VALUE OF VIRTUAL WATER IN FOOD: PRINCIPLES AND VIRTUES

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Abstract

The value of virtual water of a food product is the amount of water per unit of food that is or that would be consumed during its production process. Five principles for assessing the value of virtual water are proposed. The first one considers common standard values per food product; which is appropriate for global studies on trade. The second one considers the marginal water requirements for an alternative production close to the consumption site. The third one introduces the nutritional equivalence between food products. The fourth one focuses on the substitution (or reallocation) to transform virtual water imports into real water savings. The fifth underlines the need for historical studies to account for gain of productivity and deflated values of virtual water.

Application of these principles illustrates some important features of virtual water. Virtual water trade is shared evenly between energetic product, fat products and protein products. Virtual water trade not only generates water savings for importing countries, but also global real water savings due to the differential in water productivity. Food storage also generates real water savings in time. The value of virtual water in sea products is globally significant, accounting for 8 percent of the total. Impacts of diet changes on water requirements for food are significant but the gain in water productivity in food production is more influent. Assuming that the gain in water productivity reaches 50 percent of yield growth, we estimate that in Europe 15, water requirements for food per capita and per day have decline in real value from 5 400 litres in 1961 down to 3 600 litres in 2000. This conservative assumption on water productivity shows that at least 1 800 litres per day per capita has been saved since 1961, thanks to the agricultural productivity.

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Introduction

By definition virtual water is the water embedded in a product, i.e. the water consumed during its process of production. This concept emerged in the 1990s and receives more and more attention from people concerned with water management and in particular with water related to food production. Increasing intersectoral competition for water, the need to feed an ever growing population and increased water scarcity in many regions of the world, are some important reasons to look at the way water is managed on our planet, and on how human needs are considered. The water requirements for food are by far the highest: it takes 2 to 4 litres per day to satisfy the biological needs (drinking water) of a human being and about 1000 times as much to produce the food. This is why the concept of virtual water is so important when discussing food production and consumption. In simple words, a country that imports 1 million ton of wheat is importing, and therefore enlarging its water resource by, 1 billion m^3 of water.

The importance of virtual water at global level is likely to dramatically increase as projections show that food trade will increase rapidly: doubling for cereals and tripling for meat between 1993 and 2020 (Rosegrant and Ringler, 1999). Therefore the transfer of virtual water embedded in the food that is traded is becoming an important component of water management on global as well as regional level, particularly in the regions where water is scarce.

One of the fundamentals of management is the ability to measure or evaluate fluxes and volumes of the considered good, and virtual water is no exception. Its value is generally expressed per volume (m^3) which results from multiplying the quantity of product (kg) by the unit value per product, expressed as volume of water per kg of product (m^3/kg). As we do for real water, we have to have a common understanding of the values of virtual water. We have to have standardized measurement tools and methodologies to assess these values.

Still at its infant stage, virtual water has had its pros and cons, its virtual supporters and its real sceptics and vice versa. The question of its utility, and of the domains it should focus upon, are still to be answered, although preliminary studies show that improving information on virtual water is likely to put pertinent lights on the water management debate. Another important point related to production and trade, is the fact that "water" is not the only facet of the decision process. The issue of comparative advantage which is central here implies considering land, jobs, rural development, access to markets (Wichelns, 2001). It is clear that looking at water in food trade is not enough but at least, it should be well understood, and this is one purpose of current works on virtual water.

This paper aims to specifically investigate the issue of the **value of virtual water**. How can Virtual Water Value (VWV) be defined and practically assessed? This will be done by considering two points of view:

1. The global point of view on food production, trade and consumption.

2. The point of view of a decision maker in position to decide on food import/export, agricultural policy and natural resources management.

The paper focuses on concepts and principles in assessing the value of virtual water, and on some virtues of virtual water.

Part I
Visions and issues on virtual water

THE SUPPLY DRIVEN VISION: VIRTUAL WATER IN FOOD PRODUCTION AND TRADE

The general and common concept of virtual water is applied for expressing various visions or perspectives on virtual water:

- **The strategic vision for food security:** a country uses the international markets for part of its food supply in order to relieve the pressure on natural resources and in particular on water, that otherwise a self-sufficiency policy would create. This is especially important for low endowed countries, and this explains also why the first studies on virtual water have focussed on arid countries in the Middle East (Allan J. A.; 1999 - Wichelns D. 2001).
- **The liberal vision**: virtual water through food imports is seen as a means to open the national water market and in ensuring that water will be channelled to its more profitable use (Allan J. A.; 1999 - WWC 1998).
- **The ecological vision**: virtual water is meant to help implementing a softer approach of natural resources management, and redirect production to areas where the natural conditions are best to match efficiency as well as sustainability (Turton A.R., 2000).
- **The solidarity vision:** it recognizes that decisions about agricultural production in areas producing surplus of food, may have real impacts on the pressure exercised on water resources in poorly endowed countries and areas. This solidarity vision makes sense in particular at regional level as illustrated by some of the solutions contemplated for solving current food crisis in the SADC region (Meissner R. 2003).

These four previous visions are all based on **the quest for optimal production sites** (comparative advantage) to satisfy food needs with the minimum pressure on the environment. They are basically **supply driven visions** which focus on **fluxes of food and virtual water** from production sites to consumption areas. This vision for water flows is very well portrayed through the idea that a second virtual Nile river is flowing towards the Middle East and North Africa (MENA) region through food imports (Allan, J.A., 1998).

THE DEMAND DRIVEN VISION: VIRTUAL WATER IN FOOD CONSUMPTION

Another vision on virtual water brought by Renault & Wallender (1999) is more demand driven: **the consumption vision**. This vision considers that the amount of water required for food production is not only driven by population but also by food habits (diets) and therefore the debate on “water for food” should be also placed at consumption level. For instance a survival diet would require 1 m^3 of water per day and per capita whereas a diet mostly made with animal product needs some 10 m^3 per day and capita. More common diets are ranking from about 2.5 m^3/capita/day for low animal product intake, e.g. in North Africa, to 5 m^3/capita/day for high animal product intake such as in Europe or in the United States of America.

It can be shown that changes in food habits can have a real impact on water requirements for food. As we do for other uses of water, we have to tackle water for food from both sides: the supply and the demand. In many wealthy countries the demand side contains a water-field that can be tapped to save water uses and narrow the gap between the demand and supply of water.

Food storage as reservoirs of virtual water

The issue of optimal production is not only a problem of location of agricultural production sites but it is also time related, as it has to do with performance of agricultural seasons. Except for irrigated agriculture, agricultural performance is highly dependent on variable climatic conditions. Thus in many rainfed farming areas we have the "good years" and the "bad years". Food storage is then used to smooth the variation of the production: storing during the good year and supply during the bad ones. This constitutes a carry over of food and virtual water from the wet years to the dry ones. This dynamic vision must also be included in the conceptual approach and in the debate on virtual water.

Food storage can be expressed into virtual water as already done for food trade. The stocks of grains worldwide represent a virtual reservoir of 500 billion m^3 of water (500 km^3). This value rises up to 830 billions m^3 when sugar, meat and oil are added. This latter value represents 14 percent of the real capacity of water in the existing reservoirs, i.e. 6 000 billion m^3 (Shiklomanov I. 2000). Furthermore if living cattle and sheep are accounted for, the total virtual water storage jumps to 4 600 billion m^3 of water (77 percent of the real storage value).

The passage from real to virtual water: transfer from production to consumption

To produce food, real water is consumed by evapotranspiration on the production site. Thus every food product can be linked to a ratio of water consumed per kg, which varies in space and in time according to the local productivity and local conditions of water supply in green water (rainfall) and in blue water (irrigation). Once the product leaves the production site (farm gate) for the consumption market, water abandons its real and tangible status to become virtual.

In the consumption domain, the value of virtual water is not strictly connected to the real production conditions and has more to do with a virtual production site and growing period closer in space and time. For instance for a nation importing cereals, the value of virtual water embedded in the imports is not the real value consumed at production site, but the value that the country would have consumed if it had to produce the food itself (value on a virtual production site). A similar reasoning applies for food transfer in time. The value of virtual water embedded in the amount of food coming from internal storage is not the value recorded during the real production period but the value that would have been consumed to produce the same amount the same year of the consumption period.

Virtual water has often been associated with trade, but it is not the process of crossing a boundary that changes the nature of water from real to virtual. This is the very passage (transfer in space and in time) from the production domain to the consumption domain which transforms real into virtual water. For the consumer, water embedded in the food he is swallowing is always virtual.

The virtual water value: water evapotranspired at field level

Crop water production is governed only by transpiration. However since it is difficult to separate transpiration from evaporation from the soil surface between the plants (which does not contribute directly to crop production), defining crop water consumption in terms of evapotranspiration rather than transpiration makes practical sense at field level. Under rainfed agriculture water consumed is only green water, while for irrigated agriculture water consumption consists of green water (rainfall) and blue water (irrigation). When studying irrigated agriculture in saline areas, the leaching requirement, i.e. the amount of water that needs to percolate to maintain root zone salinity at a satisfactory level, should also be included together with evapotranspiration as the amount of water consumed (depleted) during plant growth.

Furthermore, with irrigation supply the real water consumption must account for the irrigation application and conveyance efficiencies. However, efficiencies are very much site and system specific, as seepage and deep percolation water losses are very much variable depending on techniques in use, the skill of users and the re-use of water at basin level. When losses generated in the transport and the applications of irrigation water are no longer of use, then efficiency should be accounted for and real water consumption should include both ET and water losses. The issue of water productivity and water use efficiency, however, is a topic in itself.

At this stage we purposely put aside considerations on efficiency and additional water requirements (leaching) and keep the water consumption as the fraction of water evapotranspired (green +blue). The virtual water value is then defined as the quantity of water evapotranspired at field level (ETa or ÓETa) to the yield (increment or total yield). It is expressed in m^3 of water per kg of crop.

$$VWV = \frac{ETa(m3)}{Yield(kg)} \tag{1}$$

The concept of marginal virtual production site

How much water is saved when you import cereals? It is advocated here that the value of water saved has much to do with the inverse of the marginal water productivity on the consumption site, i.e. where the decision for importing is made, rather than with the water quantity really consumed on the production site.

In the first studies and discussions on virtual water and on water productivity for food, figures like 1 kg/m^3 of water for cereals have been abundantly used. Various estimations of virtual water trade are based on this unit value. This kind of worldwide reference can be used, provided that we are dealing with global trade. However, once we focus and desegregate the approach at regional, country or state levels, this type of reference might be misleading (Earle A.2001). This is the big question of average versus marginal, which is of great importance in this case because the general idea of virtual water lies on comparative advantages of different production sites (Renault & Wallender, 2000). Decisions are based and/or impact on the fringes of the resources mobilized for production (land, water, economy, etcB). Therefore the marginal approach is usually more relevant when addressing the decision making process.

What is the virtual water value of a sea fish?

The above definition of VWV does not allow estimation of the value of a food product that does not consume water in its production process. For example, how should the virtual water value of sea products be estimated? A response to this question is proposed in the following.

Part II
Principles in assesing virtual water values

Five principles are suggested for the assessment of virtual water values. The first two principles deal with the reference in computing the virtual water value. The first considers common values, as a sort of standard values, based on actual water consumption recorded on selected real production sites. The second principle considers the marginal water consumption of the location where the decision of producing or importing is made. Depending on the nature of the study on virtual water, one has to decide which of these two principles suits best the objectives. The third principle is on nutritional equivalence, which provides a means to compare food products. The fourth principle is on substitution or finding an alternative water consumption, which bounds the scope of water saving linked to virtual water. The fifth principle specifies that, thanks to water productivity gains, virtual water values are deflated at a significant pace and this principle must be considered when looking at past or future evolution of virtual water.

P1: The principle of common values

For global analysis on virtual water and to allow comparison between virtual water fluxes there is without doubt a need to use the same common values of virtual water as standards. The real water consumed at some reference production sites can be used as reference values of virtual water.

Questions remain though on how to assign these standards, with what type of productivity and where should it be measured. It seems that three options can be considered:

a. the average world wide water productivity for each product;
b. the productivity recorded in the main exporting and/or producing country of each product;
c. the highest national productivity recorded for each product.

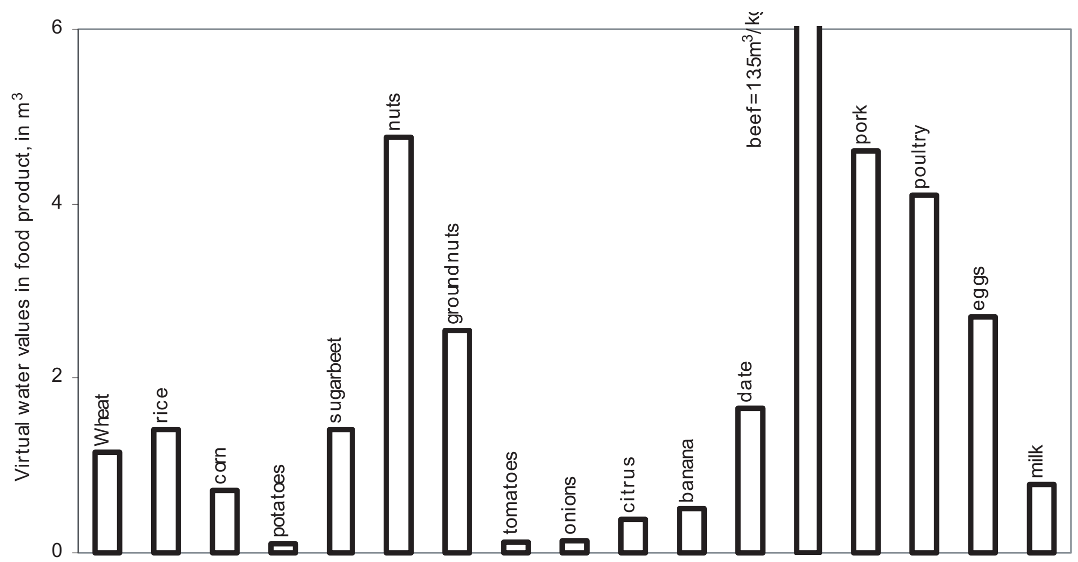
As the virtual water discussion is about opportunity with regard to production sites, it would seem logical that those countries or states with the highest performing agricultural production sites should be selected to set the standards.

Figure 1 displays virtual water values of various agricultural products in 1990, with reference mainly to Californian production sites, except for a limited number of crops that are not produced in California (Renault and Wallender, 2000). Here, values of virtual water have been estimated considering for each product either option b or c.

P2: The principle of the marginal gain in water productivity

For decision-makers in charge of water and agriculture policies, the value of virtual water that must be considered cannot be a standard value registered in a remote production site, but has to be related to the local alternatives. Water saved from internal water resources when imports of

FIGURE 1
Virtual water values for various food products, with reference to Californian production sites - average productivity (after Renault & Wallender, 2000)



goods are increased, is the quantity of water that would have been mobilized to produce internally the same quantities of goods. Therefore this is the marginal water productivity of the site where the decision about producing or not is made, that gives the value of virtual water. The same reasoning holds for deciding to export more; the additional water that needs to be mobilized depends on the marginal water productivity of the production site.

Furthermore, as said earlier transfers of food are not limited to spatial transport from production to consumption sites, but cover also time transfers between producing and consuming periods thanks to storage capacity. Thus the value of virtual water of food storage is not the value recorded during the production period but the value at the time of the consumption period.

One major consequence is that Virtual Water Value is neither constant in space nor in time. A more practical consequence of importance is that when food is transferred from high performing production sites or periods to lower performing sites or periods, it generates real water savings. This virtue is illustrated in part III.

According to the above definition, a formula of the value of virtual water can be proposed as follows:

$$VWV = \frac{1}{\text{Local Marginal Gain of Water Productivity } (kg/m^3)} \qquad (2)$$

The water productivity of food products is thus central to assess VWV. As water productivity varies a lot with the agricultural conditions, average values over a large area have little meaning for the assessment of VWV. Examples of values of water productivity recorded for cereals in various countries and for various practices are given in table 1. A similar pattern is found for each country; irrigated cereals are more productive than rainfed cereals, and the marginal productivity of supplemental irrigation is high.

P3: The principle of nutritional equivalence

When alternatives are discussed, for instance production vs. import, there are cases for which there is no local alternative to grow the crop under consideration. For example, Germany cannot grow rice, therefore the marginal water productivity of rice has no meaning for this country. The only alternative for Germany would be to produce other products (one or several) that are equivalent to rice. To do that, we need to have a set of indicators that can be used to compare food products. Weight is obviously not the good criteria, we cannot compare one kg of cereals and one kg of tomatoes and the economic value ($) is neither appropriate to this exercise.

In fact the value of any agricultural product in terms of food is measured through nutrients. Therefore the only domain we can think of for equivalence is the nutritional content of food products. The nutritional content is made up of multiple elements; the main indicators being energy, protein, fat, calcium, iron, etc... By introducing the principle of nutritional equivalence we allow comparison of wheat with potatoes for example, or of wheat with a set of products. In figure 2, an example of productivity for energy is displayed for main food products, with reference to water productivity estimated in California. From this figure it can be derived that potatoes are much more productive than wheat: 1 m^3 of water on potato produces the same amount of energy as 2.5 m^3 of water on wheat.

The principle of equivalence states: local alternatives for a food product should be either the same product or a set of other food products leading to the same nutritional values.

Table 1
Productivity of water and related virtual water values

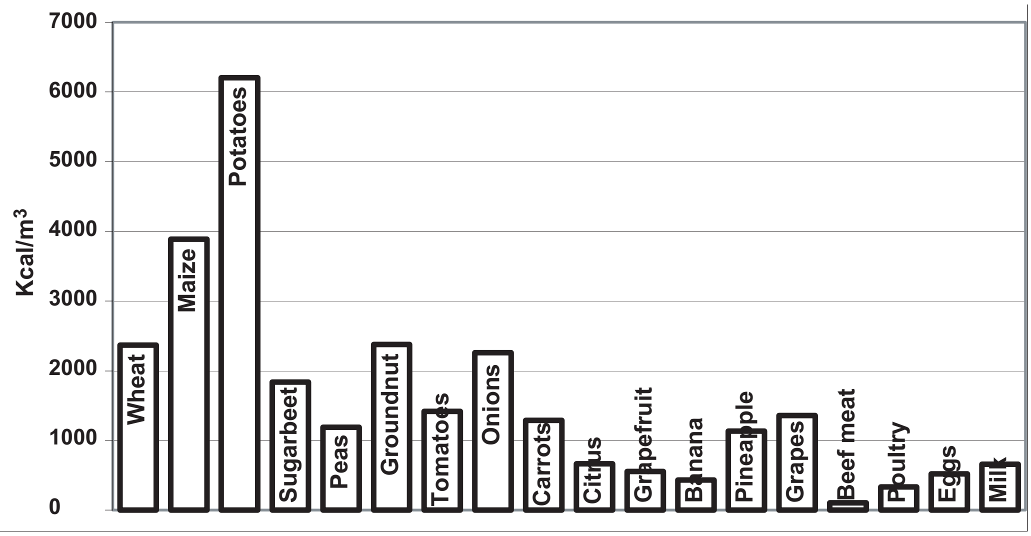
	Productivity of water in kg/m^3		**Productivity of supplemental irrigation in kg/m^3**	**Virtual Water Value in m^3/kg**		
	Rainfed agriculture (Green water)	**Irrigated agriculture** (Green and blue water)	(Blue water)	**Rainfed** Green water	**Irrigation** Green and blue water	**Supplemental irrigation** Blue water
Wheat Durum Morocco 1985-1986 (Ambri Abdel I. 1990)	0.7	0.8	1.12	1.45	1.23	0.9
Wheat Durum Tunisia 1986-1987 (Bouzaidi A. 1990)	0.6	0.85	2.3	1.63	1.17	0.43
Wheat Syria (1987-1990) (Oweis *et al*. 1999)	0.73	1.28	2.75	1.37	0.78	0.36
Wheat Egypt (Wichelns D., 2001)	**	1.32	**	**	0.75	**
Maize France (AFEID, 2001)	1.6	1.9	2.5	0.62	0.53	0.4
Maize India 1981-1985 (Sachan R.C. and Smith G.D. 1990)	*	*	0.55	*	*	1.82
Maize Egypt (Wichelns D., 2001)	**	0.89	**	**	1.12	**

* Data not available; ** in Egypt only irrigated cereals are grown.

For comparison the reference average values for California used in Figure 1 are respectively

VWV wheat = 1.16 m^3/kg; VWV maize = 0.71 m^3/kg.

Figure 2
Nutritional productivity in energy for various food products (after Renault and Wallender, 2000)



P4: The principle of substitution

The potential water savings imbedded in imported food will only materialize locally, if the decrease in food production frees up local water resources that can be made available for other uses. It must be said that this is not always the case. Some water used for crops and food products cannot be substituted with another use of water, as for instance in the case of cattle which feed on natural rainfed pasture.

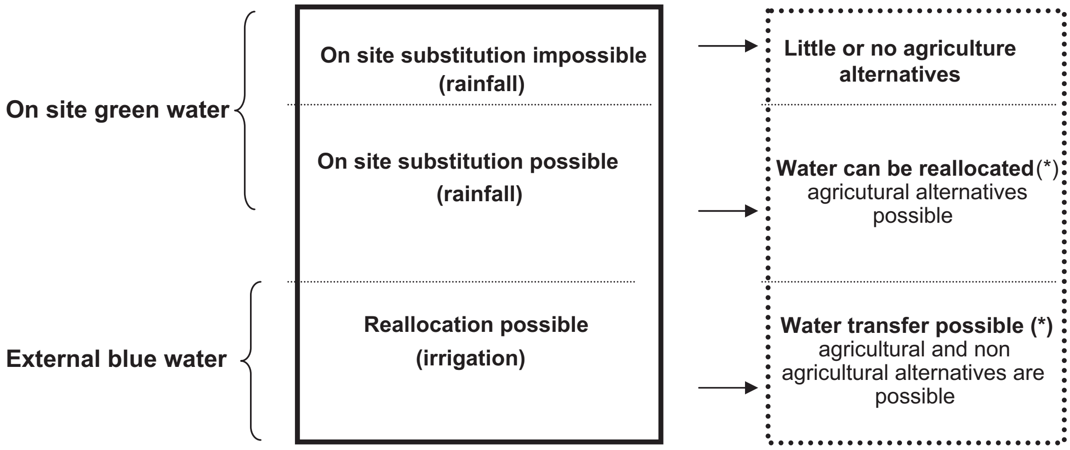
Mauritania, for example, is exporting huge quantities of virtual water through the export of goats (140 000 heads in 1994), this country is a net exporter of virtual water (FAO, 1997), which is a paradox for a very arid country. However, any attempt to reduce goat production and exports will be vain as far as water saving is concerned. The herds of goats in Mauritania are taking advantage of a huge territory where little rain can still produce (food or fodder), but would otherwise be lost for production. In this case if there is no substitution for the local goat production[1] then the impact of virtual water in the decision process is irrelevant.

The question of substitution is important for virtual water. In figure 3, a grid of possible situations in that respect is presented. The Mauritania case mentioned previously is an example of the top box in Figure 3.

In fact the principle of substitution is already included in the principle of the marginal gain. When no substitution is possible, the marginal gain is simply set to zero, which means that the potential of savings is nil. However, for the purpose of clarity we maintain the two principles separated.

[1] Assuming there is no over exploitation of pasture lands and therefore no need to restore natural vegetation.

FIGURE 3
Analytical sketch of the substitution principle in the production domain (after Renault, 2002)



(*) Transfer and reallocation are bounded by biophysic conditions of the watershed.

P5: The principle of deflation

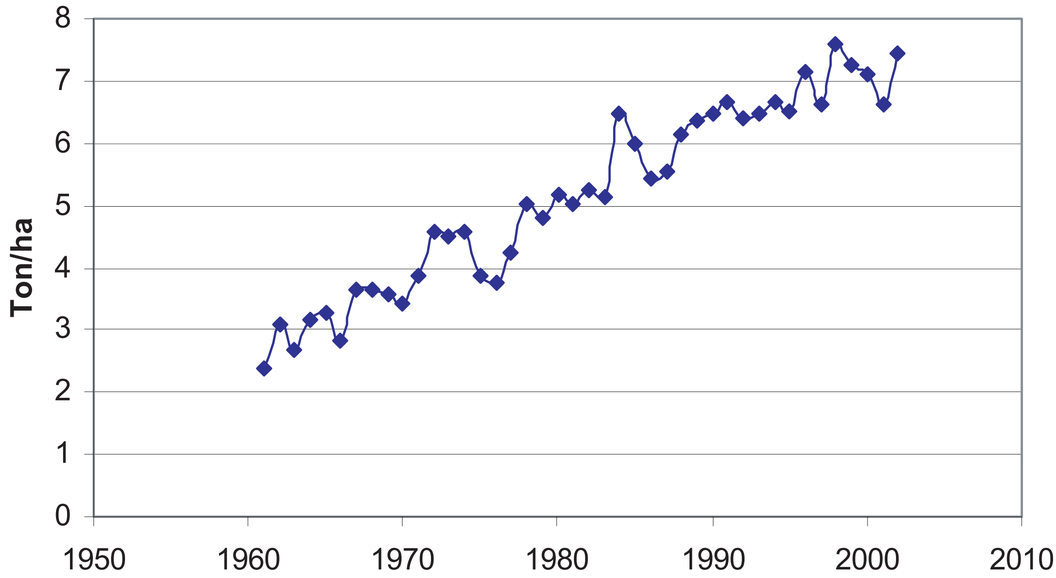
Historical approaches are important for studies on food trade and food consumption as well as those related to water management. It is important to look at past evolution of fluxes to identify trends, noticeable breaking points, and also to allow more accurate projections. The problem comes from the fact that productivity of water is not constant with time, therefore the values of virtual water (VWV) varies with time.

As productivity of land and water has increased significantly in past decades, virtual water values have decreased in the same proportion. Therefore constant values of VW cannot be used for historical analyses. VWVs need not only be reliably assessed for one time period, but also their evolution over the past need to be indicated. An example is given in Figure 4, which illustrates the gain in yield for wheat recorded in France. This evolution of yield (3 percent per year) is quite representative of the water productivity gains during that period as wheat is mainly rainfed in this country; i.e. the increase in yield occurred with hardly any variation in water consumption. The wheat yield has tripled between 1961 and 2000, and as a consequence the virtual water value of wheat in France has been reduced in 2000 to one third of its 1961value.

Virtual water value

To summarize the previous points, one can say that the whole debate on the value of virtual water is about water productivity and its variation in space and time. The value of virtual water of a food product is site and time specific and equal to the water that would have been consumed locally to produce the same quantity of nutrients. For global studies and comparisons, there is a need though to have common values (P1) of water productivity and VWV. For decision making analysis, on the other hand, only local productivities and VWV (P2) must be considered.

Figure 4
Recorded wheat yields in France between 1961 and 2000 (FAO database)



The previously described principles can be put into the following formula:

VWV (m^3/kg) = Marginal local water consumption [x,y,t, product] (4)

Where

- x and y express the variation of the VWV with the location,
- t expresses the variation of VWV in two ways, variations of water productivity with agro-climatic years, general trend of deflation due to the continuous water productivity gain,
- product expresses the alternative in terms of products having same nutritional values.

Summarizing the previous, the following definition for VWV is proposed:

Virtual Water Value of a food product is site and time specific and equals to the marginal water requirements for a local alternative production of the same quantity of product or its nutritional equivalent.

Part III
Applications and features of virtual water

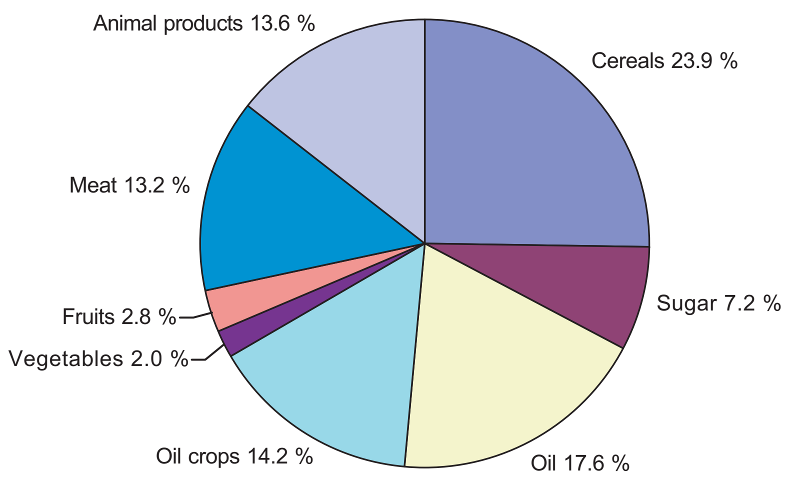
In this part it will be illustrated how the five principles can be applied, underlining some features of virtual water.

1. Computing virtual water trade at global level

Virtual water trade can easily be computed by combining data on trade with data on virtual water values. Using values of virtual water adapted from Renault & Wallender (2000), it is estimated that for 2000 the global water requirements for agricultural food products amounted to 5 200 billion m^3, and the virtual water trade totalled 1 260 billion m^3; i.e. 25 percent of the total water use for food. The latter figure includes animal product trade for 390 billion m^3, and crop trade for 870 billion m^3, a figure rather close to the 695 billion m^3 found by Hoekstra and Hung (2002) for the period 95-99.

Figure 5 shows the breakdown of virtual water transferred around the world per main type of agricultural product. This figure is quite interesting because it shows that cereals, which have captured most of the attention in food security and virtual water studies, account only for 24 percent of the total volume of virtual water exchanged. Of course when it comes to nutritional values, and for arid regions, the importance of cereals is much greater than one fourth. In 2000, cereals contributed to 40 percent of the food energy trade (Zimmer and Renault, 2003).

Figure 5
Global virtual water trade partitioned in main types of agricultural food products



2. Applying the principle of marginal gain in estimating virtual water

The alternatives to import/export are respectively increase/decrease of internal production. When considering increasing internal production of a given food product, leaving out investing into techniques for yields improvement which are long term actions, there are basically three options with immediate effects:

1. expanding rainfed production areas
2. expanding irrigated production areas
3. transforming rainfed areas into irrigated areas.

Corresponding water productivities are of course different, and furthermore within each option productivity of water varies with the local situation. Usually the more productive internal sites are already used and therefore the expansion of areas occurs on land that deviates from the average fertility conditions. The water productivity curves for additional input being land or water are often declining. Figure 6 shows water productivity curves as function of additional unit water used, for rainfed and irrigated practices. These curves are of course site specific, but often the slope of decline of water productivity for rainfed conditions is higher than for irrigation, because the soil water storage capacity is critical for yield.

Assuming that productivities of existing production systems lie between A and B for rainfed and between C and D for irrigated agriculture (Figure 6), the options for production increase and corresponding productivities are:

- Option 1 expand rainfed production areas (Point B): marginal productivity equals to WP2
- Option 2 expand irrigated production areas (Point D): marginal productivity equals to WP4
- option 3 transform rainfed areas into irrigated areas: marginal productivity jumps from AB to CD (on average from WP1 to WP3)

With the example of Maize in France (see table1), the average productivity of rainfed area (WP1) amounts to 1.6 kg/m^3 and the average virtual water value against this option is 0.62 m^3/kg. As shown in figure 6, the marginal water productivity value can be lower than this value (e.g. -25 percent), hence the VWV would be greater (respectively +25 percent). The same reasoning holds for the irrigated maize expansion although the expected variation of productivity is lower for irrigation than rainfed. If expansion happens on lands close to the average conditions then the average productivity will apply 1.9 Kg/m^3 and the VWV will be 0.53 m^3/kg, and if the expansion occurs on less fertile soils, VWV will increase (e.g. +10 percent).

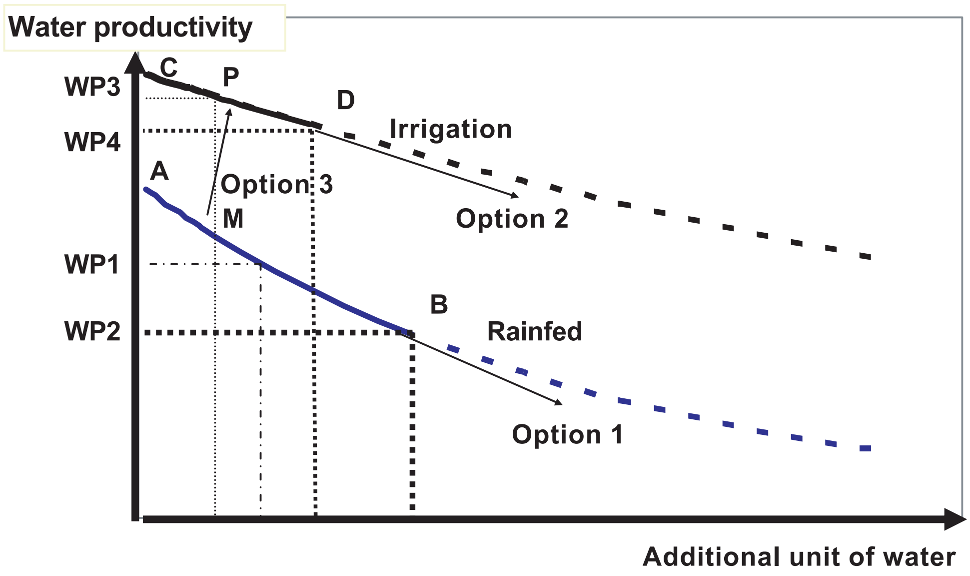
Finally, transforming rainfed to irrigated areas will lead to benefit from the high productivity of supplemental irrigation (average 2.5 kg/m^3) and corresponds to a low virtual water value of 0.4 m^3 of water per kg. The marginal gain from rainfed to irrigated conditions can deviate from average by a positive or a negative deviation.

The average VWV for maize in France is thus ranking from 0.4 to 0.62 m^3/kg, and the marginal VWV is likely to be within 0.4 to 0.8 m^3/kg. An increase of production in France would certainly combine different options, thus a value of about 0.6 m^3/kg can be used as the value of virtual water for maize in France.

3. Virtual Water imports generates real water savings

The most straightforward effect of virtual water is about water savings for the countries or the region that imports food products. This effect has been widely stated in virtual water studies

FIGURE 6
Water productivity curves per unit of water



(Allan, 1999). The savings are directly the result of the quantity of imports multiplied by the value of virtual water estimated using the marginal gain principle.

Water savings (m³) = Import (kg) x VWV(local site) (5)

For instance, Egypt imported some 5.2 Millions tons of maize in 2000. With a VWV for maize estimated at 1.12 m^3/kg (Table1) this represents a water saving of 5.8 billions m^3 of water from national allocation, i.e. about 10 percent.

4. Virtual Water Trade generates global real water savings

As the value of virtual water varies with location, virtual water does not obey to the mass conservation law. Food trade generates transfers of virtual water having variable values. In many cases (but not all) these transfers occur from high performing production sites to lower performing sites, which lead to real water savings as a whole. The water saving corresponds to the differential of productivity between the production site and the consumption site.

Water savings (m^3/kg) = VWV(consumption site) + VWV(production site) (6)

For instance, transporting 1 kg of maize from France (taken as representative of maize exporting countries for water productivity) to Egypt transforms an amount of water of about 0.6 m^3 into 1. 12 m^3, which represents globally a real water saving of 0.52 m^3 per kg traded. The maize imports in Egypt and the related virtual water transfer have thus generated a global saving of about 2.7 billions m^3 of water in 2000. The global real water saving is quite significant: a first rough estimate at global level shows that water savings due to virtual water transfer through food trade amounts to 385 billions of m^3 (OKI et al, 2003).

The assumption of virtual water flowing from high to low productive sites is not always met. Some countries are facing limitations in allocation of water resources for food or in another input for agriculture (land, labour...). Thus despite sometimes having high productive agricultural sites, countries must import food products from countries with lower productive sites but benefiting from greater resources. This is the case of Egypt which has high water productivity for pulses but still imports large quantities of pulses, mostly from USA where productivity is much lower. In that particular case the imports of pulses (260 000 tons in 2000) save in Egypt some 450 millions m^3 of water, but consumes in producing countries around 760 millions of m^3. Resulting thus in a net additional consumption at global level of 310 millions m^3. This example illustrates the fact that equation 6 can be sometimes negative, although the global trend is that virtual water trade saves real water.

5. Food storage generates real water savings

As said earlier VWV varies with the climatic season. Again the mass conservation law does not apply for food transfer in time. In most cases storing food is made during wet and highly productive years, whereas tapping the storage occurs during dry and low productive years. The water saving corresponds to the differential of productivity between production and consumption periods.

$$\textbf{Water savings (m}^3\textbf{/kg) = VWV(storing period) + VWV(using period)} \qquad (7)$$

For instance in Syria, the year 1988 has been a good year for the cereal production with high yields (1.6 ton/ha) leading to a volume of production higher than consumption, thus 1.9 Million ton of cereals were stored during that year. The following year was a very dry one, and the cereal yield dropped to a low 0.4 ton/ha. A volume of 1.2 million ton of cereals has then been used from internal storage to complement internal production and imports. Water productivities recorded these years has been estimated to 1 kg/m^3 for 1988 and 0.3 kg/m^3 for 1989 (Oweis, 1997), which corresponds respectively to VWV of 1m^3/kg to 3.33 m^3/kg. Thus the use in 1989 of 1.2 million ton of cereals from storage is equivalent to 4 billion m^3 of virtual water. On a two years period of reference (88-89) some 2.8 billion m^3 of water has been saved by the food storage capacity.

One major conclusion here is that the value of virtual water stored in food must be estimated using the low productivity years. Thus the virtual water value of the global food grain storage estimated in the introduction part using average value (500 billion m^3 of water) must be hold only as a minimum.

6. The high value of Virtual Water of sea products

The sea products (Fish and others) contribute significantly to the food supply and the food trade. Although the process of production of sea products does not imply water consumption, it would not be wise not to account for their virtual water values. Importing and consuming sea products corresponds to a virtual water consumption which needs to be estimated through local alternatives.

Here, the principle of equivalence (P3) is used to identify a set of products equivalent on nutritional properties that could replace sea products. The average nutrient content of a kg of sea product is 640 Kcal/kg - 98 g protein/kg + 23 g fat/kg. Because of the specific nutritional properties of sea products - high in protein and low in energy and fat + the equivalence must be made considering on one side sea products plus some energetic product such as cereal or sugar, and on the other side a set of products as the alternative.

Obviously there are many options to reach the equivalence. An alternative for vegetal products is the result of increasing intake from pulses for protein, and oil for fat and a significant decrease from cereals. Simulation shows that the virtual water value of the equivalent set would be in that case approx. 1.5 m^3. It must be underlined that equivalence on energy, protein and fat is only part of the spectrum. There area many other micro nutrients in sea products which are not supplied by pulses, this is obviously one limitation in replacing sea products by vegetal products. To increase the equivalence fit would require a more diversified set of vegetal products and therefore would increase the value of virtual water. It seems therefore reasonable to set the equivalence for vegetal at around 2 m^3/kg.

Alternatives for sea products based on animal products (beef, pork, poultry, eggs and milk) lead to a value of virtual water of around 5 m^3/kg. The equivalence of animal products to sea products is generally considered by the nutritionists as better than for vegetal products.

As a conclusion it is proposed to associate a virtual water value for sea products adapted to the local food diet and specifically to the balance between animal and vegetal products. VWV for sea products would then range from 2 for vegetal products to 5 m^3/kg for animal products.

Using the animal products alternative (5m^3/kg) the weight of sea products is 8 percent of the global virtual water budget and 14 percent of the global virtual water trade (Zimmer and Renault, 2003)

7. Impacts of diet changes on water requirements

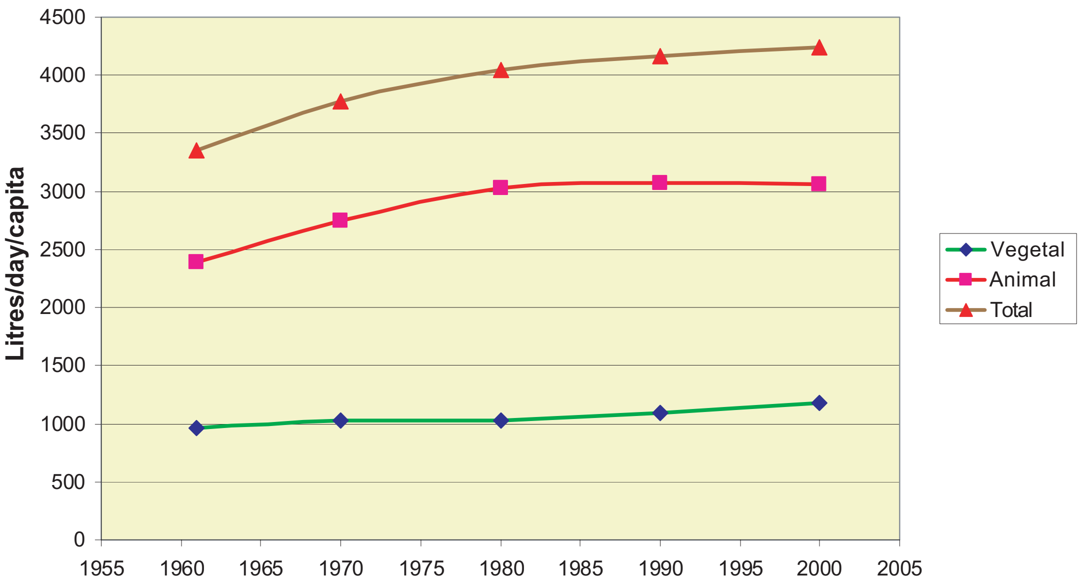
The impact of diets on water requirements for food is significant because food products have variable virtual water contents, as illustrated in Figure 1. Beef meat has a high VWV around 13 m^3/kg whereas cereals vary around 1m^3/kg. Food diets and habits vary among cultures and with economic development. Usually countries, the economy of which are developing tend to see consumers going for more meat and less cereals. This trend is obviously putting more pressure on water resources for food production. However, in developed countries the growth in water for food recorded during the sixties and seventies is slowing down.

Figure 7 depicts the evolution of water requirements for food per capita in European Union countries (EU15) for the years 1961 up to 2000, using constant virtual water values estimated for 1990. One can see that up to 1980 water consumption per capita for animal products was on the rise, while that for vegetal products remains constant; the total being a significant rise of water needs from 3 340 to 4 050 litres/day/capita. After 1980 the opposite occurs: water for animal products stays constant while it increases for vegetal products, and the total slightly increases to 4 240 litres/day/capita. Within animal products, beef meat consumption reached a high peak in 1980, and the reduction since then has been compensated by increase pork and poultry. The increase in vegetal product since 1980 is mostly driven by the increase in oil consumption.

8. The historical decline of water needs for food

Without further care, we could have said from the above analysis (Figure7) that water requirements for food have increased for EU by 900 litres/day/capita between 1961 and 2000. However this analysis does not considers the gain in water productivity of cereals (Figure 4)

Figure 7
Impact of changes in food habits on water requirements, through the evolution of water for food in European Union (EU 15), with constant virtual water values (References 1990)



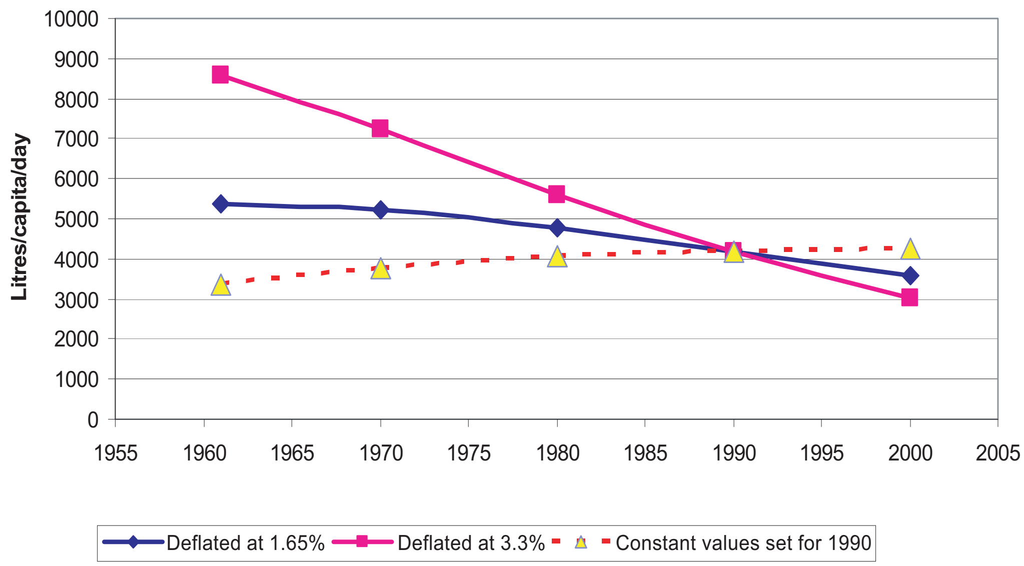
and of other food products, therefore using constant VWV of 1990 might be absolutely misleading.

In fact yields of maize in Europe have been raised by an averaged 3.3 percent increase per year between 1961 and 2000. At least part of this gain of grain yield productivity has been converted into gains of water productivity. The question remains of course how much of the yield gain is converted into water productivity increases, knowing that on the one hand, producing more biomass requires more transpiration, on the other hand the ratio of grain to biomass has also been increased consistently. Thus this question is difficult to answer with certainty. It obviously requires more attention to come up with reliable assumptions.

In Figure 8, the evolution of the virtual water content in food consumption for developed countries is given with 2 options for productivity gain. One considers that the entire gain in yield (3.3 percent) has been converted into water productivity gains, which is of course extreme. The other considers that the increase of water productivity reaches 50 percent of the yield growth (1.65 percent).

This shows that the previously mentioned increase in water consumption per capita from 1961 to 1990 (VWV 1990 in Figure 7) does not reflect reality. With the 1.65 percent deflated rate, which is a conservative assumption about water productivity gain, water consumption from 1961 up to 1990, has decreased steadily in Europe 15 from 5 400 to 3 600 litres/day/capita: a huge water saving of 1 800 litres/day/capita. Further detailed studies should be made to give more accurate figures on which deflation rates per product should be considered. What seems to be quite clear though is that water for food per capita in Europe has been reduced by thousands litres per day. Similar patterns are found in many countries including USA and at global level.

FIGURE 8
Evolution of virtual water content for food in Europe 15, with various deflation rates of virtual water values (Reference 1990)



PERSPECTIVES

Again it is important to recall that decisions on importing/producing any good, and in particular food products, are not only based on the virtual water value as described in previous section. However it is important that virtual water is properly assessed in terms of its value in space and in time.

One of the following steps should consists in defining accurate common virtual water values, and setting reliable methodologies for computing volumes of virtual water embedded in food trade, particularly looking at the way to deal with secondary products like meat to avoid double counts of primary and transformed products (meat, oil, sugar, etc..). Another step would be to analyze how virtual water is considered at policy level on food trade, water management and agriculture.

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