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Unfolding the potential of the Virtual Water concept.
What is still under debate?

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Abstract

The concept of *virtual water* refers to the volume of water used in the production of a commodity or a service. The concept was identified by the geographer Tony Allan in the early 1990s, to draw attention on the global economic processes that ameliorate local water deficits in the MENA region and elsewhere. Since its inception, the virtual water concept has inspired a flourishing literature on how to address global water resource scarcity *vis-à-vis* commodity production and consumption in a variety of disciplines, but also has been the object of a number of critiques. Against this backdrop, the aim of the study is, first, to conduct a thorough review of the conceptual definition of the concept, its critics and applications. Secondly, to analyse its theoretical underpinnings and, in particular, its relationship with economic theory. The study argues that, despite not being a policy tool itself, the virtual water concept can reveal aspects related to production, consumption and trade in goods which monetary indicators do not capture. Its potential as an indicator for informing decision-making in water management and policy, as well as commodity trade policy, still has to be fully unfolded.

JEL codes: F18, Q25, Q56

Keywords: virtual water, water footprint, green and blue water, water scarcity and security, water policy, international trade

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1. Introduction

In the early 1990s, the geographer Tony Allan coined the term "virtual water" in order to draw attention on the global economic processes that ameliorate local water deficits in the Middle East and North African region as well as elsewhere (Allan 1993). Since then, it has steadily gained prominence as an *indicator*[1] that relates water inputs and industry outputs as well as for analysing commodity trade flows in terms of water resources. Any products has in fact a virtual water content, that is, the volume of water that is actually used to produce that good.

The exchange of water as 'embedded' in traded goods brings about the so-called *virtual water trade* (VWT) (Chapagain and Hoekstra 2003). If a country exports water-intensive products to another country, it also 'exports' in fact the volumes of water 'embodied' in those products[2]. Commodity exports (imports) fundamentally act as channels to transfer substantial amounts of water (from) abroad in the form of an input 'embedded' in the exported (imported) commodities via trade. It has been shown that this market-mediated mechanism have enabled water-scarce regions, such as the Middle East and North Africa, to cope with water scarcity over the past few decades without implementing major changes and reforms in water allocation, management and policy, while avoiding conflicts over water (Allan 2001, 2002, 2003a; Antonelli *et al.* 2014). VW steps beyond traditional accounts of 'real' water flows, to include a traditionally invisible dimension that links global and national economies (Warner and Zeitoun 2008). By making visible the linkage between consumers in water-deficit countries and producers and water resources in distant water-surplus economies (Allan 2003a), VW reveals the global dimension of water resource scarcity (Hoekstra 2011; Hoekstra and Mekonnen 2012).

The concept of VW has been used as a novel quantitative indicator for the study of water resources use in agriculture and livestock production worldwide, and has provided the conceptual ground for the development of the *water footprint* indicator, developed by Arjen Hoekstra in the early 2000s (Hoekstra 2003). The two concepts are often erroneously used as synonymous although the perspective they bring to water resources management policy is dramatically different (Velázquez *et al.* 2011).

Finally, the use of the VW concept has drawn attention on the different sources of water 'embedded' in agricultural products and, more specifically, emphasised the role that soil water - also referred to as 'green water' - invisibly plays in underpinning global water and food security. Green water was first identified by Falkenmark in 1995, but its importance has been neglected in water resources assessments until very recently. It supports rainfed agricultural production as opposed to 'blue water', which is the water source for irrigated agriculture, as well as for industrial and municipal use.

Despite the VW concept has been very helpful in gaining the attention of public officials and policy makers, the extent to which it can be used as a policy criterion is still under debate (Wichelns 2010). Several authors have conducted empirical analyses

[1] In what follows, the words 'indicator' and 'concept' will be used as synonymous when referred to virtual water.

[2] This mechanism is not only limited to water, but can be extended to any other input factor employed in the production process. Potentially, one might compute the virtual labour, the virtual land, the virtual oil, and the many other "virtual factors" embedded in any good.

of VW 'flows' between countries, by comparing water requirement of crops and livestock products involved in international trade, concluding that some countries are net importers of VW, while others are net exporters. On the basis of these results, combined with the 'prescriptions' of traditional international trade theories, these studies suggest that water short countries should import water intensive goods and services, whereas water abundant countries should export water intensive products. Other scholars claim instead that this line of reasoning is not based on a legitimate conceptual framework and that it can lead to inaccurate or even misleading policy recommendations. These issues will be addressed in detail in Section 3 and Section 5.

Another source of critique regarding the reliability of the concept as a policy criterion comes from the usefulness of the distinction between the *green* and the *blue* water components of VW and water footprints. While agreeing that such dichotomy has helped to increase public awareness of an important dimension of water resource management, some authors say that the notions do not establish a new conceptual framework that can be used alone to guide policy decisions. Other authors, supporting the importance of the distinction, legitimate their thought on the basis of the different opportunity cost of the water sources, proposing the 'trade' of green VW (which has a lower opportunity cost) in exchange of blue VW (which has a higher opportunity cost) when possible, to generate meaningful water savings. Yet, there is no a common legitimate conceptual framework regarding how to compute the opportunity costs of water. These issues will be addressed in detail in Section 4.

The criticism against the VW concept mainly originated from two interrelated aspects: on the one side, there still exists some ambiguity associated with the meaning of the VW concept itself, that is, "what is VW and what is not", generated by its trans-disciplinary nature; on the other side, *virtual water* suffers from being inevitably associated with one of the most complex good from a physical, social, ethical and economic point of view, that is water[3]. There is no other comparable concept, with maybe the exception of concepts of virtual carbon and more recently virtual land, which has generated a similar vast body of (debated) literature.

The present review aims to address these critical aspects regarding the VW concept/indicator and its applications, providing a comprehensive and discussed review of: (i) the debate on the economic foundation of the concept; (ii) the contributions which distinguish between the sources of water, when computing the VW 'flows'; (iii) and the relevance and the reliability of this indicator in guiding policy decisions. Compared to other surveys available in the literature, our work adds a novel contribution to the literature, as it goes beyond the mere water footprint concept critique (Chenoweth 2014; Perry 2014) and the policy purpose limitations of the concept (Frontier Economics 2008).

[3] From a physical point of view, water is a partially renewable resource, whose renewability differs over space and time. From an economic point of view, unlike other scarce goods, water does not typically possess a formal market in which prices can be formed and used as information signals in the allocation of resources. Overexploitation, unsustainable economic development, lack of efficient coordination among economic agents are all unavoidable consequences. All these issues, together with those regarding the socio-ethical considerations about the water right and security, generate ideological thoughts and subjective judgments, which unavoidably affect and alter the meaning and the usefulness of the VW concept.

The remind of the article proceeds as follows. Section 2 provides a brief introduction on the origin of the VW indicator, clarifying what it is intended for, how it is computed and its main field of applications. Section 3 discusses the strengths and flaws of the concept found in the current economic literature. Section 4 reviews the strands of literature on virtual water that distinguish between the sources of water 'embedded' in commodity trade. Section 5 discusses the application of the VW concepts as an indicator for providing policy recommendations. A final section draws some conclusions and points to further developments of the concepts.

2. Background

The virtual water *content* (or simply virtual water) is an indicator used to compute the volume of water that is actually used to produce a good or a service. Virtual water *trade* is the amount of water embedded in international traded commodities. A virtual water *flow* is the amount of water virtually flowing from one place to another as a result of commodity trade.

Since its inception, the concept of VW has been the object of a flourishing literature (among others, Bouwer 2000; Allan 2001; Earle 2001; Wichelns 2001; Allan 2002; Yang and Zehnder 2002; Allan 2003a; Lant 2003; Merrett 2003; Wichelns 2004). Over the past few years, a number of global studies have quantified the amount of VW 'flowing' across borders (Hoekstra and Hung 2002, 2005; Zimmer and Renault 2003; Oki and Kanae 2004; Chapagain and Hoekstra 2004; De Fraiture *et al.* 2004; Hoekstra and Mekonnen 2012). The most recent estimates provided by the Water Footprint Network reveal that the global sum of international VW 'flow' related to trade in agricultural and industrial commodities in the period 1996-2005 accounted for 2,320 Gm^3/y on average, of which 68% originated from green (soil) water; 13% from blue (surface and ground-) water; and 19% from grey (polluted) water resources (Hoekstra and Mekonnen 2012). VW 'flows' between nations are substantial, accounting for over 1,000 billion cubic metres annually (Hoekstra and Hung 2002; Chapagain and Hoekstra 2003; Zimmer and Renault 2003; Oki *et al.* 2003). North and South America, Australia, most of Asia and central Africa are major 'exporters' of VW. Europe, Japan, the Middle East, North and Southern Africa, Mexico and Indonesia are net VW 'importers' (Hoekstra and Mekonnen 2012).

VWT has been studied at different spatial scales but mostly for a specific time period (such as, Yang and Zehnder 2002; Velázquez 2007; Roson and Sartori 2013). The analysis of the temporal evolution of VW 'exchanges' can be found instead in Liu *et al.* (2007) and Oki and Kanae (2004). More recently, a number of studies have applied complex network analysis to study VWT as a global network (Barrat *et al*. 2008), unveiling the main characteristics of its topological structure (Konar *et al*. 2011; Tamea *et al*. 2013; Shutters and Muneepeerakul 2012; Suweis *et al*. 2011; D'Odorico *et al*. 2012), as well as its temporal and geographical evolution (Carr *et al*. 2012; Dalin *et al*. 2012; D'Odorico *et al*. 2012).

VW has been defined as a "genuinely trans-disciplinary subject" (Hummel *et al*. 2006: 3). Originating within the field of geography, VW and derivative concepts – such as, the water footprint – have steadily been employed in other fields, and have been used as analytic tools in several research areas, ranging from natural to social sciences, and encompassing environmental, economic, social, cultural, political and institutional aspects at the local, regional and global scale (e.g. Hoekstra and Chapagain 2008; Hoekstra and Mekonnen 2012).

In what follows, the concept of VW will be reviewed and commented upon. A second sub-section is devoted to a short description of the main methods for computing the VW content of products and VWT 'flows' originating from commodity trade.

2.1 Virtual water: insights behind the concept

Water use has traditionally been managed in a national or local perspective. Countries formulate national water plans by looking at national demand and supply. However, since water is implicitly or explicitly traded as an input factor through the international trade of goods and some water resources are transnational, a widened and more global approach to water resources seems to be necessary to tackle the water scarcity issue in a sustainable way. To this end, the concepts of virtual water, virtual water trade and water footprint have been introduced. Based on the idea that water is "virtually" embedded into goods and services, as a factor of production, these indicators highlight the relationship between water use, production and consumption of commodities.

The concept has both an *intensive* and an e*xtensive* component (Allan 2003a). The former describes the role of water in food production and the role of trade in providing food security; the latter instead, refers to the 'invisible' link that trade establishes between the source of water demand and the site of water consumption. Over the years, the concept has provided a useful analytical perspective for analysing how water-scarce nations achieve water security and has been variously applied as a 'metaphor' for describing the water 'embedded' in crops traded in the global market. It has played an important role in gaining the attention of public officials and in encouraging the consideration of scarcity values with regard to the inputs used to produce goods and services when designing public policies (Wichelns 2005). The political dimension of the concept and the role it plays in solving geopolitical problems (Allan 1998), and in mitigating conflicts over transboudary water (Zeitoun and Allan 2008), have been emphasised.

Two different approaches have been applied to provide a more precise quantitative definition of the term "virtual water". In the first approach, the VW content of a commodity, good or service is defined as "the volume of water used to produce it, measured at the place where it was actually produced". In this case the adjective *virtual* "refers to the fact that most of the water used in the production is in the end not contained within the product" (Hoekstra 2008). Accordingly, estimates of the VW content of a product must consider the place and period of production, the point of measurement, the production method and associated efficiency of water use, as they influence the amount of water used in the production chain (Hoekstra 2003). The second approach instead, defines VW as the amount of water that *would have been* required to produce the product at the place where the product is consumed (Hoekstra 2003). The former definition takes a producer perspective; whereas the latter emphasises the potential water savings brought about by VWT to the importing country.

In both the approaches, VW refers to the sum of the water that has been (or would have been) used to produce the good or service in the various steps of the production process, as opposed to the *real* water content of that product. The real water content of a product is generally far lower than the *virtual* water content, and so is the volume of water required by the transformation or processing of the product (Zimmer and Renault 2003). For instance, the VW content of a ton of wheat is, on global average, 1300 m^3; whereas the real water content is less than 1 m^3/ton (Chapagain and Hoekstra 2004).

The insight behind the concept could be usefully applied to any natural resource or other embedded input that moves across boundaries with the aim of measuring the external cost associated with the use of that natural resource. It has been applied, for instance, to describe the 'virtual' carbon content of imports and to investigate carbon emissions generated by foreign consumption, which are often referred to as 'carbon leakage' (Atkinson *et al*. 2010).

2.2 Computing the virtual water content and virtual water 'trade' flows

The VW content of a product is the volume of water that is actually used to produce that good. It depends on several aspects, such as its production conditions, including water use efficiency and the place and time of production. For instance, producing one kilogram of grain in an arid country can require two or three times more water than producing the same amount in a humid country (Hoekstra 2003).

There is no uniform methodology to compute such indicator. Traditionally, it is calculated applying the method proposed by Hoekstra and Hung (2002). Based on the idea that different products and different production processes require different amount of water, they propose three methods, each associated with a product category: primary crops, crop products and life animals. The computing procedure is here briefly explained.

The VW content or the specific water demand SWD (m^3/ton) of a primary crop *c* in a certain country *n* is computed by dividing the crop water requirement CWR (m^3/ha) by the crop yield CY (ton/ha). In formula:

$$SWD_{n,c} = CWR_{n,c}/CY_{n,c} \tag{1}$$

There are two main models generating the data on SWD: the FAO's CROPWAT model and the H08 global hydrological model (Hanasaki *et al*. 2008a, 2008b). More recently, Fader *et al*. (2010) developed a dynamic global vegetation and water balance model (LPJmL) to better quantify the VW content of two primary crops: cereals and maize. The crop water requirement is computed by estimating the accumulated crop evapotranspiration, ET_c (mm/day), which is obtained by multiplying the reference crop evapotranspiration ET_0 by the crop coefficient K_c, as follows:

$$ET_c = K_c * ET_0 \tag{2}$$

The VW content of crop products is based on the product fraction (equal to the amount of crop product obtained per unit of primary crop) and the value fraction. The latter is the market value of one crop product divided by the aggregated market value of all crop products derived from one primary crop. Finally, the VW content of life animals is calculated considering the VW content of their feed and the volumes of drinking and service water consumed during their lifetime.

Based on the methodology so far described, Zimmer and Renault (2003) extend the analysis of Hoekstra and Hung (2002) to five products categories (primary products, processed products, transformed products, by-products and multiple products) identifying specific accounting methods for each of them. More recently, Antonelli *et al.* (2012) put forward a systemic input-output method to compute the VW contents of agricultural and other products, pointing out that the traditional accounting method for VWT consider only direct (final) water usage (the SWD) thus ignoring the many indirect (intermediate) uses of the resource as a fundamental input to production. The use of this methodology brings about consistently different results in the VWT among the Mediterranean countries, compared with non-systemic accounting methods.

The computation of VWT is based on the calculation of product and site-specific VW contents, as defined above. As previously mentioned, VWT refers to the exchange of water that takes place as implicit in conventional commodity trade (Allan 2001; Chapagain and Hoekstra 2003). When a good is exported (imported), its VW content is implicitly exported (imported) as well. VWT are therefore computed on the basis of international trade data by multiplying the country-specific VW content of the various crops by the traded volumes of goods. That is, a trade matrix of value or quantity can be translated in terms of VW equivalent 'flows', enabling us to appraise the *virtual water balance of a country*. The VW balance of a country is equal to the 'gross import' of VW minus the 'gross export', over a certain period of time (Hoekstra *et al.* 2011). A positive VW balance indicates a 'net inflow' of VW to the country from other countries; whereas a negative balance indicates a 'net outflow' of VW.

3. Virtual water and economic theory: the debate

The legitimacy of the VW concept in terms of economic theory has been questioned by a number of authors. Following Reimer (2012: 135), this paper upholds that the idea of virtual water concept is an "inherently economic concept". In what follows, the economic foundation of the concept are discussed with the aim of clarifying a number of unsolved issues which are still under debate within the current literature on virtual water economics.

3.1 Economic origins of the concept

The concept of VWT revolves around a number of economic paradigms developed in the standard international trade literature, in particular within the Ricardian theory of comparative advantage and the H-O model of factor endowments (Heckscher 1919; Ohlin 1933; Samuelson 1949). The economic dimension of the concept was also stressed by the founder of the VW concept, who defined it as a descendant of comparative advantage" (Allan 1997, 1998, 2001, 2003a).

The conventional theory of comparative advantage, better known as the Ricardian model, is the economic theoretical frameworks behind the VWT concept. According to the theory of comparative advantage, a country is in fact considered to have comparative advantage in producing a good if the opportunity cost of its production, with respect to other goods, is lower than in its trading partners. According to this theory, a country should therefore specialize only in the production of goods and services in which it does have a comparative advantage, thus in relation to its production technology. Through trade, a country can consequently obtain a net gain by exporting the products for which it possesses a (relative) comparative advantage in production, while importing products in which it has a (relative) comparative disadvantage. Applied to water, a water-scarce country should have a comparative disadvantage in producing water-intensive goods and thus be a net importer of these goods. Under the predictions of the Ricardian model, virtual water trade flows from a water-rich a to water-scarce country are simply the natural consequence of the comparative advantage a water-rich country has in producing water-intensive goods.

The second conventional international trade model used to test the economic foundation of the VW concept is the Heckscher-Ohlin (H-O) model (Heckscher 1919; Ohlin 1933). It explains international trade flows on the base of relative factors' abundance, positing that an economy will be a net importer in the goods whose production is intensive in the factors that are relatively scarce within the country. It stems from the Ricardian paradigm, because it relates the comparative advantage of a country in a certain sector to the relative abundance of primary resources endowments used in that industry. Since primary factors include water resources, when the H-O model is applied to water, it implies that a water-scarce economy will be an importer of water demanding goods. However, this is not the case for many economies in the world, which (i) produce (and export) water-intensive goods and (ii) have a positive VWT 'balance' (i.e., exports minus imports of VW, Hoekstra *et al.* 2011) under sever water scarcity conditions. This fact is at the base of most economic critique to virtual water.

The discrepancy between the Ricardian/H-O model prescriptions and the actual VWT 'flows' can be explained by the fact that, despite the proved gains from trade, several real aspects are normally ignored in these standard neoclassic models. First, as Tietenberg (2006) pointed out, resource costs (here water) are not accounted for in the neoclassical production function, where output is only a function of labor and capital inputs. If water is completely free or under-priced, market distortions and inefficiencies in the use of the resource consequently arise. In water-surplus countries, water resources are consumed (and polluted) for producing (also) export commodities, but neither the charges for water use nor the price of traded commodities reflect the economic and environmental cost of production. This (partially) explains why it is very unlikely that global production and trade patterns will reflect different water endowments and comparative advantage in water resources unless the value of water is recognised (Wichelns, 2004).

Second, Ruhl *et al*. (2007) claim that VW in agricultural products mainly originates from rainfed (*green*) water, whose costs are not accounted for. This is also the case of the costs of pollution at the place where a commodity is produced (Qadir *et al*. 2007). Transport costs are also neglected by assuming them to be zero, and if considered, they are underestimated because of the several energy subsidies which keep the energy price (and then the real cost of transportation) below the true marginal opportunity costs, thus distorting international (food) trade (Daly and Farley 2004). Verma *et al*. (2007)

highlight that there are several practical constraints associated with the concept of VW transfer, which include, among others, the need for nations to follow a policy of food self-sufficiency instead of food security. Finally, the production of most water-intensive goods, such as crops or livestock products, requires land as a complement to water. Thus, land availability can play a more influential role than water in determining whether a country is a net importer or exporter of VW, especially in the case of free, under-priced or unregulated water resources.

In fact, the literature offers several contributions which focus on the relationship between water endowments and agricultural trade flows (such as, Yang *et al*. 2003; De Fraiture *et al*. 2004; Ramirez-Vallejo and Rogers 2004; Yang and Zehnder 2007; Debaere 2014; Fracasso 2014) and water endowments and VWT 'flows' (Kumar and Singh 2005; Novo *et al.* 2009; Fracasso *et al.* 2014). These studies attempt to determine to what extent water availability affects agricultural trade and VW international trade respectively, finding contradictory results (that is, agricultural imports are not necessarily linked to relative water scarcity) with the H-O model predictions.

As usefully pointed out by Roson and Sartori (2010), however, trade patterns comply to the H-O model only in properly functioning and competitive markets, which is not the case of water resources. Water prices are in fact generally kept artificially low, possibly reversing the H-O theorem so that water-scarce countries turn out to be VW 'exporters' and, vice versa, water-rich countries are virtual water 'importers'. As Reimer (2012) put it, "we should not be surprised (...) if water is not a major determinant of trade patterns" as water generally accounts for a share of production costs which is very small or often close to zero. Moreover, most of the existing H-O studies so far applied to the relationship between water endowment and VWT have not included the green water component, or have not accurately distinguished between the different water components (i.e., green, blue, grey), so they could have originated misleading and inadequate results and predictions.

Another pertinent comment to this discussion can be derived from Chichilnisky (1994) and her model of trade in the context of different property rights. Unlike the neoclassical H-O framework, this model assumes that property rights are not well defined and enforced in the case of environmental resources, like water, and that differences in property rights between two countries may act as an incentive for trade among otherwise identical regions. By applying this model to water, the 'export' of VW can be harmful (Ansink 2010): countries with weak property rights, independently from their availability of water resources, might have an advantage in relative costs of producing (and exporting) water-intensive goods, since the social cost of water extraction is generally not accounted for from a societal point of view. As suggested by Chichilnisky (1994), when property rights are not well defined, there exists an overexploitation of the resource and severe distortions.

Decisions on a specific good trade are influenced by many more factors than relative water abundance or shortage. These are the availability of labor and land, knowledge and capital, as well as a country's comparative advantage with respect to certain types of production, national policies, domestic export subsidies and import tariffs on food products, market-failures and other distorting measures associated with water resources trade barriers (Chapagain and Hoekstra 2004; Kumar and Singh 2005; Zeitoun *et al.*

2010). Having all factors an important role in world water distribution, it is not suggested, that the idea of releasing domestic water is always the main driver behind the VW 'imports' (Hoekstra 2008). This implies that global 'trade' in VW can only *partly* be explained on the basis of relative water abundance or shortage (De Fraiture *et al.* 2004).

Besides the Ricardian theory of comparative advantage and the H-O model of factor endowments, it is useful to refer to Krugman's new trade theory (1990), stating that there are inherent advantages to specialization, even if there are no differences in endowments and production technology between countries. According to this theory, trade, especially between similar countries, mainly takes place because of the need to specialize and take advantage of increasing returns, rather than taking advantage of inherent differences between trading partners. In this sense, trade is mainly influenced by and is a result of economies of scale (Krugman 1980, 1990, 1991). However, most of the agricultural commodities, which originate the largest share of trade in VW (over 90% according to Mekonnen and Hoekstra 2012), are not characterized by economies of scale.

3.2 Main critics from economists

One of the first economists who initiated the economic debate on the VW concept is Merrett (1997, 2003), who argued that there was not such thing as virtual water 'trade', as the amount of water contained in traded goods is always far lower than the totality of water that was used in their production. In his view, VW is thus only a 'metaphor' (1997) as it is *food* that is traded and not water. The 'virtual water flow' term is thus too vague and suggests that authors simply write of 'food imports'. A late reply arrives from Reimer (2012:135), who comments on Merrett's statement claiming that it fundamentally overlooks "the long and well-established tradition in international economics that views trade as the international exchange of the *services of factors* embodied in goods", which makes VWT the import of the services of water.

A second flow of critics comes from Wichelns (2004) who, instead, criticizes Allan (2003a) and Lant (2003) for drawing a close parallel between comparative advantage and the concept of VW. He claims that the concepts cannot be related in such way, as VW addresses only water resource endowments, i.e. only *one* of the factors that should be considered when determining a country's comparative advantage, while ignoring the role of both opportunity costs and production technologies in influencing trade patterns. In other words, he insists on the fact that VWT cannot entirely rely on the comparative advantages theory. VW addresses resource endowment but not technology. Nonetheless, the latter has a non-negligible role in determining water intensive commodity specialization. Technology has an important transfer cost, most especially in agriculture, where rates are high, implying strong diversity between countries. In other words, Wichelns adds that the key issue in determining comparative advantages is the opportunity cost of production, and this may not necessarily be consistent with expectations based on resource endowments in two trading regions. In a later work, Wichelns (2007) clarifies that VWT on its own only considers water resource endowments and this does not make it equivalent to the economic theory of comparative advantage, without taking into account the scarcity of water or its opportunity costs, as well as production technologies and relative scarcity of other key resources such as land, labour and capital.

Reimer (2012) reacts to Wichelns by arguing, on the contrary, that the VW concept is consistent with comparative advantage as a country's relative abundance (scarcity) of water endowments *does* represent a source of comparative advantage (disadvantage). However, this source of comparative advantage is often *latent* due to the very high costs and the policy-related trade barriers associated with agricultural trade, which fundamentally distort prices and obscure any potential comparative advantage (or disadvantage) arising from relative water endowments. As a result, the pattern of VWT deviates from the predictions of the H-O theorem and comparative advantage. Reimer concludes that any theoretical and empirical shortcoming associated with the concept of VW are due either to deviations from its theoretical assumptions, or arise because what happens in the real world deviates from the assumptions of economic theory.

Later, Ansink (2010) refutes the use of comparative advantages to judge the role of virtual 'flows' on global water saving. The author claims that trade can lead to water saving only if the country that has a comparative advantage in water, also has an absolute advantage in the resource. In this context, if the exporting country has a relative advantage, while the importing country has an absolute one, then the latter will increase his already important water resources. This can explain confusing results, such as, why countries such as Norway or Sweden are net VW 'importers', regardless of their abundant water endowment. This is explained by the fact that these developed countries are rich in the second factor of production: capital. Thus, they have a comparative advantage in non-water intensive goods. Moreover, in these countries, the abundance endowment of water is not associated with likewise arable land. The positive correlation between a country's VW 'exports' and the amount of arable land per capita is emphasized also by Kumar and Singh (2005), stating that the quantity of both available land and freshwater limit the production of agricultural goods, thus affecting the 'export' of VW.

Reimer (2012) replies to Ansink's argument, demonstrating that it is false, and that an economic approach regarding VW 'flows' based on the theory of comparative advantages is justified. He believes that the problem is that if the foreign country has more water in absolute terms but not in relative terms, then it must have more capital both in absolute and relative terms. The country is therefore bigger and benefits from more water but consumes relatively less water it compared to the rest of the world. Once the borders open, relative factor consumption of the foreign country will near its partner's, it will balance itself out. Ansink then refutes the theory by assuming that a small country, specialized in water-abundant products, can always be a net importer of VW, if it imports enough capital intensive goods. Reimer proves that VW 'exports,' intrinsic to the water intensive good, will never be cancelled out by the water found in the capital intensive good. According to his studies, the existence of this limit is due to the consumers' budgetary constraint.

The VW concept has, therefore, a great deal of legitimacy when viewed from the perspective of standard international trade theory. As Reimer (2012) states, any weak performance arises when real world situations deviate from the assumptions of the standard trade model. For this reason, a correct definition to avoid misconceptions, when referring to virtual water trade, is "trade in the services of water". "This type of phrase has indeed a long history of use by international trade economists, and recognizes that in trading goods across national borders, we are effectively trading the services of water that was used to produce the goods" (*ibidem*: 139).

4. Green and blue water and virtual water 'trade'

Virtual water studies have mainly focused on the water-saving effect brought about by international food trade and on the role it plays in compensating for local water deficits. The differentiation between the different sources of water 'embedded' in traded products, i.e. the water used in the production process originates, has been introduced only recently, in the early 2000s. A few studies have differentiated VW 'flows' between surface and underground flows (hereby referred to as *blue water*), or water in the root zone (*green water*).

Green water refers to precipitations that seep and stock in non-saturated soils to take the form of moisture (Falkenmark and Rockström 2006). It is the water resource used by non-irrigated agriculture, therefore it is highly correlated to a country's precipitation pattern, soil profile and climatic conditions. According to Fader *et al.* (2011), green water accounts for the overwhelming majority of total water use in the agricultural sector (84%) as well as of the water 'embedded' in global exports of agricultural products (94%). Blue water instead flows from rivers to oceans, and can be found in lakes, ground-water sheets and canalizations. It can be qualified as 'liquid' and is used for irrigated agriculture as well as for industrial and municipal uses. Managing water as an *economic good*, in order to achieve efficient and equitable use and also to encourage conservation and protection of water, has been stressed by the Dublin International Conference on Water in 1992 (OECD 2010).

The majority of the works stress the importance of considering the role played by green water in global food and water security (Allan 2001; Rockström 2001; Falkenmark and Rockström 2004, 2006; IWMI 2007; Rockström *et al.* 2007; Aldaya *et al.* 2008; Rost *et al.* 2008; Yang and Zehnder 2008; Liu *et al.* 2009; Rockström *et al.* 2009; Rost *et al.* 2009; Aldaya *et al.* 2010; Hoff *et al.* 2010; Rockström *et al.* 2010; Gerten *et al.* 2011; Allan 2013), whereas some others have incorporated the notions of green and blue water by differentiating the two sources in VW 'flows' for different crops and aggregations of agricultural goods (Hoekstra and Hung 2002; Yang *et al.* 2006; Liu *et al.* 2009; Aldaya *et al.* 2010; Hanasaki *et al.* 2010; Mekonnen and Hoekstra 2010a, 2010b; Zeitoun *et al.* 2010; Fader *et al.* 2011; Mekonnen and Hoekstra 2011; Hoekstra and Mekonnen 2012; Konar *et al.* 2012; Antonelli *et al.* 2012).

When studying the economic value of water for the purpose of formulating policy-relevant recommendations, it is essential to distinguish between these two sources of water. First of all, the distinction put forward a different market value for the two types of water, which is related to their different opportunity cost. Given the relatively easy way to use it for other purposes than irrigation (Mekonnen and Hoekstra 2010), blue water has a higher the opportunity cost than green water. In this perspective, only blue VW 'exports' can thus be valued. When it comes to green water, the costs regarding green VW are not measurable, given the encountered difficulties to measure its opportunity cost (Novo *et al.* 2009). It is therefore almost impossible to attribute a marginal profit -*the willingness to pay for an extra unit of water*- to green water. Households, firms and countries are in fact less aware of green water costs than they are of blue water costs.

This dichotomy becomes of outmost importance when referring to agriculture in developing countries and population growth. The latter implies a higher need for food and consequently, water. The necessary water amount to eradicate hunger before 2030 in developing countries is of 4,200 km^3/year (Falkenmark and Rockström 2006). If covered by irrigation, water extraction from aquifers and rivers will have to be more than doubled, with unbearable impacts on ecosystems. Moreover, it must be pointed out that loss in water due to agriculture is considerable, with a water efficiency (i.e., the ratio of well consumed water by irrigated agriculture to the extracted water from its source) of only 30% in developing countries today. This situation leads to thinking of a solution *via* better management of green water, consisting in limiting rain evaporation and/or increasing groundwater absorption. In this context, a number of studies have drawn attention to the role that green water plays for food security and the need to unlock its potential and increase productivity of its use (among others, Falkenmark and Rockström 2004; IWMI 2007). Inefficiency in rainfed farming is mainly due to land degradation and declining soil fertility, which results in high levels of evaporation and runoff, as well as to inadequate water management practices (IWMI 2010). In these contexts, there are significant opportunities to develop agricultural output and water productivity while avoiding irrigation lock-in and the risks of over-allocating blue water (Gilmont *et al.* 2012). It has been suggested that by unlocking the potential of green water, the challenge of feeding future populations *sustainably* can be met (Falkenmark and Rockström 2006; IWMI 2007).

It has been shown that green water accounts for the largest share of global VW ‘flows’, with exports going from countries rich in green water towards blue water economies (Aldaya *et al.* 2010). Traded agricultural commodities are mainly produced on rainfed farms (Yang *et al.* 2006; Fader *et al.* 2011; Hoekstra and Mekonnen 2012). In these cases, VW ‘flows’ could lead to better management of natural resources. Good production for trade can be favourable, as in Ghana, Côte d'Ivoire or Brazil, where water, being majorly green, stimulates the economy. On the other hand, in a country such as Thailand, which exports 28 Gm3/year, high agricultural production involves a non-negligible pressure on blue water resources (Chapagain *et al.* 2006).

5. Policy implications

Over time, a rich literature has addressed both the empirical and conceptual issues relating to VWT. A number of studies have suggested that the ‘import’ of VW can be regarded as an ‘exogenous’ source of water (Haddadin 2003) through which water-scarce countries can release the pressure on domestic water endowments and save water for ‘higher’ value uses - such as for domestic purposes, industrial activities and environmental conservation (Lant 2003). Other studies have pointed instead, to the economic and political barriers that can have detrimental effects for poor economies in terms of ‘dependency’ and their food security, due to their vulnerability to the erratic fluctuation in world market prices (Wichelns 2001; Merrett 2003). A thorough assessment of the impact of VWT trade has been conducted for the case of Spain

(Garrido *et al.* 2010).

Although international trade is not (directly) influenced by water scarcity, water scarcity *does* influence trade. Water-scarce countries are in fact forced to rely on the import of water-intensive commodities, such as foodstuffs, as the water available locally is not sufficient to meet local demands. Further liberalisation of global trade might double VW 'flows' between countries (Rogers 2003 in World Water Council 2004).

The transfer of *real* water over long distances is generally costly, whereas *virtual* water transfers in the form of commodity trade is economically feasible (Hoekstra 2003, 2008), especially in a world of low food prices, and can be mobilised very quickly (Allan 2003a). Using the 'import' of VW as a tool to secure food and water-related needs has thus become very attractive to a number of water-stressed countries (Zehnder *et al.* 2003). This is the case of many economies in the MENA region, where the volume of water available locally for food production has not been sufficient to meet increasing demands since the 1970s (Allan 2001). In the region, higher incomes combined with rapid population growth generated an increase in the demand for food, which could be satisfied only by increasing the levels of water-intensive food imports. This virtual water 'trade' *solution*, however, has been scarcely acknowledged publicly and has enabled the procrastination of politically stressful reforms in the water sector[4]. VWT provides a "dream solution" to water deficits, as it is "economically invisible and politically silent" (Allan 2003c: 23).

Hoekstra and Hung (2002) suggested that VWT between nations can be used as an instrument to increase *global water use efficiency,* by transferring water from "a nation where water productivity is relatively high to a nation where water productivity is relatively low implies that globally *real water savings* are made" (Hoekstra 2003: 14). Chapagain *et al.* (2006) estimated that the total water amount that would have been necessary in the importing countries, if all imported goods were to be produced on national ground, is of 1,605 Gm^3/year. These goods are produced with only 1,253 Gm^3 per year in exporting countries, thus suggesting total water savings amounting to 352 Gm^3 per year.

In general, international trade can contribute to enhancing both local and global water use efficiency if commodities are traded from areas of high water productivity (ton/m^3) to areas characterised by lower productivity, thus resulting in global net water savings (Oki and Kanae 2004; De Fraiture *et al.* 2004; Aldaya *et al.* 2010). Studies of global water savings as a result of international trade have shown that the net effect of the VWT is *global water savings* (Oki and Kanae 2004; De Fraiture *et al.* 2004; Aldaya *et al.* 2010). Reimer (2012) suggested that VW 'importers' do not actually "save water" but, through trade, they are enabled to consume *more* water than is available locally. What trade brings about is thus an enhanced capacity for water-scarce country to "consume the services of *more* water". While the 'import' of VW does not actually bring about real water savings, the capacity to engage in trade provides water-scarce countries with water and food security (Allan 2001). VWT is thus a "securitising" rather than a 'saving' process. However, as VW generally 'moves' from regions that achieve high

[4] The political concern generated by the public's perception on a nation's dependence on imports for securing its food and water-related requirements is an important argument behind the reluctance of public officials in the MENA region to acknowledge the role of VW 'imports' (Allan 2001).

returns to water (especially *soil water*), the result is a saving at the global level when the 'imports' are to economies that achieve poor returns to water, enhancing water use efficiency. Indeed, Wichelns (2004) argues that, by shifting production to regions with high water productivity and low opportunity costs, water resources could be reallocated to activities with higher economic value.

VW 'imports' in crop products have increased the overall 'water supply' and released blue water from irrigated agriculture to higher-value uses. As pointed out by Aldaya *et al.* (2010), in the main exporting countries of wheat, corn and soya beans agriculture is heavily dependent on green water resources, whereas most importers would have had to rely on their blue water resources in the absence of such imports. VWT has also increased overall water and water-dependent food security (Allan 2001; 2003a; 2003b; Aldaya *et al.* 2010). The economies that are able to satisfy large proportions of their food needs may perceive a higher sense of security and stability than those that have to rely heavily on food imports. However, as Wichelns pointed out, "the cost of attaining that sense of enhanced national security may be quite high, as measured by the opportunity cost of scarce land, water and capital devoted to domestic food production" (2001: 134).

Freshwater globalization leads to both risks and opportunities. First of all, consumption indirect effects might be externalized to other countries: while water in the agricultural sector is always at lower price than its real cost, an increasing quantity is used to produce goods for foreign demand. Since water extraction costs in the exporting country are not included in the final good's price of the importing country, consumers do not pay for the water problems inherent to the country where goods are produced. In this context, a pre-condition to achieve efficient and equitable trade is that consumers should bear the total cost of production and its impact. A second issue is that many countries are gradually more dependent on intensive water commodity imports, raising concerns about self-sufficiency and national food security (Allan, 2001; 2003a; 2003b). In the case of Jordan, for example, the country yearly imports a VW volume that is five times higher than its own renewable water resources (Mekonnen and Hoekstra 2011). Consequently, while Jordan saves its own resources, it also amplifies its dependence on other nations and their water resources, and magnifies its exposure to international food crises and staple prices fluctuations.

To conclude, the concept of VW can be interpreted both as an analytical and descriptive indicator, which may be helpful in the definition of a country's (water management) political strategy to avoid politically-hazardous decisions. As an analytical concept, VW can be seen as a "medicine against undue 'hydrocondia'", i.e. the Malthusian argument that population growth will lead to water crisis (Warner in Hummel *et al.* 2006: 16). As a prescriptive concept, it has been highlighted that reliance on VWT to meet local water demands in water-short economies can delay important allocative choices as well as political, economic, and ecological reforms (Allan 2001).

International political economy and the characteristics of global food market (e.g., trade barriers, public interventions, price regulation, etc), however, make virtual water trade vulnerable to a variety of shocks and exogenous pressures, undermining its validity as a "policy prescription". For instance, the price of food in temperate zones does not reflect the cost of many inputs, such as labour, energy and water; subsidies sustaining the agricultural sector – mainly in the EU and the US – do distort prices and have adverse impacts on agriculture in poor countries. Notwithstanding, the use of virtual water as an indicator of water usage in commodity production, consumption as well as of the global water exchange implicit in commodity trade enables one to see the otherwise invisible the water dimension of such human activities and has the potential to inform wiser decision-making in the productive sectors and trade. Enhancing virtual water as a indicator for informing policy-making will require to improve understanding of its relationships with national and regional water resources management, as well as with natural, socioeconomic, and political conditions of the world's political economies. As argued by Yang and Zehnder (2008), clarifying the conceptual foundations of virtual water and integrating it in multidisciplinary assessments, is necessary in order to unfold the potential of the concept as "an integral component in the whole package of integrated water resources management".

6. Conclusion

The virtual water and derivative concepts, such as the water footprint, have brought much-needed attention to fundamental issues regarding water resources, within the boundaries of national economies and also at the global level. It can be argued that the adoption of these concepts as analytical tools has globalised the discussion on water security, environmental sustainability, food security and consumption (Roth and Warner 2007). They provide a unique analytical perspective to analyse how water-deficit economies meet their water requirements for food production and achieve water security. Global trade establishes an invisible link between the source of water demand and the site of water consumption. The capacity to engage in trade, however, is asymmetric and depends on socio-economic development. The extent to which water-stressed countries will be able to diversify and strengthen their economies will determine their capacity to solve their water scarcity problem in the future (Allan 2001).

Despite the numerous critics these concepts have received on their validity as policy prescriptive tools, they have been helpful in gaining the attention of public officials and policy makers. Current patterns of water allocation and use often reflect underlying market failures that could be corrected, or whose effects could be overcome, through appropriate policy interventions. The existence of virtual water 'trade' increasingly calls for a new governance approach that considers water in its *sub-continental* or even *global* dimension, besides that of the river basin (Hoekstra and Chapagain 2008). The concepts are also helpful in drawing the attention of media, civil societies and citizens onto water issues by bringing new perspectives.

To the extent that agricultural trade depends on many further significant factors than water resources endowments, such as the availability of arable land, labour, knowledge, capital and complementary inputs, the level of competition (comparative advantages) in certain sectors, the existence of property rights, subsidies, protectionist policies, national food security goals, poverty reduction targets and many others, the lack of consistency between virtual water trade prescriptions resulting from the traditional international trade theories and actual trade patterns should not come as a surprise.

To conclude, this study has argued that, despite not being a policy tool itself, the virtual water concept can reveal aspects related to production, consumption and trade in goods which monetary indicator do not capture. Because of the ambiguity associated with the meaning of the VW concept itself, generated by its trans-disciplinary nature, its potential as an indicator for informing decision-making in water management and policy, as well as commodity trade policy, still has to be fully appreciated.

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