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"Virtual water": An unfolding concept in integrated water resources management

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[1] In its broadest sense, virtual water refers to the water required for the production of food commodities. Issues relating to virtual water have drawn much attention in scientific communities and the political sphere since the mid 1990s. This paper provides a critical review of major research issues and results in the virtual water literature and pinpoints the remaining questions and the direction of research in future virtual water studies. We conclude that virtual water studies have helped to raise the awareness of water scarcity and its impact on food security and to improve the understanding of the role of food trade in compensating for water deficit. However, the studies so far have been overwhelmingly concerned with the international food trade, and many solely quantified virtual water flows associated with food trade. There is a general lack of direct policy relevance to the solutions to water scarcity and food insecurity, which are often local, regional, and river basin issues. The obscurity in the conceptual basis of virtual water also entails some confusion. The methodologies and databases of the studies are often crude, affecting the robustness and reliability of the results. Looking ahead, future virtual water studies need to enhance the policy relevance by strengthening their linkages with national and regional water resources management. Meanwhile, integrated approaches taking into consideration the spatial and temporal variations of blue and green water resources availability and the complexity of natural, socioeconomic, and political conditions are necessary in assessing the trade-offs of the virtual water strategy in dealing with water scarcity. To this end, interdisciplinary efforts and quantitative methods supported by improved data availability are greatly important.

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1. Introduction

[2] The term "virtual water" was originally developed in the context of water scarce Middle Eastern and North African countries which import a large portion of their food. By doing so, they reduce substantially the water demand in domestic food production and compensate for a lack of water. For these countries, importing food is virtually equivalent to trading water. *Allan* [1996] termed the water embodied in food import as virtual water. Over the years, both the terminology and the scope of virtual water have been extended beyond the original purpose [*Wichelns*, 2005]. Currently, the most accepted definition of virtual water is the water required for the production of commodities [*Zimmer and Renault*, 2003; *Merrett*, 2003; *Oki and Kanae*, 2004; *Hoekstra and Hung*, 2005]. As food production in most countries is by far the largest water user, discussions on virtual water issues have focused primarily on food commodities.

[3] Virtual water is economically invisible and politically silent [*Allan*, 2003a]. This had made it possible in the past for water scarce countries to cope with the water deficit by importing food without cultivating a policy discourse of national water scarcity. Since the term virtual water explicitly came to the light in the mid 1990s, it has drawn a growing attention among policy makers, scientific communities, and the general public. Virtual water has been a topic discussed recurrently at many international conferences and meetings, notably the World Water Forum (held every 4 a) organized by the World Water Council and the Stockholm World Water Week (annual event) convened by the Stockholm International Water Institute. Publications on the relevant issues have been increasing rapidly in the international journals. Debates are intense on the usefulness of the concept and the feasibility to import virtual water to alleviate local water scarcity.

[4] After over a decade of efforts in virtual water studies, it is time for a critical review of the relevance of virtual water concept in advancing our understanding of real water resources management. The present paper serves this purpose. In the virtual water literature, three issues have been tackled the most: water resources availability and food trade relations; virtual water flows and water use efficiency embodied in the food trade; and the role of virtual water in conflict mitigation and national and regional water

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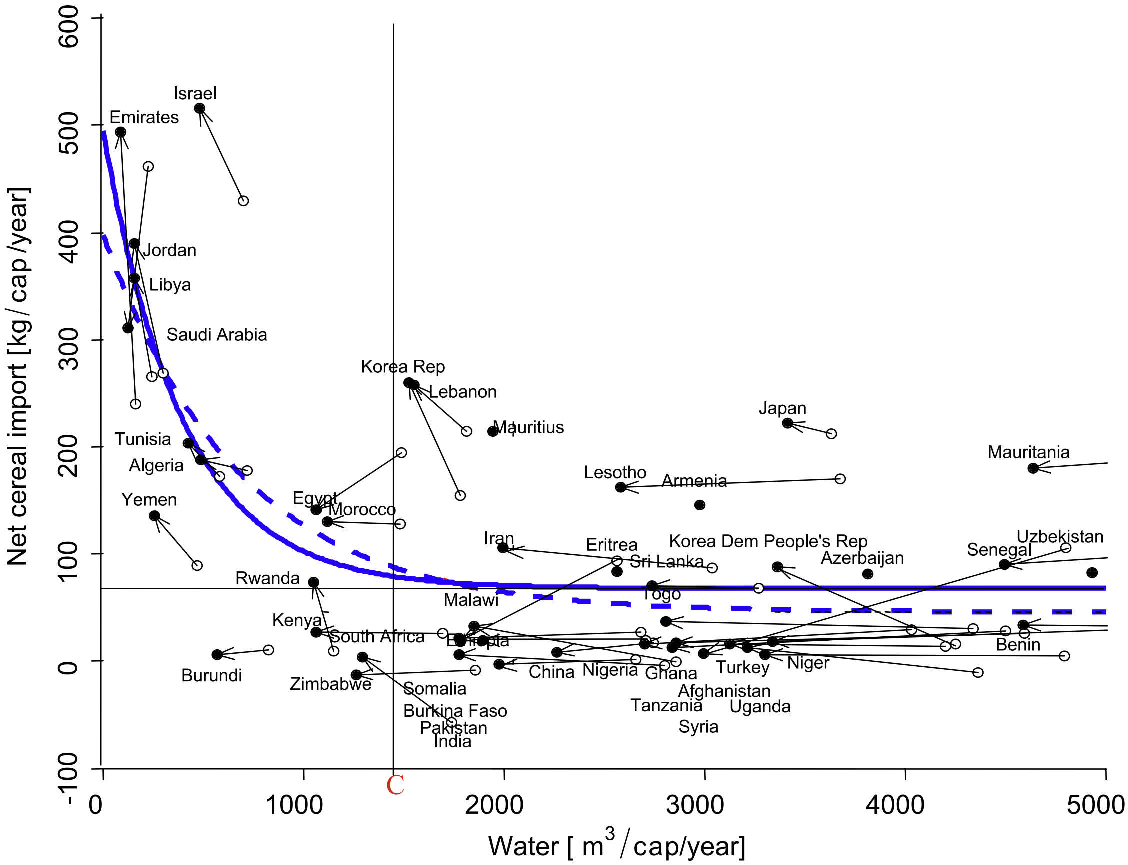

Figure 1. Per capita net cereal import versus per capita available water resources. Dashed curve and open circles are the fits of the model with the water variable only for the investigation period 1980–1984, and solid curve and solid circles with country names are the fits for the investigation period 1996–2000. Arrows in the diagram indicate movements of the positions of the countries from the first to the last period. The position of the parameter C is the renewable water resources below which a significant dependence exists between net cereal import and water resources availability at the country level. The variations in the net cereal import per capita for countries with similar water resources are captured by gross domestic product and arable land in the model. Adapted from *Yang et al.* [2003].

scarcity management. This study addresses the state of the art and the shortcomings in the previous works. On the basis of the review, some aspects where the future virtual water studies need to devote more efforts are pinpointed. At the end of the paper, we make brief comments on the conceptual basis of virtual water. The "unfolding" process of the concept is highlighted. Comments are also made on some common criticisms on negative impacts of virtual water import. This review mainly covers the literature in the international journals, while acknowledging some important studies that have been only available in the form of working papers and reports.

2. Water and Food Trade Relations

[5] Following Allan's initial elaboration of food import in compensating for the water scarcity in the Middle Eastern and North African countries, there have been some studies devoted to systematic investigations of relationships between water resources availability and virtual water trade.

[6] *Yang and Zehnder* [2002] found that the volumes of net cereal import in the southern Mediterranean countries were correlated inversely to their water resources availability. In Israel and Libya, where water resources are extremely scarce, 90–95% of the domestic cereal supply relies on import. In continuation to the initial finding, *Yang et al.* [2003] modeled the relationship between water resources availability and cereal import for the countries in Asia and Africa. They identified a water scarcity threshold of approximately 1500 m^3 $capita^{-1}$ a^{-1} (Figure 1). Below the threshold, a country's demand for cereal import increases exponentially with decreasing water resources. Above the threshold, no systematic relationship exists between cereal import and water resources availability. The modeling results also showed that gross domestic product per capita is highly significant in explaining the variations in the level of cereal import among countries with similar water resources.

[7] Several other studies also investigated water and food trade relations. It is noteworthy that studies with a blanket coverage of all countries have tended to reject the notion that water scarcity is a motivation for food import. For example, *Kumar et al.* [2005] analyzed renewable freshwater availability and net virtual water trade of 146 countries across the world. A relationship was not found between

virtual water import and water resources availability. They attributed the situation to the negligence of soil water, or "green water", which is determined by accessing to arable land of a country. *Ramirez-Vallejo and Rogers* [2004] examined the impact of trade liberalization on virtual-water trade. Their result suggested that virtual water flows at the global level are independent of water resources endowment. The study by *Brichieri-Colombi* [2004] derived a similar conclusion.

[8] The results of the previous studies are seemingly contradictory. A closer look, however, reveals that they are rather consistent. As elaborated by *Yang et al.* [2003], the water and food import relations could only be established for the countries where water resources are scarce. This point is supported by *Fraiture et al.* [2003] and *Yang et al.* [2006] who found that only about a quarter of the global cereal trade occurred from water abundant to water scarce countries. Both studies suggested that water scarcity plays a relatively minor role in shaping the current global cereal trade flows. In this case, pooling all the countries for an aggregate analysis would very likely obscure any direct relationship between water scarcity and food import.

[9] Further to the previous efforts, *Yang et al.* [2007] zoomed into the southern and eastern Mediterranean countries to probe in more detail the water scarcity and food trade relations with respect to different crops. They found that during the last two decades the decline in per capita water resources availability was a dominant factor in explaining the increase in the import of water intensive crops, namely cereal, vegetable oil and sugar in these countries. No significant relationship was found between water resources availability and the trade of fruits and vegetables. This may be explained by the relatively high value of water use in fruit and vegetable production. The results support the general view that for water scarce countries it makes economic sense to import a portion of water intensive crops consumed domestically and export high-value crops of fruits and vegetables. This trade pattern is regarded as the virtual water strategy [*Bouwer*, 2000; *Qadir et al.*, 2003; *Renault*, 2003; *Yang et al.*, 2007].

[10] So far, studies of water and trade relations have only considered blue water availability. Green water resource has been generally neglected. In its broadest definition, green water resource is the water stored in the unsaturated soils. It is the water source of rain-fed agriculture. Blue water resource refers to the waters in rivers, lakes, reservoirs, ponds and aquifers. Irrigated agriculture typically uses blue water as a supplement to insufficient rainfall. Currently, the available data at the country level only include blue water resource. The information on green water resource is mostly absent. This is partly related to the technical and conceptual complexity in quantifying green water resource. For example, green and blue water resources are interrelated in the hydrological system. They are not two separate resources. Further complicating the quantification is that green water resource is a stock, whereas blue water resource is a flux. They are not on the same dimension. Some detailed discussions on the issue are given by *Falkenmark* [1995], *Savenije* [2000], *Rockström and Gordon* [2001], *Gerten et al.* [2005], *Falkenmark and Rockström* [2006] and J. Schuol et al. (Estimation of freshwater availability in the West African sub-continent using the SWAT hydrologic model, submitted to *Journal of Hydrology*, 2007, hereinafter referred to as Schuol et al., submitted manuscript, 2007). The neglect of green water resource underestimates the water endowment of a country or region, which may distort the examination of water and food import relations, particularly for a country dominated by rain-fed agriculture. In many of the North African and Middle Eastern countries, however, the contribution of rain-fed agriculture to the domestic food production is small. Thus the conclusion that the lack of water is one of the driving forces for food import in water scarce countries and regions still holds.

3. Virtual Water Flows and Water Use Efficiency Associated With International Food Trade

3.1. Magnitude of Virtual Water Flows

[11] In contrast to the relatively few studies investigating the water and food trade relations, there is a large number of studies devoted to the quantification of virtual water flows embodied in the international food trade, especially the trade of cereals.

[12] The water that is required for the production of a unit of food commodity is termed the "virtual water content" of that commodity, expressed in m^3/kg [*Renault*, 2003; *Hoekstra and Hung*, 2005]. It is simply the inversion of crop water productivity measured in kg/m^3. Virtual water content of a given crop is a function of climate conditions, agronomic practices and field management. The value differs largely across geographical locations. In quantifying virtual water flows, some aggregate ratios have often been used. For example, 1 m^3/kg was used as the virtual water content for a mix of cereal crops [*Allan*, 1997; *Zehnder*, 1997; *Turton*, 1999; *Yang and Zehnder*, 2001]. Some other studies used virtual water contents measured in fields or experimental sites to take care of the spatial variations [*Renault*, 2003; *Oki and Kanae*, 2004; *Liu et al.*, 2007a, 2007c]. Although an improvement over the aggregate ratios, the virtual water contents based on specific locations are still inadequate to reflect the variations on large scales. In the hitherto virtual water literature, a modeling approach by *Hoekstra and Hung* [2005] is worth mentioning. They applied the CROPWAT model developed by *Food and Agriculture Organization* [1986] to estimate the virtual water contents for major crops in different countries. Their study was the first systematic approach in estimating virtual water contents for individual countries with a global coverage. However, only one site was selected in each country (mostly the capital city) for the simulation. The value was used to represent the virtual water content of the crop for that country. For large countries, like China, India and the USA, this is apparently too coarse.

[13] In view of the shortcomings of *Hoekstra and Hung* [2005], *Liu et al.* [2007b] developed a model that integrates GIS with a crop growth model EPIC, named GEPIC. Supported by GIS, the GEPIC model is capable of simulating crop water productivity of individual crops with high spatial resolution on geographical scales ranging from field, catchment, region, country to the whole world. One application of the GEPIC model was to estimate water productivity of wheat at the global level with a spatial resolution of 30 arc min (Figure 2).

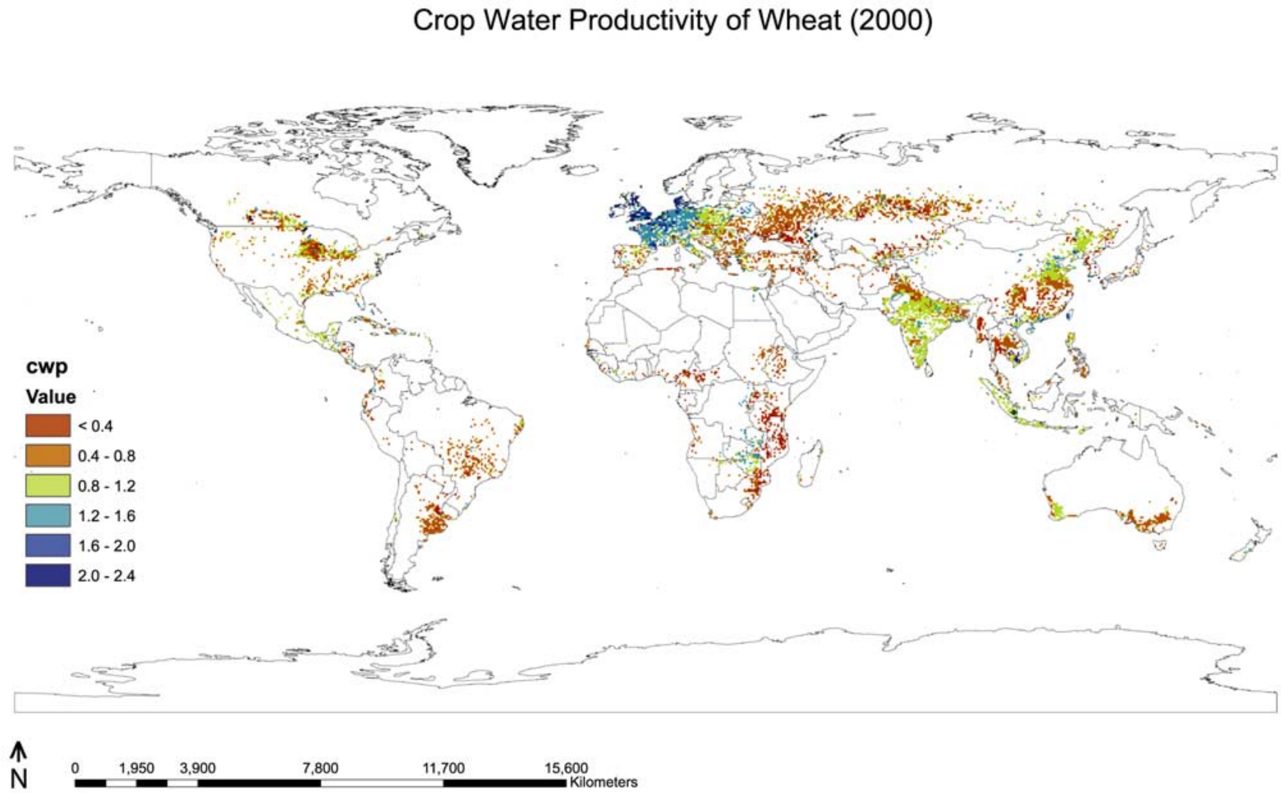

Figure 2. Simulated water productivity of wheat for the year 2000. Adapted from *Liu et al.* [2007b].

[14] Multiplying the virtual water content of a particular crop with the quantity traded derives the volume of virtual water flow for that crop. *Allan* [1997] estimated that the virtual water embodied in cereal import into the Middle Eastern and North African countries exceeded the total annual water use for food production in Egypt. Following Allan, many other studies have quantified virtual water flows at various geographical levels. One of the most cited studies was by *Hoekstra and Hung* [2005]. They estimated the virtual water flows between nations at about 1000 $km^3\ a^{-1}$ at the turn of the last century (from the perspective of exporting countries). Of which, 695 $km^3\ a^{-1}$ was attributed to crop related trade.

[15] It is worth noting that variations are rather large in the estimated virtual water flows at the global level as well as at the country level among different studies. The variations mainly stem from the inconsistency in the following four aspects: the value of virtual water content, the coverage and aggregation of crops, the period considered, and the source of trade data. The estimation of virtual water flows is highly sensitive to the values of crop virtual water contents. For example, *Liu et al.* [2007b] estimated the virtual water embodied in the global wheat trade using the crop virtual water content values simulated with the GEPIC model. The result was 159 $km^3\ a^{-1}$ for the year 2000 in comparison to about 200 $km^3\ a^{-1}$ estimated by *Hoekstra and Hung* [2005]. The difference is mainly due to the different virtual water content values used for individual countries. The grid-based estimation of virtual water content by *Liu et al.* [2007b] was able to account for variations within a country. Also, food trade consists of a large number of commodities. Variations in the coverage of the crops and the ways of aggregation can lead to different estimations of virtual water flows among studies. Furthermore, trade volumes of individual crops fluctuate from year to year. Studies using different periods of data result in different estimations. Last, the food trade data from different sources often vary to some extent. Different sources of data lead to varying estimations. For all the reasons specified here, the results from different studies are often difficult to compare.

[16] Apart from food crops, the quantification of virtual water flows is extended to other commodities, such as animal products and livestock, cotton, and some reference consuming goods, such as a cup of tea and coffee [*Zehnder*, 1997; *Yang and Zehnder*, 2002; *Chapagain and Hoekstra*, 2003, 2007; *Chapagain et al.*, 2006b; *Renault*, 2003; *Zimmer and Renault*, 2003]. *Hoekstra and Chapagain* [2007a] also made attempts to quantify virtual water involved in the production of some industrial products, such as computer chips and shoes made of bovine leather.

[17] Early virtual water studies had mostly been undertaken from the production side, e.g., estimating the water use for the production of certain commodities. The idea of "water footprint" is developed by Hoekstra and his peers to address the virtual water from the perspective of water consumption [*Hoekstra and Chapagain*, 2007a, 2007b; *Chapagain et al.*, 2006b; *Chapagain and Hoekstra*, 2007]. In analogy to "ecological footprint" which quantifies the area needed to sustain people's living, the water footprint indicates the water required to sustain a population. They distinguished the internal water footprint and external water footprint based on the sources of water for

producing the goods and services consumed by a country and individuals in the country. The latter is equivalent to the virtual water import. The results showed that the aggregate external water footprints of all nations in the world constitute roughly 16% of the total global water consumption. Water footprint establishes the linkages between people's water consumption in one place with the water use and the associated environmental impacts in another place. The most eloquent description of this point was given in their study for cotton [*Chapagain et al.*, 2006b]. They stressed that water problems in major producing areas cannot be solved without holding consumers in other areas responsible for some of the economic costs and ecological impacts, which remain in the producing areas.

[18] The quantification of virtual water embodied in the international food trade provides some insights into the role of virtual water in redistributing (virtually) the global water resources. It is useful in raising the public awareness of water resources and environmental impacts through addressing virtual water embodied in the commodities they consume. However, the sole quantification of virtual water flows, especially at the global level with a rather poor accuracy, lacks direct policy relevance to the water-food challenges faced in water scarce countries and regions and to the world community at large. Meanwhile, a general quantification of global virtual water flows associated with international food trade tends to cause confusions on the scope of virtual water. One related problem is that the phrase "virtual water trade" is often used in place of international food trade by many people, both supporters and critics of the idea of virtual water. Allan felt uncomfortable about the overstatement involved in attaching the world food trade to virtual water [*Allan*, 2003a]. One of the obvious reasons is that if the virtual water were simply another word for international food trade, there would be no need to discuss virtual water in the first place because there are well established theories of international trade. As will be addressed in section 6, what makes virtual water trade worthy of a special attention are the unique characteristics of water resources and their uses.

3.2. Water Use Efficiency Embodied in the International Food Trade

[19] In the virtual water literature, the discussion on water use efficiency has mainly focused on two aspects: water saving and green water contribution.

[20] Food production is highly water intensive. For water scarce countries, importing food can effectively reduce the domestic demand for water (both blue and green water). The reduced domestic water demand has been viewed as a "saving." Along this line, the water "saving" in the southern Mediterranean countries is the amount of virtual water imported into the region, which stood at around 40 km^3 a^{-1} at the turn of the last century [*Yang and Zehnder*, 2002]. For Egypt, the import of wheat saved at least 3.6 km^3 a^{-1} of its national water resources [*Chapagain et al.*, 2006a]. It should be noted that the water saving in this sense is different from what economists often offer, which involves a reallocation of blue water from low beneficial uses to high beneficial uses, typically from agriculture to industrial and domestic uses, or a save of water for future use. Saving green water is economically insignificant because reallocating green water to industrial and domestic uses is difficult, if not impossible. So far, evidence is lacking in water scarce countries regarding a reallocation of irrigation water to nonagricultural uses under a virtual water import arrangement. Strictly speaking therefore virtual water import has not generated a real saving of blue water in water scarce countries. However, it allowed more people to be better nourished.

[21] Quantification of water saving was also made at the global level. The idea underlying such quantification is the variations in crop water productivity across countries and regions. At the global level, when a food crop is transferred from areas where water productivity is high (thus the virtual water content is low) to areas where water productivity is low (thus the virtual water content is high), less water would be used globally for the production of the traded food than if there were no trade, holding other factors constant. The reduced amount of water use represents a global water saving. The reported volume of water saving in the global trade of major crops and livestock products ranges between 300 km^3 a^{-1} and 600 km^3 a^{-1} [*Zimmer and Renault*, 2003; *Oki and Kanae*, 2004; *Hoekstra and Hung*, 2005; *Yang et al.*, 2006; *Chapagain et al.*, 2006a]. The results indicate that the water productivity is generally higher in the major food exporting countries than in the importing countries.

[22] *Yang et al.* [2006], however, pointed out that the significance of water saving is perspective- and scale-dependent. For water scarce countries, food import may reduce the local water demand for food production and thus alleviate local water scarcity. For the countries with abundant water resources, viewing water use efficiency from water saving perspective could be misleading. This is because saving water is not a motivation for the food import in these countries. An influx of foreign food could even suppress the domestic efforts in mobilizing the internal water resources. In the major exporting countries, the high water productivity is partly due to the high inputs of chemical fertilizer and pesticides. Pollution caused by the excessive application of chemical fertilizers and pesticides has become a major environmental concern in many food exporting countries [*Zehnder et al.*, 2003; *Davis and Koop*, 2006].

[23] At the global level, the volume of water saving depends on the width of the water productivity gap between exporting and importing countries and the quantity of food trade. The narrower the gap, the smaller the volume of global water saving holding other factors constant. Clearly, if the food importing countries can improve their water productivity, the gap will be narrowed and the volume of global water saving will decline. The improved water productivity may also enable importing countries to produce more food with a given amount of water. Food import requirement will be smaller and so will the volume of global water saving. For this reason, *Yang et al.* [2006] pointed out that viewing water use efficiency from global water saving per se is completely misaligned.

[24] *Horlemann and Neubert* [2006] rejected the global water saving from the perspective of the hydrological cycle on the Earth system. They argued that the global water cycle is quantitatively constant. From the global point of view, water cannot be conserved because transpired water is reusable a few days later as precipitation, though at another place.

[25] Green water contribution is another aspect in viewing the water use efficiency of virtual water trade. *Yang et al.* [2006] and *Chapagain et al.* [2006a] pointed out that the opportunity cost of the use of green water is lower than that of blue water for food production. This is because blue water has many functions and irrigation often generates a lower return than that from other uses. However, their analysis was qualitative based on some characteristic indicators of green and blue water resources. Neither of them has been able to provide a quantitative analysis.

[26] Although green water resource can only be used in situ, it can be ‘‘moved’’ and exported through agricultural production and trade [*Allan*, 2003b]. Several studies have quantified the green water contribution in food production and global virtual water flows [*Gerten et al.*, 2005; *Yang et al.*, 2006; *Chapagain et al.*, 2006a; *Liu*, 2007]. The results show that virtual water export is overwhelmingly ‘‘green’’ in the major food exporting countries, such as the USA, Canada, Australia, and Argentina. On global average, over 95% of crop related virtual water trade has the origin in green water. For individual crops, variations exist because of different prevailing production conditions in the major exporting countries of respective crops. Overall, an efficiency associated with virtual water trade may be said subject to the opportunity cost of green water use being indeed lower than that of blue water use in the exporting countries.

4. Virtual Water in Conflict Mitigation and National and Regional Water Scarcity Management

4.1. ‘‘Virtual Water Eliminates Water Wars?’’

[27] Water is a key strategic natural resource. The literature on water issues in the Middle Eastern and North African countries has been overwhelmed with elaborating conflicts and political tensions among the countries over the shared waters. Many have predicted that the increasing water scarcity in the region will inflame political tension among the countries and amplify the risk of wars over water [*Gleick*, 2002]. Statements made by some internationally high-profile people are particularly sensational. For example, in 1995, the World Bank Vice-President I. Serageldin stated that ‘‘many of the wars of this century were about oil, but wars of the next century will be about water’’ [*Crossette*, 1995]. In 2000, United Nations Secretary General K. Annan echoed that ‘‘fierce competition for freshwater may well become a source of conflict and war in the future (message to the Second World Water Forum in The Hague, delivered on his behalf by K. Toepfer, Executive Director of the United Nations Environment Programme, 22 March 2000)’’ The counter hypothesis, that water scarcity leads nations as well as people to cooperate, was largely ignored. This is despite the fact that thorough reviews of water events in the last 50 a suggested that they were to a large extent cooperative and only few were conflictive [*Revnborg*, 2004; *Wolf*, 1998, 2002; *Hefny and Amer*, 2005].

[28] On the basis of the observation on how food import had helped the countries in the Middle East and North Africa to cope with water scarcity without major wars over water, *Allan* [1996] pointed out that virtual water provides the water scarce countries with a potential solution to water scarcity and political conflicts. Much of his subsequent works were devoted to further elaborating this point [*Allan*, 1997, 2003b]. Several other studies also addressed the possibility of using virtual water to ease the political tension and conflicts over shared water resources among the riparian countries in the international river basins, notably the Nile, the Mekong and the Aral Sea [*Qadir et al.*, 2003; *Nakayama*, 2003; B. James, Averting conflict in the Nile basin, New Courier, 3 October, 2003, available at http://portal.unesco.org/en/ev.php-URL_ID=14364&URL_DO=DO_TOPIC&URL_SECTION=201.html]. The importance of accessibility to virtual water for conflict mitigation over water has increasingly been recognized [*Watkins and Berntell*, 2006]. However, skepticisms remain strong on politically independent governing systems that would be needed to enable an effective function of global virtual water trade for such purpose [*World Water Council*, 2004].

[29] Political relations are of importance for choosing food trade partners among countries. *Yang et al.* [2007] found that the European Union (EU) is by far the major food trade partner of the Middle Eastern and North African countries. The strategic EU-Mediterranean partnership emphasized by both sides (EU, Barcelona declaration and Euro-Mediterranean partnership, 2004, available at http://europa.eu.int/scadplus/leg/en/lvb/r15001.htm, 2004) has been conducive to forging the close trade ties. The role of the USA in the food trade in these countries is modest, except for cereal. It is noticed that the share of the USA in the cereal import to Libya is very small. The odd relationship between the two countries is apparently an important reason. The lesson learned is that virtual water trade needs the backing of amiable political relationships. Hostilities impede the development of virtual water trade.

4.2. Virtual Water Trade in Water Scarcity Management

[30] Recent years have seen increasing discussions on incorporating the virtual water strategy in the national and regional water scarcity management and food trade policies.

[31] China is one of the focusing countries of such studies. In many areas of the country, especially the North China Plain and the northwestern regions, water scarcity has been intensifying. A number of studies have suggested transferring virtual water to alleviate the regional water stresses [*Yang and Zehnder*, 2001; *Ma et al.*, 2005; *Zhao et al.*, 2005; *Yang and Zehnder*, 2005; *Guan and Hubacek*, 2007]. They all hypothesized that from the water resources utilization point of view, importing virtual water into the North China Plain may be more efficient than transferring the ‘‘real’’ water through the ‘‘South-North Water Transfer Scheme’’ (a project currently under construction that diverts water from the Yangtze River to northern China). However, they also pointed out that other factors concerning land resources, socioeconomic and environmental benefits and costs must be taken into consideration when assessing the trade-offs of different options. Nevertheless, these studies all stopped short of providing detailed analysis and quantification of the trade-offs. Similar shortcoming is also seen in the work of *Chen et al.* [2005], who investigated the water situation in the Heihe River basin in northwest China. Incorporating the virtual water strategy in dealing with the

water scarcity in the basin was suggested without providing systematic analysis of the trade-offs.

[32] Studies addressing policy implications of virtual water were also conducted for other water scarce countries and regions, such as Israel, India, South Africa, Spain, the Nile basin, and the Middle Eastern countries [*Wichelns*, 2001, 2005; *Allan*, 2003b; *Earle and Turton*, 2003; *Nakayama*, 2003; *Kumar et al.*, 2005; *Qadir et al.*, 2003; *Hoekstra and Chapagain*, 2007b; *Velazquez*, 2007]. By and large, these studies suggested a usefulness to consider the virtual water strategy in the national and regional water and food policy marking. Taking Egypt as an example, *Wichelns* [2001] discussed the virtual water strategy by describing a nation's goals regarding food security within a broader framework that includes other objectives such as providing national security, promoting economic growth, and improving the quality of life for citizens. He emphasized that virtual water alone is not sufficient to determine optimal policies for maximizing the social net benefits from limited water resources. Nevertheless, he pointed out that the virtual water perspective can be helpful in motivating public officials to consider policies that will encourage improvements in the use of scarce resources. Other examples given by *Wichelns* [2005] for illustrating policy relevance of virtual water from the food supply perspective include wheat production in Saudi Arabia and the production of sudan grass and ethanol in the United States.

[33] Almost all the virtual water studies touching the policy issues so far have only provided general suggestions and guidelines. There is no detailed research that quantifies the trade-offs of implementing the virtual water strategy in the areas concerned. One of the reasons would have been related to the fact that not all factors involved are easily quantifiable, such as food security, environmental externality of large water infrastructure, and political stability. The absence of the analysis of trade-offs impedes an active consideration of the virtual water strategy as a policy option in dealing with water scarcity.

5. Prospects of Future Virtual Water Studies

5.1. Data and Methodology Improvement

[34] Crop water productivity or virtual water content is an important basis underlying the virtual water studies. In the early virtual water literature, the data for crop water productivity were often too crude and unreliable to provide solid support to the studies on a large geographical scale with substantial internal variations. The development of the GEPIC model provided a systematic tool for estimating crop water productivity on a high spatial resolution. However, the accuracy of any model outputs depends largely on the quality of the input data. So far, detailed information on crop parameters, crop calendars, and agronomic practices is not available on a global scale. Many assumptions have to be made and default parameters have to be used in model applications. For the data that are available at the global level, such as land use and soil maps, the spatial resolution is often too coarse to meet the requirement for detailed analyses. Improving the data availability at all geographical levels and on finer spatial resolutions is one of the tasks the future virtual water studies need to undertake.

[35] Including green water resource is important in the national and regional water resources accounting and in the analysis of water and food relations. Initial work has been undertaken [*Gerten et al.*, 2005; *Falkenmark and Rockström*, 2006; Schuol et al., submitted manuscript, 2007]. For example, by applying the SWAT model (Soil and Water Assessment Tool), Schuol et al. (submitted manuscript, 2007) estimated blue and green water resources for the countries in Western Africa with monthly intervals at the subbasin level. Figures for green water storage, green water flow and blue water resources were provided with 95% prediction uncertainty (Figure 3). The country annual average data can be calculated by aggregating the monthly and subbasin figures. Making data for green and blue water resources availability at the same detail for all the countries in the world will be greatly useful for virtual water studies. In the meantime, coupling a GIS-based hydrological model (e.g., SWAT) with a GIS-based crop model (e.g., GEPIC) could also be a promising approach for strengthening the information basis of virtual water studies concerning impacts of changes in water availability on crop water productivity, and vice versa.

[36] As elaborated earlier, implementing the virtual water strategy can be an effective way to alleviate water scarcity in a country and region. Within the agricultural sector, shifting from low water use value crops to high water use value crops, and/or concentrating the production of a given crop to the areas where the water productivity for that crop is high could also improve the overall water use efficiency in the sector. The feasibility of implementing such a strategy, however, must be assessed against other alternatives and factors relating to natural, socioeconomic, environmental and political conditions and other regional and national objectives. It is important to emphasize here that the virtual water strategy is not exclusive to other options. Instead, it can be implemented conjunctively with other alternatives. Using the North China Plain as an example, options in dealing with the water scarcity at least include: increasing water supply by, e.g., transferring water into the region, desalinating seawater, reusing treated wastewater, etc. and transferring virtual water into the region to release irrigation water for other more beneficial uses. The two options are apparently not exclusive but can be implemented at the same time. Given the complexity of the factors involved, systematic analyses and modeling approaches need to be developed and applied to assess the trade-offs of individual alternatives and different combinations of them. Methods are also sought for appropriately incorporating the factors that are not easily quantifiable in the analysis.

[37] It is rather ironic that virtual water studies so far have been mostly carried out by scholars outside of water scarce countries. The discussion on the relevant issues has been overall rare within water scarce countries. One of the major reasons has been the skepticism to the reliance on food import. The overwhelming focus of virtual water studies on the international food trade has also been partly responsible for lacking interests in these countries. However, virtual water trade does not have to be confined to the international food trade. For a given country, especially a large country, resource endowments, including water resources, can vary significantly across regions/provinces. This fact renders a

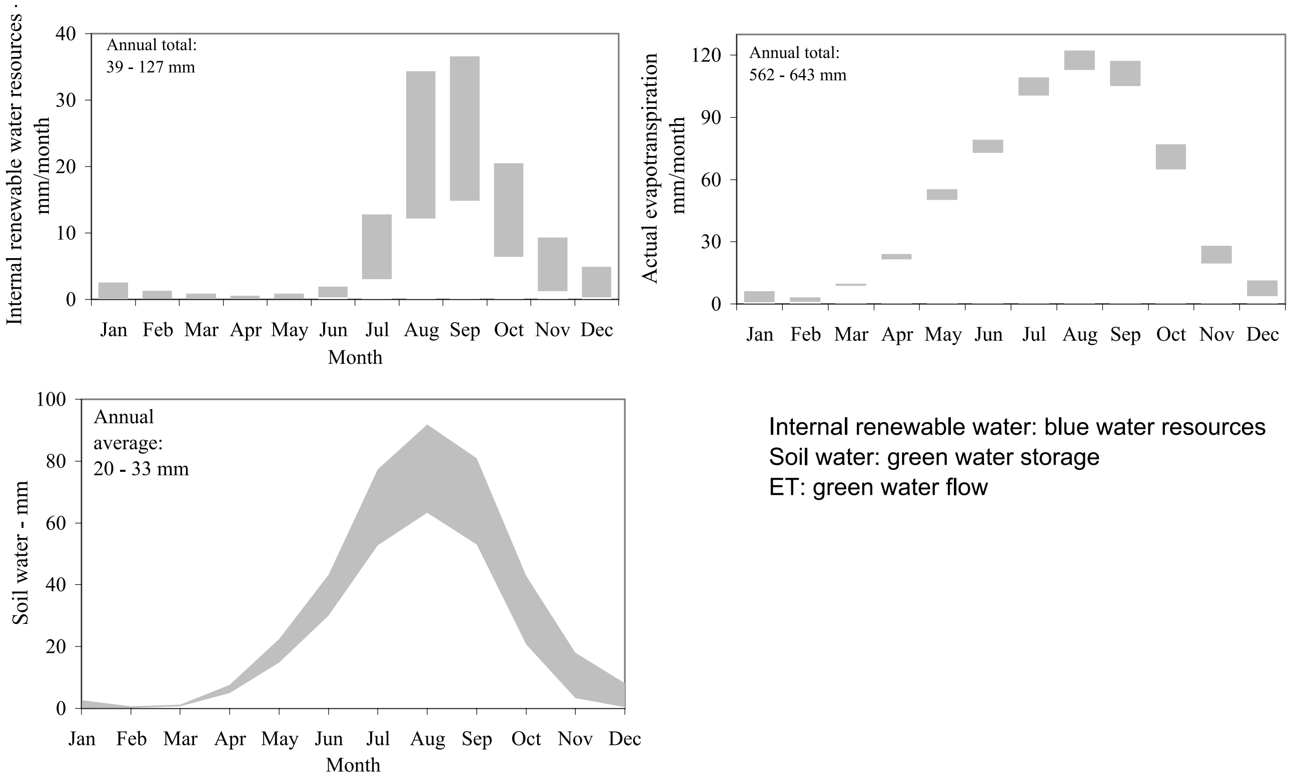

Figure 3. Water resources availability with monthly intervals and the 95% prediction uncertainty in Burkina Faso. Adapted from Schuol et al. (submitted manuscript, 2007).

possibility to apply the virtual water strategy within a country to alleviate regional water stress. More importantly, at the country and subcountry level, social economic factors and local specific conditions can be addressed more pertinently in assessing the applicability of the virtual water strategy. For this reason, there is a practical need for future virtual water studies to scale down the focus to the national and local level.

5.2. Beyond the Coping Strategy of Water Scarcity: Virtual Water in Integrated Water Resources Management

[38] Traditional water resources management was primarily conducted within administrative boundaries. Nowadays, catchment and river basin perspectives have been emphasized [*Bouwer*, 2000; *Zehnder et al.*, 2003; *Molden and Bos*, 2005; *Rijsberman*, 2006]. The consideration of virtual water further extends the scope of water resources management beyond the boundary of natural watershed. Since the water use of a given watershed can be influenced by water use outside of the watershed through virtual water transfers, it is not sufficient to confine the water resources management to the basin or catchment scale. This fact also brings the scope of virtual water beyond a coping strategy of water scarcity for food importing countries and regions only.

[39] Previous studies of virtual water have focused overwhelmingly on the food importing side. Attention has been lacking to the food exporting side concerning water endowments and resource use efficiency, as well as environmental impacts associated with the production of goods for export. Discussing water footprint is a useful step to address the interconnections of water consumption in one country and region with the water resources use and environmental impacts in other nations and regions. However, a systematic analysis of the interconnections requires quantification of the impacts and feedbacks of various intertwined factors associated with the trade from both the importing and exporting perspectives. This task involves the knowledge of many disciplines, e.g., hydrology, crop science, agronomy, social sciences, economics, political science, management, mathematics and modeling. This nature calls for the future virtual water studies to put more emphasis on interdisciplinary collaboration.

6. Comments and Discussions

[40] Considerable progresses have been made during the last decade in the virtual water studies in terms of the understanding of the role of virtual water and the methodologies for the analysis. However, many questions and debates remain. One of them is on the conceptual basis of virtual water. *Allan* [2003a] stated that "virtual water is something of a descendant of the concept of comparative advantage." *Lant* [2003] suggested that virtual water is the optimal phrase for describing opportunities to enhance water management by accounting for the water embedded in crops. In his view, virtual water trade is also an application of basic principles of economic geography, which recommends that economic activities requiring inputs with low values per unit of weight should be located close to the sources of those inputs. On the other hand, *Wichelns* [2003, 2005] argued that virtual water is merely a metaphor, not a concept because it addresses only the water endowment, but not the technology of production or the opportunity costs of

water and other limited resources. *Merrett* [2003] rejected the virtual water concept from a philosophical perspective concerning particularly the language and terminology. He argued that "virtual water" is real water, and there is no virtual water trade but food trade. In order to avoid unproductive debate and ease the anger of some economists, recent publications have seen a tendency of replacing virtual water trade with virtual water transfer or virtual water flow. *Horlemann and Neubert* [2006] pointed out that according to the Heckscher-Ohlin theory, the international trade is regulated in accordance with comparative cost advantages. As in many countries water prices either do not exist or are set so low that they in no way reflect the value of water, the current virtual water trade is not regulated by comparative cost advantages, but by absolute water scarcity. They argued that if an economically appropriate value was attached to water or to its supply, there would be no need for a virtual water trade strategy under a special promoting policy because trade would regulate itself in accordance with comparative cost advantages.

[41] On the basis of the virtual water studies reviewed in this paper, we consider that virtual water can neither be completely represented by the notion of comparative advantage nor be merely regarded as a metaphor. Virtual water concerns the water scarcity, food security and trade nexus in the context of natural, socioeconomic and political systems in regions, countries and the whole world. It is a concept of multiple facets. The challenge in conceptualizing virtual water lies largely in the unique nature of water resources: originated from rainfall which is free of charge, renewable at various rates (from hours to years), variable in space and time (values of water also vary accordingly), highly mobile, costly to store, almost impossible to possess by individuals, disastrous when too much or too little. Detailed discussions on some of these characteristics were given by *Savenije* [2002] and *Savenije and van der Zaag* [2002]. There is not any other natural resource in the economic sense that has all the characteristics of water. This has made the virtual water trade difficult to be treated directly with the classical trade theories. Clarifying the conceptual basis and reaching agreement on virtual water is important for the disciplinary development and for a proper delineation of the scope of virtual water. This will require continuous efforts and involve intense communications among the scholars from different disciplines over a considerable period of time. With the advance in virtual water studies, the concept of virtual water will continue to evolve. From this point of view, the concept of virtual water is still unfolding.

[42] Some criticisms on virtual water are also worth noting. The most common ones are that the poor countries cannot afford virtual water import and virtual water import makes the receiving country dependent upon the international market [*Kumar et al.*, 2005; *Ioris*, 2005]. These criticisms have been often voiced loudly at international meetings, workshops and on other national and international occasions. The criticisms may be understandable, but do not quite touch the point. Virtual water by its origin describes the fact that many water scarce countries are importing (although often unconsciously) a large portion of their food which has effectively and silently reduced the domestic water demand for food production that otherwise would be needed. The situation implies that when water is in absolute scarcity, virtual water import is necessary. The virtual water strategy seeks ways to consciously and efficiently utilize the internal and external water resources to alleviate water scarcity in a country or a region. This, however, by no means implies that importing food is the only response the water scarce countries and regions should and can take. Other measures concerning the supply and demand sides of water management are imperative. The argument here is that the virtual water strategy should be an integral component in the whole package of integrated water resources management.

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