2.

and destination is calculated first. All the countries are then grouped into 14 regions for visual clarity.

North America, South America and Oceania are the net exporting regions of virtual water. All other regions are net importers. East Asia, Central America, North and West Africa and the Middle East are the major destinations of virtual water. It can be seen that the volumes of virtual water differ a great deal on the exporting and importing sides. For example, the 73 km³ of virtual water exported from North America is worth 149 km³ of virtual water in East Asia. In the Middle East, the corresponding volumes are 17 km³ and 55 km³, respectively. One exception is the virtual water export from South America to Western Europe. The virtual water exported from South America is worth less in Western Europe because of the lower water productivity in the former region than in the latter.

3.4 Water “saving” viewed from the country perspective

While water constraint has been at the center of the investigation of water-food-trade relations, it has been widely recognized that not all countries import food because of water scarcity (Yang et al., 2003; Fraiture et al., 2004; Oki and

Kanae, 2004). Japan is a good example in point. The country imports 75% of the cereals consumed (FAO, 2004a). This import, however, has no connection with its water resources, which stood at 3380 m³/capita in 2000. It is more the scarcity of land resources that shapes the country’s food import policies (Oki and Kanae, 2004).

To examine the significance of water saving in the countries with different water endowments, all the net virtual water importing countries are divided into three groups. The water threshold of 1700 m³/capita defined by Falkenmark and Withstand (1992) is used as a scarcity indicator. A minimum of 2500 m³/capita is set for non-water scarce countries. This is based on the observation that above this level, a country is very unlikely to endure a nationwide physical water resources scarcity, though some regions may have water stress. The countries with water resources availability between 1700 m³/capita and 2500 m³/capita are at the margin, which may or may not endure a widespread water scarcity. Table 4 shows the shares of the three country groups in total net virtual water import.

The total net virtual water import of all net importing countries is around 715 km³ annually. Of this volume, about 20.4% occurs in the countries with water resources below

Table 5. Characteristics of blue and green water.

Type of water	Blue	Green
Sources	rivers, lakes, reservoirs, ponds, aquifers	water that is stored in the unsaturated soil and can be used for evapotranspiration
Mobility	highly mobile	highly immobile
Substitution of sources	possible	impossible
Competitive uses	many	few
Conveyance facilities	required	not required
Cost of use	high	low

1700 m³/year, 11.5% is in the countries with water resources between 1700 m³/year and 2500 m³/year. The rest of 68.1% is in the non-water scarce countries. From these figures, one can conclude with a confidence that water scarcity has a relatively limited role in shaping the global virtual water trade flows.

By importing food, water scarce countries reduce the domestic water demand (or water use) for food production. This reduced amount may be viewed as a “saving” of domestic water. The limited domestic water resources can be used for the activities with higher values of water use. For these countries, the virtual water import plays an important role in balancing the water budget and alleviating water stress.

However, a bulk of the net virtual water import occurs in non-water scarce countries. The reasons for the import can be many, but is very unlikely that of water resources constraints. For developed countries, such as Japan, Switzerland, Italy, etc., pursuing comparative advantages would have been an important drive for food import (Fraiture et al., 2004; Würtenberger, 2006). Water saving *per se* would be of little benefit to them. For many poor countries in this group, agriculture is an important economic sector and a large proportion of the population relies on farming for living (Rosegrant et al., 2002). The water “saving” from importing food could actually have negative effects on these countries in utilizing their own water resources and in improving the food security. This point will be elaborated in more detail in Sect. 5.

4 “Green” vs. “blue” water in agricultural production and virtual water trade

4.1 Efficiency of green and blue water use from the viewpoint of opportunity costs

The opportunity cost of water is its value in other uses, such as in municipal, industrial, or recreational activities and ecosystems. Green and blue water have different characteristics, which are reflected in the opportunity cost of the use of these resources. Table 5 summarized some of the features of green and blue water that are pertinent to opportunity cost.

Green water comes from rainfall. Such water is a “free good” in terms of supply. Plants other than food crop (which often have lower direct economic value of water use) are the major competitive users of this water (Yang and Zehnder, 2002).

In contrast, blue water has many functions. Irrigation often yields the lowest economic value among all other functions (Zehnder et al., 2003). The opportunity cost of irrigation water is high. Meanwhile, blue water requires facilities for storage and distribution before it can be delivered to users, and the supply of water involves cost. Moreover, excessive irrigation can cause severe salinization, water logging and soil degradation, which are evident in many areas of the world (Postel, 1999). From the viewpoint of opportunity cost of the use of water resources, trading green virtual water is overall more efficient than trading blue virtual water, holding other factors constant.

The ratio of irrigated areas to total crop areas indicates the dependence of a country’s agricultural production on blue water. Figure 2 shows that in major food exporting countries, especially the USA, Canada, France, Australia and Argentina, the irrigation ratio is low. This situation indicates that food production in these countries is dominantly rainfed. A further inference is that food exporting countries generally

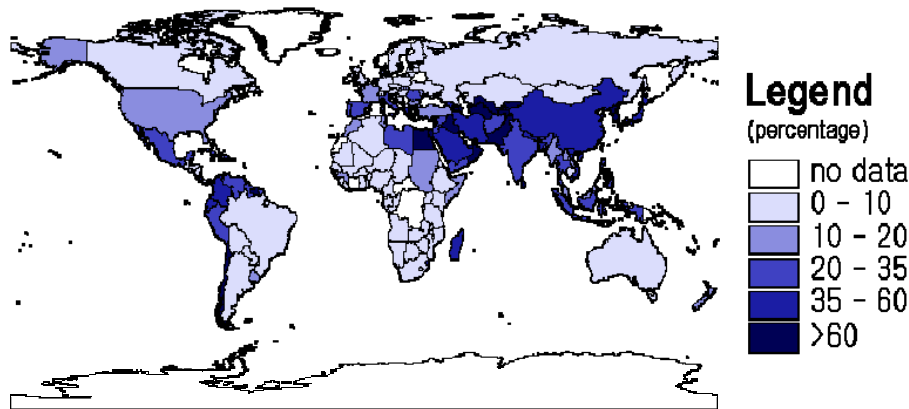


Fig. 2. Ratio of irrigated areas to total cultivated areas, average over 1997–2001.

export their green virtual water. In food importing countries, irrigation ratio varies widely. It is noted that many water scarce food importing countries have a high dependence on blue water for agricultural production (see Table 4 for the water scarce countries). This is not surprising given the close links between low precipitation, need for irrigation and the demand for virtual water import. For water scarce countries, the opportunity cost of irrigation is high. However, the high opportunity cost is often taken as a trade-off for easing other more pressing concerns, typically food security, rural employment and political stability (Wichelns, 2001). It is also noticed that in many poor countries, the irrigation ratio is low irrespective of their water resources. This situation is no doubt partly related to the lack of financial ability in these countries to bring blue water into irrigation.

4.2 Contribution of blue and green virtual water in the global food trade

The contribution of green and blue virtual water in the global food trade can be estimated with Eqs. (10) and (12). In order to estimate P_{bw} , quantities R , A_{irr} and A_{rf} for each country need to be defined. As R is not available for most of the countries, an average crop yield ratio of 1.5 suggested by the United States 1998 agricultural census (USDA, 2003) is used for all the net food exporting countries. The use of this ratio is reasonable because the major net food exporting countries are mostly located in the temperate climate zones where irrigation is often supplementary rather than essential. Meanwhile, an average percentage of irrigated areas in the exporting countries is used for all the crops considered. In reality, the percentage of irrigated areas for cereal crops, except for rice, is usually lower than that for vegetables and fruits. Using the average percentage of irrigated areas in the partitioning tends to overestimate the contribution of blue water in the virtual water trade.

Figure 3 shows the result of the virtual water partitioning for the seven largest food exporting countries. These

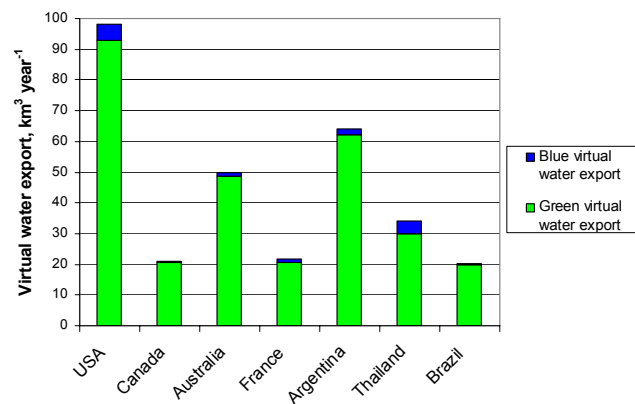


Fig. 3. Net blue and green virtual water export in major exporting countries, average over 1997–2001.

countries account for about 80% of the total net virtual water export. It can be seen that the proportion of the blue virtual water export in these countries is considerably small. In Canada, it is negligible. The result shows clearly that the virtual water export is overwhelmingly “green”. For major exporting countries, exporting green water constitutes a low opportunity cost in water use as opposed to irrigated food production, holding other factors constant.

It should be noted that green and blue waters are not completely independent in the hydrological cycle. For example, changes in land use can affect the green and blue water partitioning in a watershed (Rockström, et al., 1999). Also, there are “grey areas”, such as water harvesting, where deliberate local interventions are made to capture local runoff. The separation of green and blue water resources in this study is mainly for illustrating the opportunity cost of the water use in irrigated and rainfed production and the virtual water trade associated with the different water uses.

5 A discussion on the economic and environmental impacts of water “saving” in international food trade

The previous sections examined the efficiency gains of global virtual water trade with respect to water savings as well as the opportunity cost of green and blue water use. In this section, two questions relating to the assessment of efficiency gains are raised to draw attention to the complexity of the issue and the needs for a broader view in the assessment. These questions are: 1) What are the effects of virtual water trade on the water use efficiency in importing countries? 2) What are the environmental impacts of virtual water trade on the food exporting countries?

5.1 Effects of the virtual water import on the water use efficiency in importing countries

Virtual water import effectively reduces the water use for food production in food importing countries. For the countries where water resources are scarce, virtual water import helps alleviate water stress. For many of them, it is often cheaper and less ecologically destructive to import food, especially the water intensive cereal crops, than to transport water to produce the same commodity locally. This strategy has been particularly efficient when the world prices of food commodities are lower than the cost of production in the food importing countries (Wichelns, 2001; Qadir et al., 2003). Over the last 30 years, the world prices for major cereal crops have declined by about 50% (Yang et al., 2003). Water deficit countries have been able to access the virtual water at advantageous prices. However, it has been projected that in the coming years the decline in food price will be at a slower rate (Rosegrant et al., 2002), posing a disincentive to food import.

As shown in Table 3, however, much of the virtual water import is in fact to non-water scarce countries. Many of them are poor. Increasing food production by better agronomic practices and water management, including bringing water resources into use, is one of the important ways to improve the rural income and livelihood (Rockström et al., 1999; Rosegrant et al., 2002). The influx of food to these countries often undermines this effort as farmers cannot compete with the cheap and often subsidized food surpluses from the major exporting countries. The food dumping to poor countries depresses local prices and reduces domestic production (Rosegrant et al., 2002). Poor and small farmers are hit the most. In this case, virtual water import could be detrimental to food security in these countries. It has been well-known that agricultural trade is one of the central issues debated at WTO meetings. Poorer countries are strongly against the current rules relating to agricultural trade, especially the European and U.S. subsidies on their own agriculture and the lack of access to those markets (Shaffer and Brenner, 2004). A reduction in the import of cheap food could raise local prices and the production in poor countries, improving the utiliza-

tion of local water resources. This would lead to a lower level of virtual water trading, and consequently smaller global water saving. The reduced water saving should be viewed as an overall improvement in the efficiency of the use of global water resources. For this reason, “water saving” *per se* can not be used to make any judgment on the benefits and costs of global virtual water trade.

5.2 The environmental impacts of the virtual water trade on the exporting countries

As elaborated previously, the water saving in the international food trade is achieved from the relatively high water productivity in major food exporting countries in comparison to many food importing countries. A question that should be asked, however, is the sources of the high water productivity in the major exporting countries. It is well-known that these countries generally have high inputs, including fertilizers and pesticides, in food production. In the USA, for example, the average fertilizer application is 140 kg/ha compared to the average of around 100 kg/ha in the developing countries (FAO, 2004a). In many exporting countries, the excessive application of fertilizers and pesticides is rapidly becoming a major environmental hazard (Zehnder et al., 2003; Davis and Koop, 2006). What is not clear is how much of the high crop water productivity in the major exporting countries is due to better management and efficient use of water resources. Before this can be specified explicitly, it is difficult to judge whether the water saving in the international water trade is indeed a result, or at least part of the result, of more efficient use of water resources in the exporting countries, or mainly a result of higher levels of inputs. If the latter is the case, it would be more efficient for the poor and water abundant importing countries to improve the production by increasing agricultural inputs. This would lead to an improvement in water productivity in the poor countries. The volume of global water saving would decrease due to both a smaller amount of import and a narrowed gap of water productivity between importers and exporters.

Although food production, especially cereal production, in the major exporting countries is dominated by rainfed agriculture, irrigation has seen a significant increase in some food exporting countries. In France, Australia and Brazil, for example, the increase between the early 1980s and the late 1990s was over 50%. In the United States, the rate is over 11% (FAO, 2004a). Overexploitation of water resources has occurred in many regions of these countries. In the central and western United States, for example, many rivers and aquifers have been over-exploited causing serious regional water resources depletion and environmental degradation (Postel, 1996; Gleick, 2003). It is estimated that under the business-as-usual scenario, about 17% increase in irrigation water supply would be needed worldwide to meet the demand for food in the coming 25 years (Rijsberman, 2002). Although most of the increase would be in food importing

countries, an expansion in irrigated areas in food exporting countries could also be expected as a result of the increasing demand for their virtual water. This could aggravate the regional resource depletion and environmental degradation in food exporting countries on the one hand and increase the opportunity costs of the virtual water trade on the other.

The above analysis suggests a complexity in assessing the water use efficiency in the virtual water trade when the perspective is extended to non-water scarce countries and to the exporting countries. The assessment of the effects of water saving is not as simple as computing the water required for production in one location and comparing this with the water required in another location. It involves many interwoven issues concerning gains and losses of the efficiency for all the parties involved. As demonstrated in this study, the scales and perspectives can have significant influence on the results obtained. For this reason, a sub-country level assessment would also be necessary, but is beyond the scope of this study. Much more research is needed to address the trade-offs between gains and losses in the global virtual water trade before the assessment of water use efficiency can be useful for supporting policy making.

6 Concluding remarks

This study attempted to provide a critical assessment of the water use efficiency embodied in the international virtual water trade. The characteristics of green and blue water and their contributions in the global virtual water trade are elaborated.

The examination showed that a global water saving results from international food trade due to the generally high crop water productivity in the food exporting countries compared with the food importing countries. The contribution from the trading of wheat and maize to the global water saving is particularly large. However, there are high uncertainties in the estimated volumes of virtual water trade and the scale of water saving due to the uncertainties in *CVWC* used in the estimation.

The study revealed that the significance of water saving is limited when viewed at the country level because most of the net virtual water importers have abundant water resources. It also raised the awareness of the negative impacts of the cheap and often subsidized food from the major exporting countries to the local food prices and food production in the importing countries, especially the poor ones.

Major food exporting countries overall have a low irrigation intensity. The proportion of food production from irrigated areas is considerably small. The global virtual water trade is dominated by green water. Such a trade is efficient in terms of the opportunity cost of water use. However, the high water productivity in the major exporting countries is partly due to the high inputs of chemical fertilizers and pesticides. The environmental impacts have been high.

It should be pointed out that the current global food trade is primarily among the countries above the low-income level in the World Bank country classification. The low income countries have a much lower participation in the global food trade. Among many reasons, the low income and consequently the low ability to exploit natural resources and invest in agriculture are largely responsible. The lack of financial resources also deprives the poor countries of the choice to purchase food from the international market when the domestic food supply is in shortage. Therefore, one should be cautious to expect miracles from the international food trade in addressing the food security problems in poor countries. From the viewpoint of efficient use of global and local water resources and considering the lack of financial ability in poor countries to develop irrigated agriculture, greater efforts, particularly agricultural technologies and investment, should be devoted to the development of rainfed agriculture. Given the increasing pressure on the global blue water resources, more effectively utilizing green water may have to be a direction which the world agriculture will pursue in the future.

Acknowledgements. The authors wish to sincerely thank A. Hoekstra and two other anonymous reviewers of the manuscript and also the journal editor, K. Bishop, for their constructive review of the manuscript and their many thoughtful suggestions for improving the paper.

Edited by: K. Bishop

References

- Allan, J. A.: Fortunately there are substitutes for water otherwise our hydro-political futures would be impossible, ODA, Priorities for water resources allocation and management, ODA, London, 13–26, 1993.
- Cosgrove W. J. and Rijsberman F. R.: Making Water Every body's Business, Earthscan Publications Ltd, London, 2000.
- Chapagain, A. K. and Hoekstra, A. Y.: Virtual water trade: A quantification of virtual water flows between nations in relation to international trade of livestock and livestock products, Virtual water trade, in: Proceedings of the international expert meeting on virtual water trade, Delft, The Netherlands, edited by: Hoekstra A. Y., Res. Rep. Ser. No. 12, 2003.
- Davis, J. R. and Koop, K.: Eutrophication in Australian rivers, reservoirs and estuaries – a southern hemisphere perspective on the science and its implications, *Hydrobiologica*, 559, 23–76, 2006.
- Falkenmark, M. and Widstrand, C.: Population and water resources: a delicate balance, *Population Bull.*, 47, 3, 1992.
- Falkenmark, M.: Land-water linkages – A synopsis, Land and Water Integration and river Basin Management, FAO Land and Water Bulletin, No. 1, 15–16, FAO, Rome, Italy, 1995.
- FAO: Crop Water Requirements, Irrigation and Drainage Papers No. 24, FAO, Rome, 1986.
- FAO: FAOSTAT, the Database of the Food and Agricultural Organization of the UN, 2004a.

- FAO: AQUASTAT, the Database of Land and Water Division of FAO, 2004b, <http://www.fao.org/ag/agl/aglw/aquastat/main/index.stm>.
- Fraiture, C., Cai, X., Amarasinghe, U., Rosegrant, M., and Molden, D.: Does International Cereal Trade Save Water? The Impact of Virtual Water Trade on Global Water Use, Comprehensive Assessment Research Report 4, International Water Manage. Institute, Colombo, 2004.
- Gleick, P.: Soft path's solution to 21st-century water needs, *Science*, 320, 1524–1528, 2003.
- Hoekstra, A. Y. and Hung, P. Q.: Virtual water trade: a quantification of virtual water flows between nations in relation to international crop trade, in: Virtual water trade, in: Proceedings of the international expert meeting on virtual water trade, Delft, The Netherlands, edited by: Hoekstra A. Y., Res. Rep. Ser. No. 12, 2003.
- Hoekstra, A. Y. and Hung, P. Q.: Globalization of water resources: International virtual water flows between nations in relation to international crop trade, *Global Environmental Change*, 15, 45–56, 2005.
- Merrett, S.: Virtual water – A discussion – Virtual water and Occam's razor, *Water International*, 28, 103–105, 2003.
- Molden, D., Sakhivadivel, R., Perry, C.J., de Fraiture, C., and Kloezen, W. H.: Indicators for comparing performance of irrigated agricultural systems, Research Report 20, International Water Management Institute, Colombo, Sri Lanka, 1998.
- Molden, D. and Bos, M. G.: Improving basin water use in linked agricultural, ecological and urban systems: seeking new flow paths and avoiding dead ends, *Water Sci. Technol.*, 51, 147–154, 2005.
- Oki, T. and Kanae, S.: Virtual water trade and world water resources, *Water Sci. Technol.*, 49, 203–209, 2004.
- Postel, S.: *Dividing the Waters: Food Security, Ecosystem Health, and the New Politics of Scarcity*, World Watch Institute, Washington, DC, USA, 1996.
- Postel, S.: *Pillar of Sand: Can the Irrigation Miracle Last?*, Norton, New York, 1999.
- Qadir, M., Boers, T. M., Schubert, S., Ghafoor, A., and Murtaza, G.: Agricultural water management in water-starved countries: challenges and opportunities, *Agric. Water Manage.*, 62, 165–185, 2003.
- Rijsberman, F.: Troubled water, water troubles: overcoming an important constraint to food security, In: *Sustainable food security for all by 2020*, Proceedings of an International Conference, 4–6 Sept., Bonn, Germany, 2002, <http://www.ifpri.org/pubs/books/2020conpro.htm>.
- Rockström, J., Gordon, L., Falkenmark, M., Folke, C., and Engvall, M.: Linkages among water vapor flows, food production and terrestrial ecosystems services, *Conservation Ecology*, 3, 1–28, 1999, www.consecol.org/vol3/iss2/art5.
- Rosegrant, M., Cai, X., and Cline, S.: *World water and food to 2025*, International Food Policy Research Institute (IFPRI), Washington D. C., 2002.
- Seckler, D., Amarasinghe, U., Molden, D., Rhadika, de S., and Barker, R.: *World water demand and supply, 1990 to 2025: Scenarios and issue*, Res. Rep. No. 19, 1998.
- Savenije, H.: Water scarcity indicators: the deception of the numbers, *Phys. Chem. Earth (B)*, 25, 199–204, 2000.
- Shaffer, E. R. and Brenner, J. E.: International trade agreements: hazards to health?, *Int. J. Health Services*, 34, 467–481, 2004.
- United Nations Statistic Division (UN): *Commodity trade statistics data base (COMTRADE)*, CD-Rom, 2004.
- United States Agricultural Department (USDA): *Census of Agriculture, 2003*, www.nass.usda.gov/census.
- Wichelns, D.: The role of “virtual water” in efforts to achieve food security and other national goals, with an example from Egypt, *Agric. Water Manage.*, 49, 131–151, 2001.
- Würtenberger, L., Koellner, T., and Binder, C.: Virtual land use and agricultural trade: estimating environmental and social-economic impacts, *Ecol. Econ.*, 57, 679–697, 2006.
- Yang, H., Reichert, P., Abbaspour, K. C., and Zehnder, A. J. B.: A water resources threshold and its implications for food security, *Environ. Sci. Technol.*, 37, 3048–3054, 2003.
- Yang, H. and Zehnder, A. J. B.: Water scarcity and food import – a case study for southern Mediterranean countries, *World Development*, 30, 1413–1430, 2002a.
- Yang, H. and Zehnder, A. J. B.: Water endowments and virtual water trade, *Gaia*, No. 4, 267–270, 2002b.
- Zehnder, A. J. B., Yang, H., and Schertenleib, R.: Water issues: the need for actions at different levels, *Aquatic Sciences*, 65, 1–20, 2003.
- Zimmer, D. and Renault, D.: Virtual water in food production and global trade: review of methodological issues and preliminary results, in: *Virtual water trade*, Proceedings of the international expert meeting on virtual water trade, Delft, The Netherlands, edited by: Hoekstra A. Y., Res. Rep. Ser. No. 12, 2003.