Department of Economics and Finance

Bachelor's Degree in Economics and Business- Finance

International Economics

Virtual water trade: An economically silent solution to water scarcity problems

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Academic Year 2019-2020

Introduction

An economist not only has the moral obligation of investigating and innovating economic themes of public and academic domain, but also that of bringing to light areas of the economy still uncharted but, at the same time, crucial to future generations. In the light of such considerations, this thesis aims at investigating the market of virtual water.

Water is the most precious primary good present on the planet, and it represents the conditio sine qua non for human life development. It is a non-substitutable good whose abundance or scarcity depends on physical and economic factors: its scarcity, either relative or absolute, is subject to natural processes that determine not only its geographical distribution, but also its access by humans in many areas of the Earth's surface.

Given the fundamental role such resource plays in the life of all living beings on the Earth, it is necessary to be completely aware of men's dependence on hydric ecosystems and on the impact their everyday activities have on global natural resources. However, the majority of people are not fully conscious of the fact that enormous volumes of water are involved in their routine activities and this is due to the fact that they cannot explicitly see them. Human consumption of water, indeed, is not limited to its domestic use, but it also includes the amount employed during the production process of all goods and services consumed. Most of daily water consumption comes from the water people "eat", that is the water invisibly contained in all agricultural and livestock products that arrive on their tables after having been produced, transformed and distributed. The volume of water embedded in a commodity as a result of the production process is referred to as "virtual water", a term introduced for the first time in the 1990s by the British geographer Tony Allan which saw the possibility of importing water as a valid alternative to water shortage problems in the Middle East. To have a more concrete idea of the virtual water concept, it is sufficient to know that a cup of coffee and a liter of milk contain, respectively, 140 and 1,000 liters of water.

Because of its importance and uneven distribution among countries, water scarcity issues have always been addressed in terms of solidarity and generosity among nations: it is not fair that some countries are naturally endowed with more hydric resources than others and, consequently, water-abundant countries should be sensitized to carefully use their water resources to the benefit of water-poor countries. However, this thesis takes a more economic approach as it aims at identifying the major determinants, as well as the effects, of the patterns of virtual water trade embedded in the conventional international trade of goods and services, in particular food commodities.

The virtual water concept is fundamental not only because it allows to derive a more complete assessment of the impact of human activities on the environment, but also because through international food trade, water-scarce countries can save their domestic water resources by virtually importing water through commodities. Virtual water trade, in fact, takes place whenever products are traded on the market. It is as ancient as traditional trade itself.

The structure of this analysis consists of two macro-sections: a first part in which data and notions about the virtual water concept and its international market are presented to provide a general picture of the topic analyzed; a second part in which a more critical approach is adopted to compare data on imports and exports of virtual water of different countries of the world. Furthermore, two scenarios are analyzed in specific: the water footprint of Italy, to provide a more concrete idea of the volumes of water traded annually by the country, and the patterns of world trade of cereals. These data have been useful to demonstrate the impact that the exchange of cereals, a food commodity widely used in most diets, has on water depletion and savings at the global and national level. It is interesting to see how specific data on virtual water trade of a single country or of a particular commodity provide a meaningful insight about the topic under analysis.

Applying the concept of virtual water to basic economic models of international trade, it can be shown how virtual water trade through imports or exports of water-intensive commodities might represent a valid solution to the problem of uneven global distribution of natural water resource endowments. In fact, as supported by empirical evidence, countries with abundant hydric resources or high-water productivity tend to specialize in the production of water-intensive commodities which are then imported by water-poor countries that, by doing so, can alleviate the pressure on their already-scarce resources.

Chapter 1: Inside the Concept of "Virtual Water"

1.1 The Economics of Water Use

Economic resources are tangible or intangible means which, either directly or indirectly, satisfy consumers' needs. They are characterized by some degree of scarcity in relation to demand which creates a value people are willing to pay in order to receive the good. Thinking to plausible examples, many goods and services might easily come to mind. There is, however, a less intuitive and more questionable economic resource: *water*. Because of scarcity, many theoretical and practical frameworks have been developed to value goods such as land, food or cloths. The same must then apply to water.

At the International Conference on Water and the Environment (ICWE), in Dublin, Ireland, organized in January 1992, water was formally recognized as an economic good, once its economic value in all its competing uses has been taken into account. In the last decade, this idea has been put into practice in many ways, affecting the humanity as a whole. Because water is so important to the process of economic development, is essential for life and health, and has cultural or religious significance, it has often been provided for free or at very derisory prices in many situations. However, after the recognition of its economic value the scenario changed, and higher prices started to be charged for this good all over the world. In particular, the water market moved toward privatization as private companies started to take over the management, operation and sometimes even the ownership of what once were public water systems, commercialization of bottled water boomed and international development agencies that used to work with governments to improve water services now started pushing toward privatization.

Water is defined as a renewable resource with two peculiar characteristics:

- Non-substitutability
- Scarcity

Taking these two peculiarities into account, it is comprehensible that water's demand curve is extremely inelastic, and it is therefore expected not to significantly respond to changes in market price levels (Van der Zaag *et al*., 2002).

Since water is the essence of life on the Earth and pertains every aspect of our existence, water security- defined as the reliable availability of an acceptable quantity and quality of water for health, livelihood and production, coupled with an acceptable level of water-related risks[1]- became a heatedly debated issue on the international agenda over the last years. Scarcity and misuse of fresh water pose a serious and growing threat to sustainable development and protection of the environment. Human health and welfare, food

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[1] This definition of water security is based on the one provided in UNESCO's International Hydrological Programme's (IHP) Strategic Plan of the Eight Phase, endorsed at the 20th Session of the UNESCO-IHP Intergovernmental Council.

security, industrial development and the ecosystems on which they depend, are all at risk, unless water and land resources are managed more effectively in the present decade.

The major threats to water security in many countries are the increase in population, climate change, economic growth and subsequent overall increase in consumption, increase in consumption of products of animal origin, and, finally, the asymmetric availability of the resource either because of economic or geographical reasons.

Whilst the amount of water resources on the Earth is very vast and appears to remain quite stable in a closed hydrological cycle, water resources are currently put under an unprecedented pressure, in particular in arid and semi-arid regions. The accessible fresh-water resources are a slightest portion of the total water resources of the planet, about 2 per cent, and they are unevenly divided among countries. To have an idea of the disproportional distribution of this vital resource, it is sufficient to know that slightly more than the 60 per cent of the total amount of water available for human consumption belongs to only ten countries (FAO, 2003).

Regions with the most critic water-scarcity problems are located in West Asia, North Africa, sub-Saharan Africa and South America, all territories characterized by insufficient precipitations and increasing population. As a matter of facts, population growth and burgeoning water per-capita consumption are expected to exacerbate the already precarious condition. In the last century, in fact, water use growth rate more than doubled the population increase. According to a study carried out by the United Nations, as shown by Figure 1.1 which displays the predicted water availability per person in 2025, two-third of the world population could be under stress conditions and 1.8 billion people could be living in countries with absolute water scarcity by the year 2025.

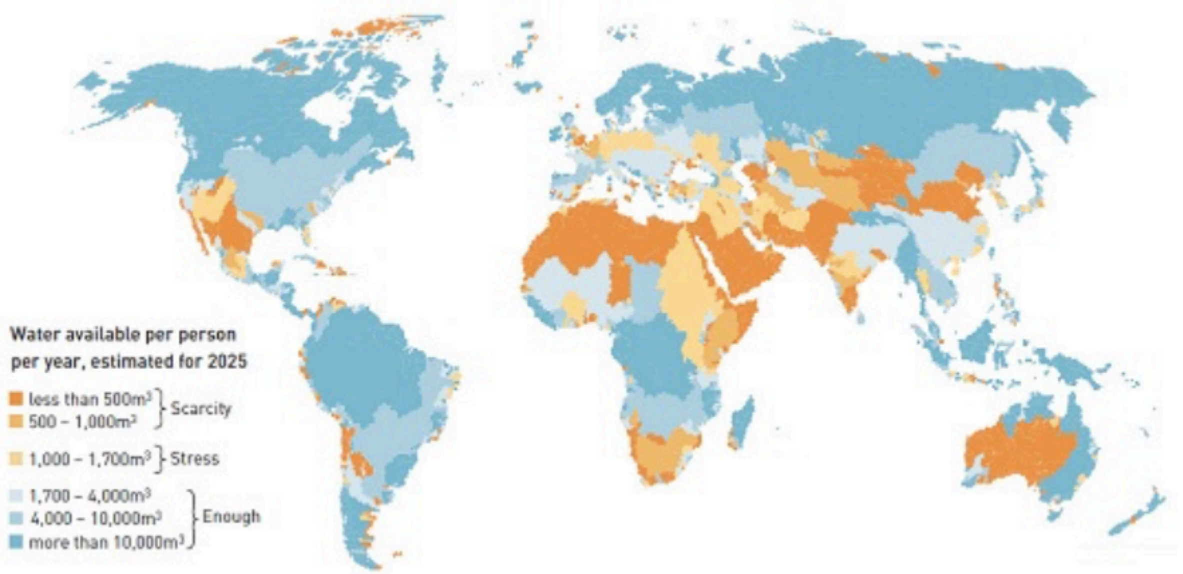

Figure 1.1, Source: The United Nations World Water Development Report 3, 2009

Since natural endowments of water across the globe vary significantly from region to region and a peculiarity of this resource is non-transportability, there is a high degree of variation in the distribution of water per capita. This is shown by Figure 1.2 which displays the relationship between per capita and total endowment of water in different regions (Afkhami et al., 2018).

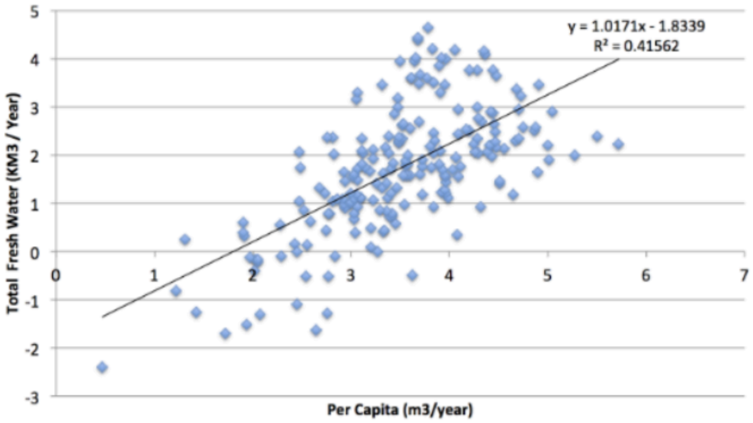

Figure 1.2, Source: Afkhami *et al.*, 2018

If global population distribution was such that a minor portion of the population occupied water-scarce regions, then the data on the scatter plot would lie around the horizontal line indicating a smaller degree of variations across countries. Not only the volume of available water resources varies over space causing some regions to face water scarcity and others to have abundant hydric resources independently of their population level and, thus, necessity, but water productivity- defined as the quantity of output produced per unit of water- substantially varies from region to region. Water productivity is the result of the interaction of many factors among which available technology, human and social capital and, most importantly, climate. A region's climate and soil ultimately determine its productivity in terms of harvest growth. Producing one kilogram of cereals in an arid country such as Israeli might require twice or even three times the water needed to produce the same quantity of cereals in a humid country such as Canada (Hoekstra *et al.*, 2002). For instance, a certain volume of water of the Nile river would yield a larger volume of output if employed to grow crops in Ethiopian highlands than if it were used to grow the same crops in the Egyptian desert. In this specific case, however, Egypt and Ethiopia have considerable differences in terms of productivity, the former being very close to its potential and the latter far below it. As a consequence, Egypt's water productivity is higher than Ethiopia's in spite of its less fertile soil due to the desert climate (Hoekstra, 2010). A direct implication of the existence of differences in terms of water productivity between countries is that comparative advantage exists for those countries that are relatively more productive in terms of water-intensive commodities.

Because of the nonequivalent geographical distribution and countries' water productivity, water supply cannot always match the demand at the country level. However, through the trade of water-abundant commodities countries with scarce water resource endowments can overcome this shortage and save their poor resources. This process is known as “virtual water trade” and it is very important since it leads to world peace alleviating potential water crises otherwise inevitable.

Water is a primary commodity necessary to human life and many water related problems are due to the fact that the majority of the world population ignores the fact that all daily activities require the use of enormous quantities of this precious resource. Human appropriation and use of water are not limited to domestic consumption. In fact, the major part of water used is the one people “eat”, that is the water contained in all food commodities after they have been produced and distributed, even if its presence is undetectable. In every production phase, water plays an indispensable role as production input either directly or indirectly- that is, intended for final or intermediate use, respectively. Water content is high in food production, especially in products of animal origin, and FAO’s slogan for the 2012 World Water Day, “The World is thirsty, because We are hungry”, perfectly captures the strict connection underlying food production and water use, that is, more subtly, between food security and water security.

1.2 Impacts of Water Scarcity on a Country’s Poverty and Political Instability

Among all the hazards of the nature, uneven distribution of water is one of the most compromising. Drought-related problems can have serious impacts on a country in terms of economic losses, livelihoods and political stability. Under many circumstances, water stress- the lack of adequate freshwater resources- can bring to life local conflicts as well as local and international migration, all long-lasting effects which are not easily overcome. The effects of droughts are not the same everywhere: they are more devastating in developing countries characterized by poverty and food insecurity. These countries’ economies rely indeed primarily on rain-fed agricultural sectors and often they do not have adequate water infrastructures. As a result, drought in such vulnerable countries can have disastrous consequences as it leads to repeated crop failures and reduced livestock, and therefore numerous deaths and displacement of people are generally observed. On the other hand, developed economies undergo bearable difficulties, such as limitations on water use for industry, services and energy security, threatening political and economic stability to a much lower extent.

In 2009, the International Food Policy Research Institute (IFPRI) carried out a study to assess the economic losses due to exceptional climate events, among which water shortages, in Malawi and their impact on agricultural production and poverty in different regions. The result of the analysis was that a severe drought, like the one experienced by the country in 1992, causes a reduction in national GDP of about 10 per cent. Water shortages like the one considered, however, are so severe that they are expected to occur with low frequency, usually once every twenty-five years. For what concerns more frequent but less extreme water shortages, such as a RP5 event, expected to occur once every five years, GDP contracts only by 0.5 per cent (Pauw et al., 2009). Furthermore, the Southern region of the country turned out to be even more vulnerable to this category of natural hazards than the rest of Malawi because of the high incidence of poverty that further exacerbates the effect on people's welfare.

Besides the Malawian case study, there is plenty of evidence providing a good indication of the impact of water stress on food security and agricultural production. During the 2002 drought, the most widespread of the previous 20 years, Indian food grain production went from 212 million tons of the previous year to 183 (Prabhakar *et al.*, 2008). In the same period, Australia's national GDP was reduced by 1.6 per cent, experiencing a loss of US $2.34 billion which was due, to a large extent, to agricultural losses due to water scarcity (Horridge *et al.*, 2005).

Water shortages also pose a risk to political stability, particularly in emerging economies where political systems are put under a multiplicity of pressures, and are, consequently, more vulnerable. In order to define a causality relation between water stress and political instability and conflicts, many relatively recent disorders in water-scarce regions of Africa have been analyzed. In particular, the result of an analysis carried out in 2017 by the CNA[2] showed that water shortage is often the root cause of discontent across many regions of Africa. In North Africa, for example, Tunisia and Algeria systematically witness unrests and protests in response to insufficient water. Analogously, in West Africa, in 2013 Senegal was the scene of a perilous water-related crisis after the main city Dakar's access to water was ceased for more than two weeks (Diadie, 2013). Finally, the Democratic Republic of Congo regularly hosts demonstrations and protests over the shortage of drinking water, often due to pollution by low-quality mining practices.

1.3 How Much Water Do We "Eat"?

Every day, people consume far more water than they believe. This is due to the hidden existence of *virtual water*: the amount of water used in growing, producing, packaging and transporting all the goods consumed on a daily basis. All the goods people buy and use- from food to clothing to computers- have a water cost embedded in the form of virtual water.

Virtual water is a fundamental concept to reveal the real water consumption. To properly understand its meaning and importance, one might simply think of an example: How much water does an average person have for breakfast in the United States?

At first glance, the answer might seem pretty obvious: a person consumes only the water used to make coffee or a cup of tea, that is about 300-400 milliliters. The correct answer, however, is definitively less intuitive. Let us suppose the breakfast is made of a cup of coffee, a slice of toast, some bacon with eggs and, finally, a glass of milk. The situation here becomes much more complicated. A simple cup of espresso,

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[2] CNA is a nonprofit research and analysis organization dedicated to developing actionable solutions to complex problems of national importance.

in addition to that used to prepare it, contains 140 liters of water. This is exactly the virtual water previously mentioned- that is, the water used in growing, producing, packaging and shipping the coffee beans used. Going on with the analysis, one slice of toast contains about 40 liters of water, bacon 480 liters for one portion, eggs 120 liters and milk 240 liters. In all, an average breakfast in the US costs almost 1,100 liters of water per day. This amount corresponds to three bathtubs filled entirely with water. Another important evidence which can be drawn from this example is that over two-thirds of these 1,100 liters of water are used in the production of animal products: milk, bacon and eggs. Thus, the meat non-vegetarian people eat is their biggest single source of water consumption. The average non-vegetarian diet in any US or European country comprises about 5 cubic meters of waters each day, which corresponds to 15 bathtubs (Allan, 2011).

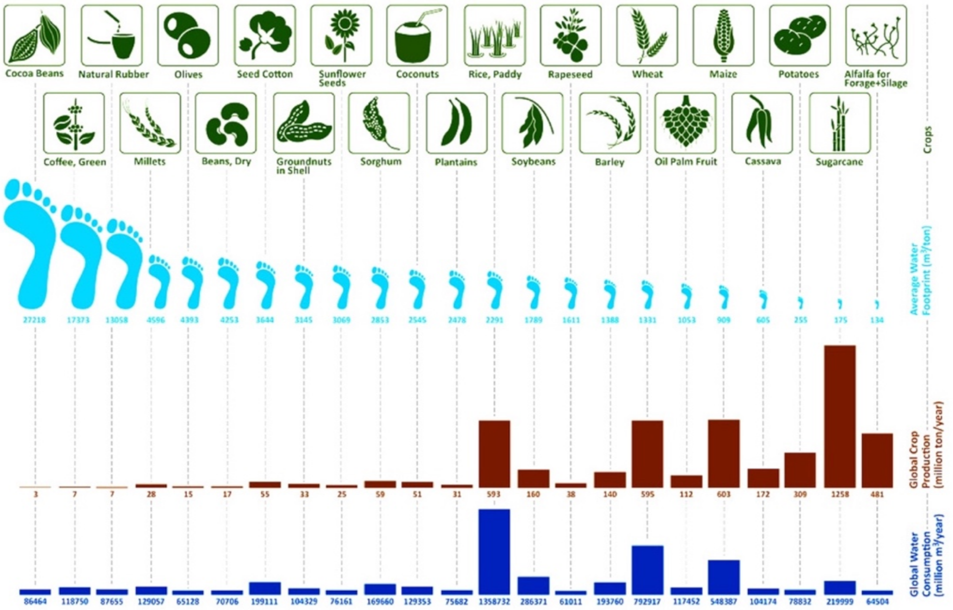

Figure 1.3, Source: Hoekstra *et al*., 2008

This simple example proved to be extremely useful to provide a first general idea of what economists mean by "virtual water", once known as "embedded water", which will be discussed more in details in the rest of the paper, together with its economic implications related to international virtual water trade. Figure 1.3 shows the global-average water footprint of crop and animal products for the year 2010 (Hoekstra et al., 2008).

Until this point, what is really important to bear in mind is that the major part of the water people deplete, about 90 per cent, comes from the food they consume, and it is therefore invisible to their eyes. People are "blind" to the quantity of water they use and to its value mostly because water, especially in the developed world, despite the privatization trend previously mentioned, is still is very cheap: it rarely accounts for more than 2 per cent of the households' income; therefore, the financial incentives to learn more about it are almost inexistent to common people.

1.4 Virtual Water: Origin and Definition

The main reason why there is a widespread erroneous consciousness of the quantity of water consumed on average daily basis by the world's population is that there exists a distinction between two approaches to the assessment of the same good: an approach based on common beliefs and another one based on a technical-scientific evaluation. The former implicates a superficial measurement based on the quantity of water people actually see and consciously consume; the latter, on the other hand, is a more comprehensive measurement which is represented by the concept of virtual water and constitutes a nexus between water, food and trade.

The first one to introduce this concept was Tony Allan (1997) which defined it as "the water embedded in key water-intensive commodities such as wheat". As a mere simplification, virtual water can be seen as the sum of all the water used in the production chain. The term has then been expanded to describe the use of water required for the production of non-agricultural products also. The virtual water concept is fundamental to understand the impact that daily lives, activities and choices of the world population as a whole have on the world's dependence on hydrological systems. It has significant implications both from an economic and environmental point of view.

Almost all products require water to be used during their production process, however the volume of water used changes accordingly to the nature of the commodity. According to UNESCO's World Water Assessment Program of 2009, the 40 per cent of total water annual consumption, which amounts to 1,625 billion m^3, is virtually involved in commodity trade patterns. Furthermore, 80 per cent of these water flows are related to agricultural products trade, while the remaining 20 per cent relates to industrial products trade. The virtual water concept is particularly important when discussing food production given the quantity of water it requires. To satisfy the biological needs of humans, 2-4 liters of water per day are sufficient, while the daily amount of water necessary to satisfy food requirements is 1,000 times higher. Moreover, the amount of virtual water depleted for food consumption depends on the type of diet considered: a "survival" diet, comprising only onions, potatoes, carrots and groundnut, would require 1 m^3 of water per capita per day, while a more consistent diet made mainly of animal products would require up to 10 m^3 of water per person per day (Renault, 2002). According to a study conducted by Renault and Wallender, in the year 2000 5,200 billion m^3 of water were used globally for agricultural food production. The production of livestock products depletes even larger volumes of water resources than crop products. This is due to the fact that animals need to be fed and hydrated during their lives before they can produce some output. For example, in an industrial farming system three years are usually necessary to produce 200 kilograms of boneless beef meat. Over these three years, the animal consumes about 1,300 kilograms of grains, such as wheat, corn and oat, and 7,200 kilograms of fibers, such as forage and dry hay, whose production comprehensively employs 3,060 m^3 of water. To complete the picture, 24 m^3 liters of drinking water and 7

m^3 liters of water for servicing must be included. All this leads to a total of 3,091 m^3 of water to produce 200 kilograms or, equivalently, 15.4 m^3 for one kilogram of boneless meat (Hoekstra, 2008).

Figure 1.4 provides a global partition of virtual water embedded in food products in 2000 as reported by Zimmer and Renault in one of their studies (Renault *et al.*, 2003).

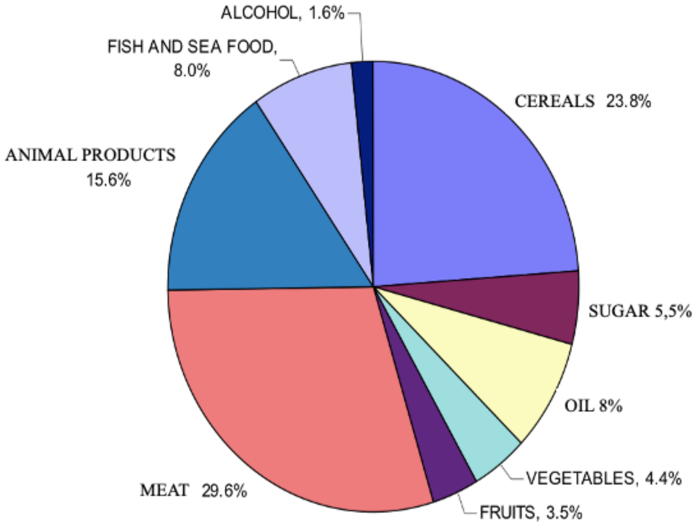

Figure 1.4, Source: Renault *et al.*, 2003

According to Allan, the first form virtual water dates back to the Neolithic Era, around 11,000 BC, when arable farming was introduced in people's lives. Until then, people could directly see the water they were consuming as they were either drinking or using it for specific purposes. As soon as cultivation became a common practice, however, people started to unconsciously divert water into food.

In the 1980s, Professor Allan spent a considerable period working in the Middle East, a region famous for its water scarcity. In that period, many local political leaders were waiting for a long-predicted armed conflict over water that did never actually take place. The explanation for this has not been instantly evident. The need for this war, in fact, has been circumnavigated by the economically invisible and politically silent "virtual water trade". Water scarcity has simply been ameliorated by the imports of water-abundant commodities which allowed to reduce the pressure on the scarcely available domestic water resources, giving the opportunity to countries to rely on alternative sources of water and, in turn, avoiding a war between Middle East countries.

Professor Allan was able to develop the virtual water concept and to come to this conclusion by looking at some grain import data for Egypt in the late 1980s. Egypt is the most populous MENA (Middle East and South Africa economies characterized by some degree of water scarcity) economy and it has been in critic water scarcity since the early of 1970s. In order to address the problem, the country tried to increase the irrigated area by 20 per cent and simultaneously began to import water-rich food such as wheat and soya. The former project did not achieve efficacious results, while trade proved to be a very valid remedy to water shortages. It takes about 1,000 cubic meters of water to raise a ton of wheat. Importers of wheat, however, do not have to deal with finding these tons of water. Notwithstanding the concept of virtual water as a solution to water scarcity might seem very clear and straightforward, it has not always been the case. In fact, when initially Egypt started to import water-abundant product, the politicians nor the general public were aware of the fact that they were actually importing water in their country: as water embedded in wheat and other products is not physically visible, they thought they were simply importing some cheap food (Allan, 2011). Their unawareness displays the two peculiarities of virtual water: its relevance and, simultaneously, its imperceptibility. At this point, the importance of virtual water is undeniable: it allows to equally redistribute water resources across countries and, as such, has always been and will remain the remedy to regional water scarcity.

Given the difficult situation the world is currently facing in terms of environment and economics related problems, virtual water plays an ever-increasing important role in order to guarantee an efficient allocation of resources all over the world which, at the same time, has the smallest environmental impact possible.

1.4.1 Why is not water all the same?

In order to provide an exhaustive analysis of the impact virtual water has on the environment, it is not sufficient to define the quantity of water associated with the production of a specific commodity, but it is essential also to specify its origin.

Contrary from what might be genuinely suggested by common sense, the water that arrives to people's tables in the form of food is not all the same. It is possible to make a distinction between two different types of water involved in the production of agri-food products: "Blue water" and "Green water". These two types can be distinguished based on the availability of their withdrawal and use: the former is the water contained in the Earth's surface (contained in rivers and lakes) and groundwater reservoirs; the latter is the water transpired by the plants that comes from rainwater stored in soil and it is hidden inside trees, shrubs and other plants (Clothier *et al.*, 2010). Blue water is available everywhere there is rain, it is easily accessible and transportable: it can be measured, contained in dams, stored and pumped in water systems to satisfy the needs of different sectors (agricultural, domestic and industrial). Because it can perform so many functions and because its supply usually requires the existence of infrastructure, it is usually costly. Blue water can be further distinguished between renewable and non-renewable sources. About 38,8 per cent of total precipitations ends up in the form of blue water and, globally, the 70 per cent of this percentage is used for irrigation purposes, according to FAO (Steen *et al.*, 1999). In some countries, especially the most arid ones, the amount of water used for irrigation exceeds the world average, reaching the 90 per cent of the total water consumption. This is the case of the Middle East and South Africa, the world's most arid regions (Clothier *et al.*, 2010).

The first one to bring attention to green water was the hydrologist Falkenmark in 1995. Initially, he provided a narrow definition of virtual water that included only the total water evaporation during crop growth.

Green water can be found everywhere except the most arid regions. It cannot be transported, pumped nor dammed and, consequently, it has a very low opportunity cost compared to that of blue water. It gets absorbed by plants from the soil, and it is eventually released back to the atmosphere. Even if it might be perceived as invisible and, therefore, worthless, if green water disappeared, the world population would quickly follow it. Green water, in fact, is of essential importance to humanity as it plays a paramount role in the worldwide production of food. It feeds all the forests and grasslands of the world and, notwithstanding this type of water results invisible to the human eye and is relatively more complicated to measure than blue water, it represents about the 84 per cent of the total water used for agricultural purposes and its use has a less invasive impact on the precarious environmental equilibrium (Fader *et al*., 2011). The reason why green water is preferred to blue water, at least to a certain extent, is that using blue water for irrigational purposes, because of its greater cost, yields the lowest economic value among all alternative uses and it is subject to significant environmental externalities.

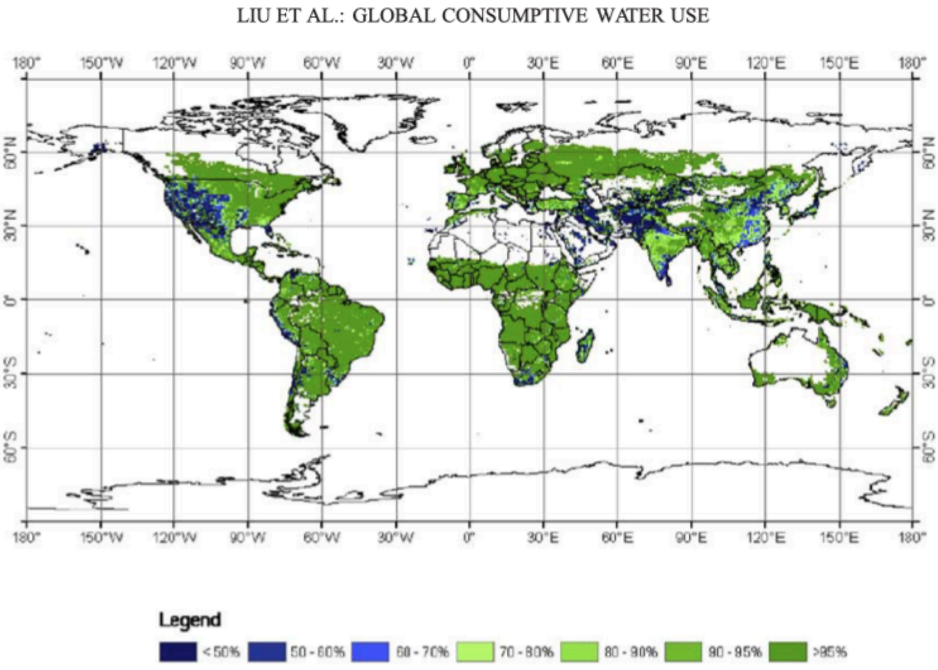

Figure 1.4, Source: Zehnder *et al*., 2009

Figure 1.4 shows the consumptive distribution of green and blue water use for crop production in the world. It is the result of the analysis carried out by Zehnder *et al*. (2009) which investigated the consumptive water use (CWU) in food production all over the world, focusing in particular on the green water component of CWU of 17 major crops (barley, cassava, cotton, groundnuts, maize, millet, potatoes, rapeseed, rice, rye, sorghum, soybeans, sugarcane, sugar beets, sunflower, wheat and pulses). As can be seen from the map, empirical data confirm that green water accounts for the main part of CWU on the globe.

In particular, in most of the areas of Africa, South America, Europe and Oceania, the 95 per cent of consumptive water use is represented by green water. The areas where green water constitutes a low portion of total water consumption are the Middle East, North Africa, Pakistan, Iran, Afghanistan, the western part of the US and the eastern part of China which all share the characteristics of being regions with high irrigation density, due to their aridity. On a global average, green water accounts only for slightly more than 80 per cent of CWU and this provides further evidence for the estimate provided above.

Once the difference between blue and green water has been clarified, the quantity of virtual water of an agricultural product results from the sum of the two: the green water evaporated during the cultivation process of the crop and the blue water used to cultivate it. To this quantity, a third source of water referred to as “Grey water” should be added. This is the fresh water used to dilute the pollutant substances generated by the production process.

Any food product is characterized by a specific amount of virtual water, usually expressed in liters or cubic meters, which can be decomposed, in turn, into green water, blue water and grey water. It logically follows that an apple irrigated with renewable water will have a less significant environmental impact than another identical apple irrigated with non-renewable water.

The whole reasoning has one important implication: a product’s water sustainability does not entirely depend on the mere quantity of virtual water contained in it, as it might seem logical to think, but rather on the typology of water contained in it. This represents exactly the reason why the recognition of the existence of virtual water, together with the distinction between blue and green water, is of vital relevance in order to properly assess the human consumption of water, that would be otherwise highly underestimated and, therefore, misleading.

1.4.2 The importance of virtual water’s geographical origin

In addition to the distinction between the different typologies of water contained in a commodity, another important step to appropriately comprehend the water-food connection, and therefore the impact of virtual water on the environment, is to determine virtual water’s geographical origin. The same product will indeed have a different environmental impact whether it has been cultivated in a water-rich or -poor area.

All regions on the Earth can be grouped into more or less humid areas, characterized by different atmospheric and water- both blue and green- availability conditions. According to the International Water Management Institute, as shown by Figure 1.5, two macro-areas can be distinguished: a water-abundant area (colored in blue) and a water-scarce area (colored in orange, red and violet). In the figure, water scarcity is considered from a natural-physical point of view as well as from a mere economic perspective. In the former case, physical scarcity occurs when there is not enough water to satisfy the demand. On the other hand, economic scarcity occurs due to a lack in investments that does not allow to efficiently exploit the natural resources in the region.

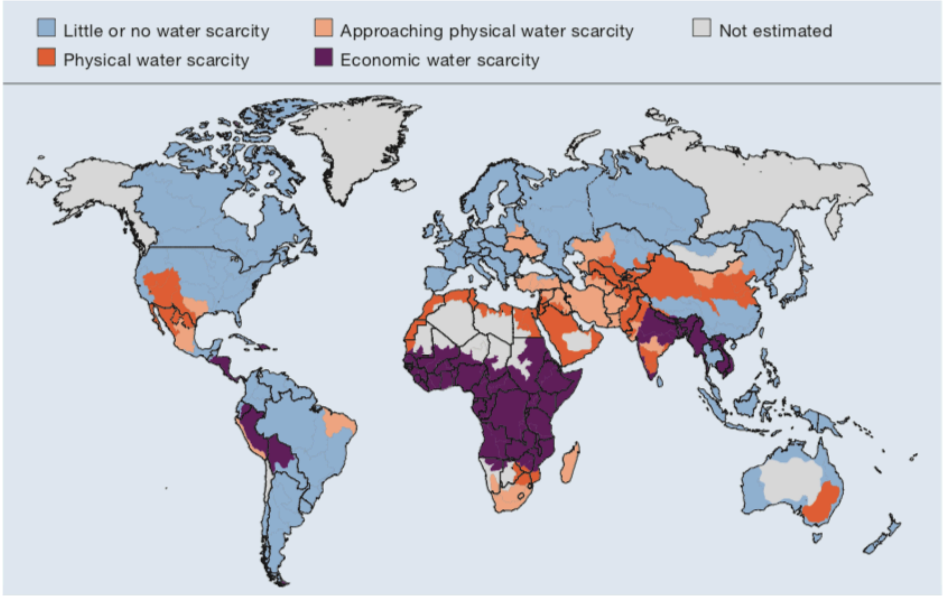

Figure 1.5, Source: International Water Management Institute (IWMI), 2007

A logical implication stemming from this excursus on the importance of the origin of water is that the use and trade of virtual water will have a different weight on the environment and on the economy depending on the virtual water's area of origin. As it is evident from the figure, exporting irrigated products from North Africa rather than from the North-East of America has a different meaning and entailments.

1.5 Water Footprint

1.5.1 Water Footprint: Definition and Origin

A concept strictly related to virtual water is that of "water footprint", introduced by the water scientist Arjen Hoekstra in 2003. The water footprint of a nation or region is the total amount of fresh water that is used to produce the goods and services consumed by its inhabitants. It is the sum of domestic water use and net virtual water import and represents a good estimate of a nation's appropriation of water resources (Hoekstra *et al.*, 2011). Water is measured in terms of volumes consumed and polluted. The total water used within a country is not the appropriate measure of it as sometimes it might happen that some countries consume goods produced elsewhere, meaning that they need more water than the one their own territory offers, while others might consume a lower quantity of water than the one at their disposition. The water footprint adjusts for these biases by controlling for the amount of water "traded". Furthermore, an additional distinction can be made within water footprint between "internal water footprint" and "external water footprint". The former refers to the volume of water used for the production of goods intended for domestic consumption; the latter, by contrast, refers to the volume of water used to produce goods abroad that are subsequently imported and consumed domestically.

The water footprint concept has been developed in analogy of the "ecological footprint" concept of a nation introduced in the 1990s by Professor William Rees. The ecological footprint represents the amount of productive land required for the production of goods and services consumed by the inhabitants of a country. The water footprint is very similar, but instead of measuring the area a nation needs to produce a certain quantity of goods and services, it indicates the amount of water needed to sustain the population of a certain nation.

The water footprint concept is strictly related to the virtual water concept as it is fundamental in translating the highly theoretical perception of virtual water into the real world, providing numbers and more pragmatic analyses.

Arjen Hoekstra, working with Professor Ashok Chapagain, analyzed the level of water trade and consumption in 140 of the 206 world economies in order to quantify the virtual water flows related to crop products and to have an overview of international virtual water trade. One of the biggest innovations of their work was that they were able to take into account also green water as, instead of trying to estimate the water use of various economic sectors as many before them did, they used production and trade datasets. The insertion of green water was actually a big revolution as this type of water, despite economically invisible, is of vital importance to the production of food and, therefore, to a more correct assessment of its environmental impact.

The result of the analysis was thereby very important as it provided an estimation of green and blue water. Going more into the specific, 5 per cent of the global water is allocated to domestic use, 16 per cent to industrial use, and the complementary percentage, about 80 per cent, is primarily destined to the production of crop and livestock of food, with a small percentage used for making fibers such as cotton. Most of the water used for domestic and industrial purposes is blue water. By contrast, the green water dominates the agricultural sector, accounting for the 70 per cent of the total amount of water used in the sector (Hoekstra *et al.*, 2002).

The model is revolutionary also in the fact that it allows to recognize virtual water flows in order to easily identify the world's net exporters and importers and to estimate potential gains or losses as a result of international food trade. These results will be analyzed in detail in the next chapter.

1.5.2 Water Footprint in Italy

In order to have a more concrete representation of what water footprint is, data about water consumption in Italy can be analyzed. On average, daily water footprint consumption in Italy is equal to 6,300 liters per person. This value is 1.65 times higher than the world average. Of these 6,300 liters, only 4 per cent is devoted to domestic consumption, according to world data. This leads to the conclusion that the remaining 96 per cent of water footprint, approximately 6,000 liters, is invisible to the consumer, notwithstanding it is the percentage associated to water consumption and pollution embedded in products ordinarily consumed and purchased (Antonelli *et al*., 2013).

The overwhelming majority of the Italian water footprint, about 89 per cent, is used for the production of agricultural products, while a relatively small percentage, 7 per cent, is designated to industrial products. Furthermore, almost half of the water footprint used for consumption of agricultural products, which constitutes about 32 per cent of the total water footprint, is devoted to the production of animal products.

Figure 1.6 provides some findings about the composition of the average Italian consumer's water footprint between 1996 and 2005 according to a study conducted by Hoekstra and Mekonnen in 2012 on national water footprint for countries with more than five million habitants.

What is interesting about such result is that in order to effectively reduce a country's water footprint and spare its hydric resources it is necessary to focus on indirect water consumption rather than domestic water usage. Indeed, limiting the use of water for domestic purposes, though useful, does not have a remarkable impact on the more serious water scarcity problems afflicting the world at the aggregate level.

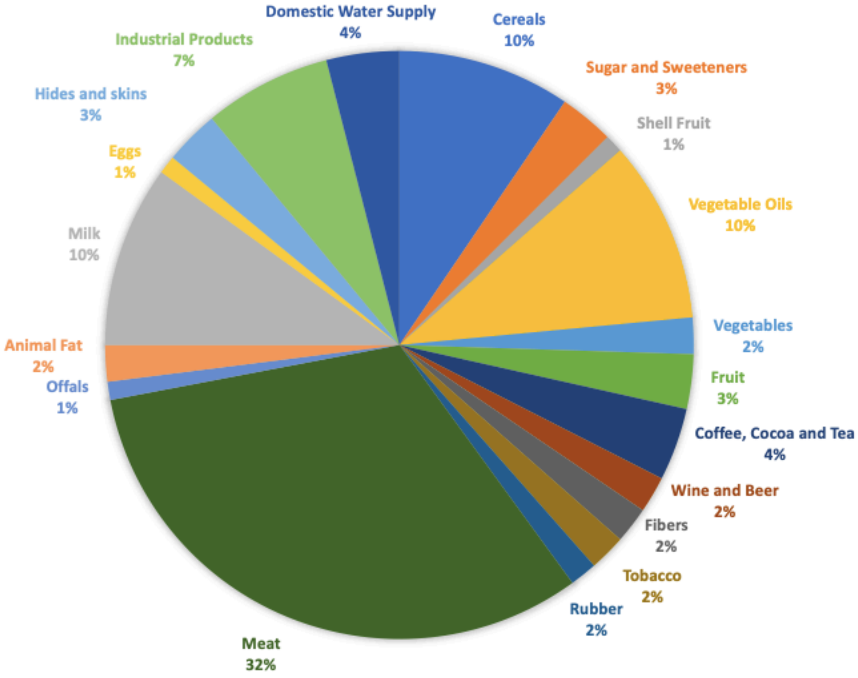

Figure 1.6, Source: Hoekstra *et al*., 2012

In 2010, Italy virtually traded about 130 km^3 of water, exporting 36.8 km^3 and importing 91.4 km^3. Of these 130 km^3 traded, 65.9 km^3 were used for domestic agricultural production. Data of the volume of imported and exported water from year 1986 to 2010 show that the amount of water traded rose significantly, with an increase in virtual water imports of about 82 per cent. In particular, over the time period considered, Italy increased its dependence on the international market to the extent that the quantity of virtual water imported has exceeded the volume of water used for domestic production. Surprisingly, the volume of water used for agricultural production has remained nearly constant over the years and even showed a slightly downward trend which as a consequence of three main factors. Firstly, during the time frame considered, from 1986 to 2010, the overall area under cultivation decreased by more than 20 per cent, from 127,000 to 97,000 hectares. Secondly, crop yields increased at the same time, raising the productivity per unit of surface. Finally, the production shifted toward more water-intensive crops (Antonelli *et al*., 2013).

To have a more concrete idea of the volume of water consumed in Italy, it could be interesting to compare these data with the river Po's annual outflow, equal to 48.6 km^3/year, as it is the most copious Italian river. In 2010, the volume of water used for domestic consumption was about 1.5 times the volume of water annually poured out in the Adriatic Sea by the Po, while the Italian imports of virtual water nearly doubled it (Antonelli *et al*., 2013). Figure 1.7 provides a very intuitive comparison of virtual water flows in Italy and Po river's outflow according to data on Italy's water consumption and trade patterns in 2010.

As it is suggested by the image, Italy consumes and imports a considerable volume of water which understandably raises concerns about long-term sustainability of the Italian hydric consumption.

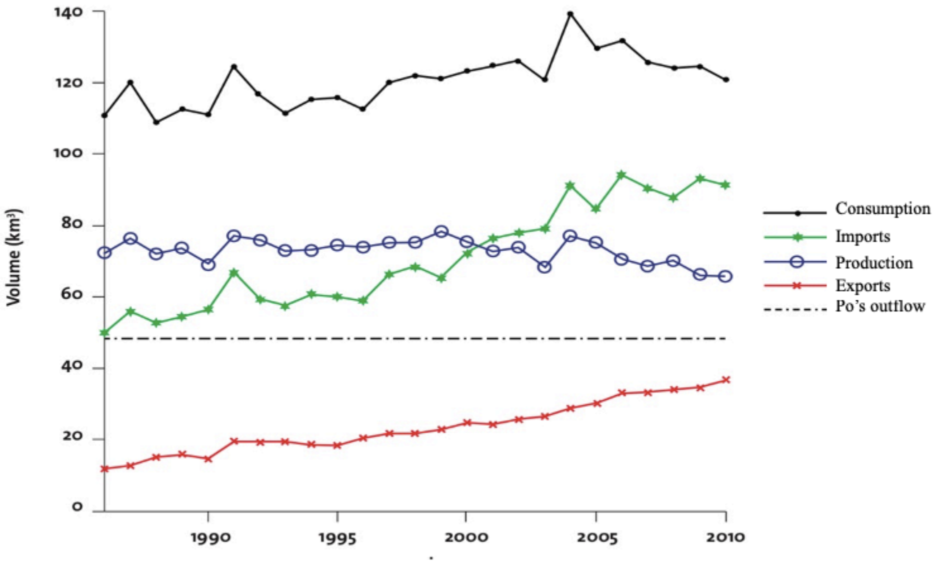

Figure 1.7, Source: Antonelli *et al*., 2013

In 2013, Tamea *et al*. conducted a study with the objective of investigating trade patterns of virtual water to discover possible trends and their evolution over time. The study initially focused on Italy, and subsequentially the analysis was extended to other ten countries in order to see how a country's water budget changes across time and different socio-political conditions.

Figure 1.8 provides a graphical representation of the flows of virtual water imported by Italy in 2010. Italy imported water mainly from other European countries, as evidenced by the line thickness. The increase in the volume of virtual water imports by Italy over the 25-year time frame considered was not homogenous for all the world's regions. In fact, while France remained the main virtual water exporter in Italy, imports from North America decreased by 28 per cent and flows from South America and Asia, in particular from Brazil and Indonesia, more than doubled (Tamea *et al*., 2013).

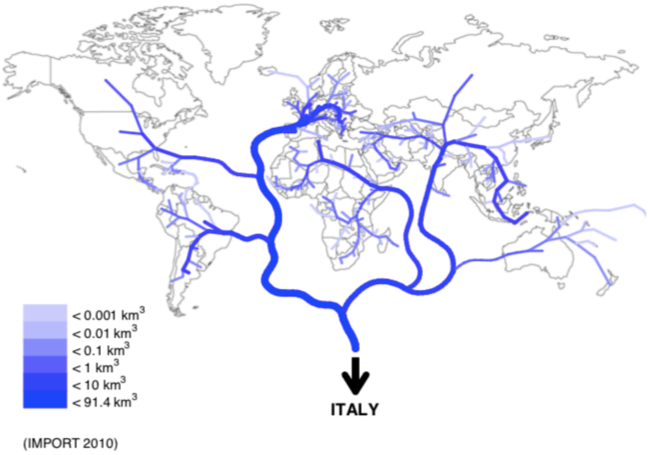

Figure 1.8, Source: Tamea *et al.*, 2013

Analogously to importing trends, more than half of Italy's exports of virtual water was destined to European countries. The registered increase of virtual water flows was even more significant for exports than for imports: export flows in 1986 accounted for only one third of the correspondent flows in 2010. In the case of exports as well, changes in patterns across countries were not homogenous: virtual water flows toward Africa and South America decreased, respectively, by 45 and 24 per cent, while imports from European countries quadrupled, going from 6.7 to 26.5 km^3 (Tamea *et al.*, 2013). Moreover, Italian products' penetration in foreign markets has substantially increased in the United States to the extent that exports exceed imports, and, to a lower extent, also in the Chinese, Japanese and Australian markets.

Figure 1.9 represents Italian net flows- that are, imports minus exports- of virtual water, where net exports are represented by the red line and net imports by the green one. The figure suggests that Italy is mainly an importer of virtual water as the net flows from all the continents is positive; this means that, overall, Italy's virtual water imports exceed its exports. Going more in the details, the figure clarifies that Italy tends to virtually import water from Mediterranean, eastern and central European countries, while it tends to export virtual water to countries in northern Europe.

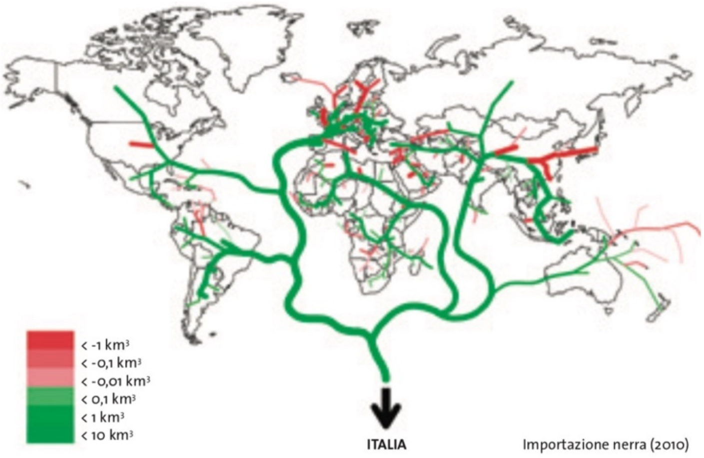

Figure 1.9, Source: Antonelli *et al.*, 2013

Chapter 2: Virtual Water and International Trade Patterns

2.1 Virtual Water Trade

Virtual water trade allows countries to implicitly cope with surpluses or shortages of water resources through the exchange of commodities. Due to natural resources' geographical unequal distribution on the planet, local water and crude oil supply might not be sufficient to satisfy their domestic demand. While crude oil has a profitable value to weight ratio, the same does not hold true for water. Therefore, the former is directly transported to meet the demand shortages through tankers or pipelines, while the latter, on the other hand, is not usually transported over long distances. A valid alternative to direct-water trade to cope with water shortages is the international trade of water-intensive commodities between countries.

This apparently easy solution enables water-scarce countries to save resources alleviating, in turn, their water-stress condition. Virtual water trade is a by-product of commodity trade because every time a country imports or exports goods or services with another country, it is simultaneously importing or exporting all the water embedded in them during the production process. It is as ancient as the exchange of food itself.

Virtual water trade allows to optimize the use of water as a scant resource in terms of social, economic and environmental value and to protect water security also in the regions of the world characterized by low precipitations and water scarcity. It benefits, at least to a theoretical extent, both importing and exporting nations. Water-poor countries could indeed ensure themselves water security importing water-intensive products rather than producing them domestically. Vice versa, water-abundant countries could exploit their overabundance of resources exporting water-demanding commodities to make a profit. The total volume of international virtual water trade is estimated to be between 1,100 and 2,300 km^3 per year (Hanasaki *et al.*, 2017).

According to data on water trade for the years 1990-1995, the biggest virtual water exporter in the world is North America, with a water surplus of 41.37 km^3, followed by Oceania, with 41.29 km^3. They each provide approximately 40 per cent of the world water surplus. Despite the aridity of much of the country, thanks also to a relatively small population of 20 million people, Australia has sufficient blue and green water resources not only for domestic consumption, but also for that of many water-scarce economies. The third world primary water exporter is South America which provides 20 per cent of the world water surplus, exporting 21.35 km^3 of water per year. On the other hand, regions with substantial net water imports are South and East-Asia, counting 40.23 km^3 of water imports, South-east Asia, with 13.83 km^3, and the Middle East, with 13.16 km^3. Other regions which rely to a smaller extent on imports of water are: Former Soviet Union, with 9.64 km^3 of virtual water imports per year, Central America, with 5.26 km^3, Western Europe, with 5.61 km^3, North Africa and Southern Africa, with, respectively, 5.35 and 2.01 km^3. Finally, Central

Africa and Easter Europe import almost negligible quantities of water equal to, respectively, 0.44 and 0.83 km^3 per year (Allan, 2011).

Figure 2.1 shows national water balances over the period 1995-1999. Countries with a greater exporting network are colored in green, while those with a greater importing network are colored in red.

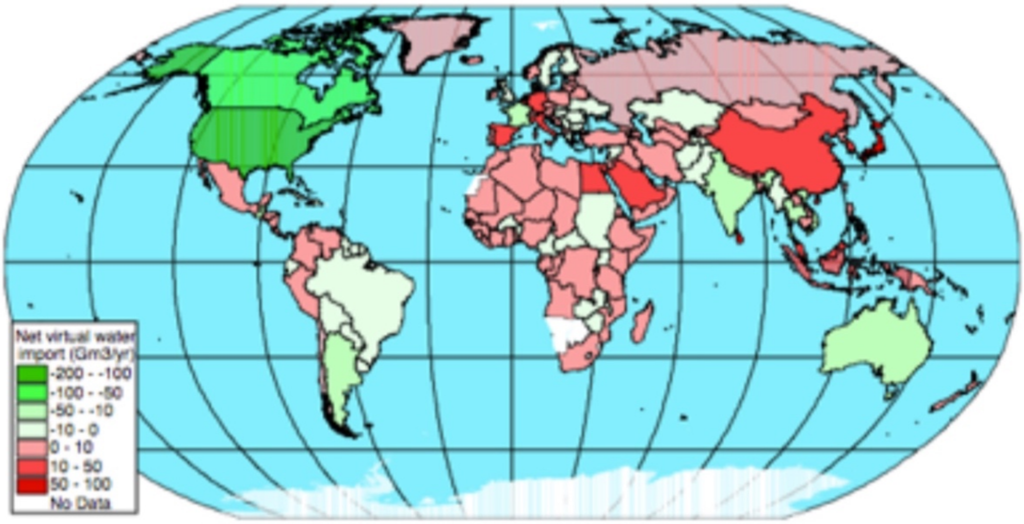

Figure 2.1, Source: Hoekstra, 2003

From the figure it can be inferred that relatively close nations, in terms of level of development and physical location, show some sort of equilibrium for what concerns virtual water trade. For example, Italy, Holland, Belgium and Germany are all net virtual water importers, while France is a net exporter. The same reasoning applies to the Middle East where, for instance, nations such as Israel and Jordan import a significant amount of virtual water, while Syria exports it. Finally, in the Former Soviet Union, the Russian Federation is a net virtual water exporter, while countries such as Kazakhstan and the Ukraine are net importers.

Figure 2.2 shows water scarcity conditions in 142 countries and the consequences of virtual water imports through agricultural products in 2012. Taikan Oki, Shinjito Yano and Naota Hanasaki estimated the volumes virtual water trade for the 142 countries under analysis which were then assigned to one of the following categories based on per-capita water resources: “average” or “greater” (5,000 m^3 per capita per year), “low” (2,000-5,000 m^3 per capita per year), “very low” (1,000-2,000 m^3 per capita per year) and, finally, “catastrophically low” (less than 1,000 m^3 per capita per year). The result was that twenty-one countries fell under the category “very low” and fifteen under “catastrophically low”. The scenario slightly changed when virtual water trade was included: the number of “very low” countries dropped to nineteen, while the number of “catastrophically low” to nine (Hanasaki *et al.*, 2017).

The extent to which including water imports affects countries’ per capita water reserves is not casual: it depends on their gross domestic product (GDP) per capita. Including virtual water imports does not have any effect on countries in the lowest two categories of per capita water resources (“very low” and “catastrophically low”) with a per capita GDP lower than US$ 700 per year, which is very close to the poverty line of US$ 2 a day. However, countries with higher levels of GDP per capita seem to show a positive relationship between water stress and agricultural product imports. For instance, countries with an annual per capita GDP between US$ 700 and 1,500, such as Tanzania, went from having very low to low per capita water resources; countries such as Morocco, with a per capita GDP between US$ 1,500 and 7,000 per year, moved from the “catastrophically low” to the “very low” category.

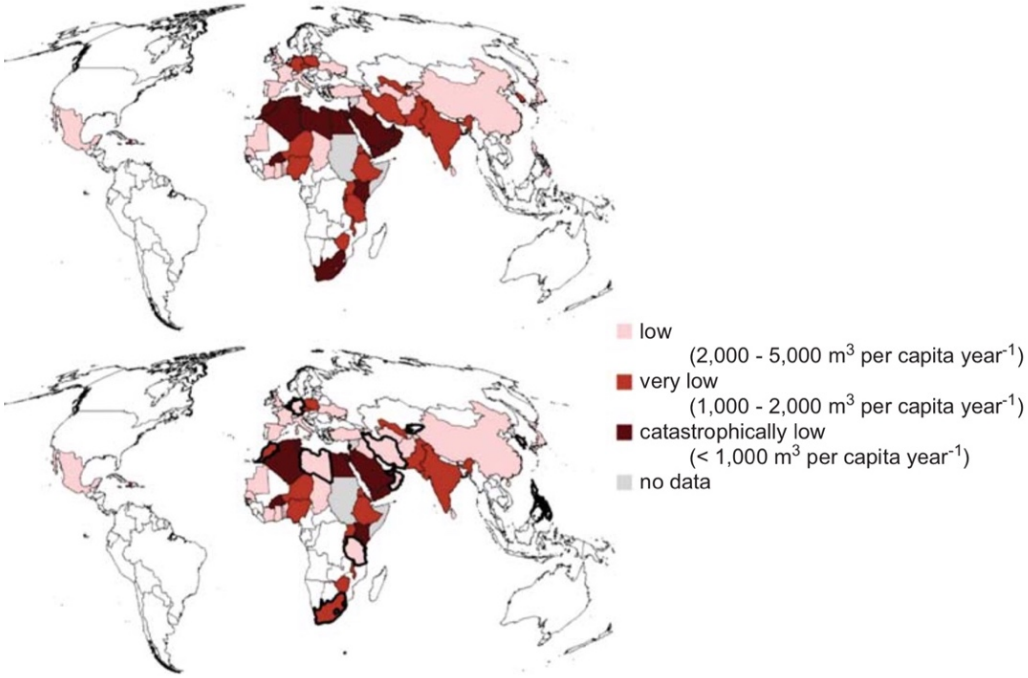

Figure 2.2, Source: Hanasaki *et al*., 2017

2.2 Economic Theories Behind Virtual Water Trade

Although virtual water trade is a fully-fledged economic concept, there is a persistent debate among economists regarding its theoretical grounding. There is plenty of literature addressing the topic of international trade which explains it in terms of differences in productivity, as predicted by the Ricardian model of comparative advantage; differences in resources endowment, as predicted by the Heckscher-Ohlin model; existence of economies of scale and monopolistic competition, as predicted by the Krugman’s New trade theory; import taxes; production surpluses and associated export subsidies; etc.

Despite this topic is widely debated, not many scholars address the question whether international trade is driven by surpluses and shortages of water resources among regions. What might be perceived as a lack of interest from economists is partly justified by the dearth of sufficient evidence proving that the import of products that require a major employment of water is effectively driven by regional water shortage problems.

2.2.1 The Ricardian model of trade

The virtual water trade concept was initially introduced as a solution to the problem of the uneven allocation of natural endowments of water resources. According to this view, water-poor countries could indeed import water-intensive commodities rather than produce them, alleviating their water-stress condition. Some scholars, applying international trade theories to virtual water trade found analogies between the concepts of virtual water and comparative advantage, as defined by the Ricardian model of international trade.

The Ricardian model predicts that a nation can gain from trade by producing only the commodities for which it has a comparative advantage and importing those for which it has a comparative disadvantage instead. In particular, the first one to apply the concept of comparative advantage to virtual water was Professor Dennis Wichelns. In conformity with the comparative advantage concept, the economic efficiency of trade of water-intensive goods and services has to be appraised comparing the opportunity cost of producing them in all the trading countries. The Ricardian model predicts indeed that exporting a water-intensive commodity makes economic sense for a country if the opportunity cost of producing it is lower in that country than in another one. Similarly, from the same reasoning follows that a country gains from trade if it imports a water-intensive good whose opportunity cost of production is relatively high. A country might have a comparative advantage because of abundant water resources or comparatively high-water productivity which allows it to produce more for each unit of water input. The opposite is true for a country with a comparative disadvantage on water-intensive commodities.

The logic consequence of this reasoning would be that water resources' availability in a country influences its pattern of trade. In particular, an analysis carried out by Yang *at al.* in 2003 shows that cereal trade contributed to a significant extent to mitigate water shortages in water-stressed countries. According to these data, below a certain threshold in endowment of water resources, a region's import of cereals and its capita per available water are inversely related and the region necessarily needs to rely on food imports from other countries with more copious water availability.

Even though empirical evidence suggests that water-scarce countries' trade paths are determined by their comparative disadvantage stemming from the production of water-intensive commodities, only a negligible portion of international trade consists of trade in water-intensive products from water-abundant to water-scarce nations. Water scarcity most certainly is a driver for imports of water-intensive commodities in water-scarce countries but other factors, such as political and economic forces, play a more decisive role. By focusing on water as the only relevant input of the production process, virtual water represents the application of the concept of absolute advantage, rather than comparative advantage. Thus, virtual water trade in terms of comparative advantage can only partly explain international food exchanges between countries based on water availability and productivity (Hoekstra, 2010).

2.2.2 The Heckscher-Ohlin model of trade

Many scholars see the virtual water trade concept as a solution to uneven water resource distribution as a direct consequence of the application of the Heckscher-Ohlin (H-O) model of international trade. According to this model, commodity trade can be seen as an implicit exchange in factors of production embedded in commodities. Two main assumptions on which the model is built are that (1) the technologies used in the production process are the same for all countries under analysis- a given amount of a factor of production yields the same quantity of output - and that (2) the factors of production cannot be traded between countries.

The simplest version of this fraction proportions model is the "two by two by two" scenario: two countries, two factors of production and two goods. The Heckscher-Ohlin model predicts that countries export goods which require factors of production they possess in relative abundance. For instance, for a country with much capital and little labor, capital will result relatively cheap while labor relatively expensive. Consequently, such a country would export capital-intensive goods and import labor-intensive goods.

More precisely, suppose there are two countries, Home and Foreign, two factors of production, water (W) and capital (K), and two goods, good 1 and good 2. Let us assume that Home is relatively abundant in water and Foreign in capital: $\frac{W}{K} > \frac{W*}{K*}$[3], or equivalently, that Home is relatively scarce in capital and Foreign in water. Furthermore, suppose that, at any factor price, good 1 is water intensive as its production requires more water relative to capital than good 2 does: $\frac{L_1}{K_1} > \frac{L_2}{K_2}$. The Heckscher-Ohlin model predicts that Home will be relatively efficient at producing good 1 because good 1 is water intensive. In order to understand the mechanisms through which differences in factor endowments give rise to international trade, the biased effect of increases in such factors of production must be considered. Indeed, an increase in the supply of a production factor expands production possibilities disproportionately toward the production of the commodity which intensively requires that factor. Therefore, an economy with a high relative supply of water to capital will be more efficient at producing water-intensive goods than an economy with a low relative water supply.

Suppose now that Home and Foreign open to international trade and that they are equal in every aspect except the factor endowments: Home has a higher ratio of water to capital than Foreign does. Since good 1 is relatively water intensive, at each relative price of good 1 to good 2, Home will produce a higher good 1 to good 2 ratio than Foreign will. In such a scenario, Home is said to be *water-abundant* and Foreign *capital-abundant*. Because for any given ratio of the price of good 1 to that of good 2, $\frac{P_1}{P_2}$, Home will produce a higher ratio of good 1 to good 2 than Foreign will, Home's relative supply of good 1 will be larger than

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[3] The asterisk (*) denotes the variables for the Foreign country.

Foreign's, as shown by Figure 2.3. In the absence of international trade, the equilibria for Home and Foreign would be, respectively, at point 1 and 3. Thus, the relative price of good 1 would be higher in Foreign than in Home. When the two countries start trading, however, relative prices converge as predicted by the model and a world relative price of good 1 is fixed at a point between the pre-trade prices.

The increase in the relative price of good 1 causes an increase in its relative supply and a reduction in its consumption in the Home country. Similarly, the decline in the relative price of good 1 in Foreign leads to a rise in its relative consumption and a fall in its production. Therefore, since Home produces more of good 1 than is consumed and Foreign produces less, market clearing equilibrium conditions require that Home imports good 2 and exports good 1 and, vice versa, that Foreign becomes an importer of good 1 and an exporter of good 2.

Hence, the Heckscher-Ohlin model predicts that the relatively capital-abundant country will export the capital-intensive good while the relatively water-rich county will export the water-intensive good.

A direct consequence of the application of this international trade model to virtual water trade would be a positive relation between a region's water endowment and virtual water exports. This would in turn imply that water-abundant regions have comparative advantages over agricultural, water-intensive, products. Although this conclusion may seem very intuitive, it is not sustained by current empirical evidence which suggests that the H-O model performs poorly when considering virtual water.

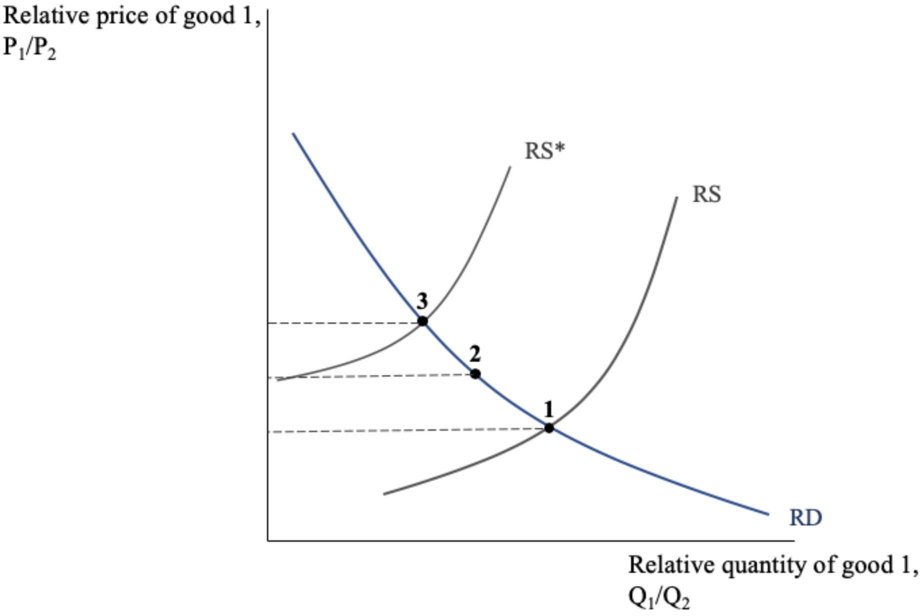


Figure 2.3

In 2001, Earle conducted an analysis on a sample of sixty-three countries to discover a potential relation between a nation's water resources and its grain trade pattern. The sample includes the 92 per cent of the global grain production and the 89 per cent of global freshwater resources, as well as countries that possess either the world's largest or scarcest water resources and those who are the major grain importers, exporters or producers. The study yielded that only the 43 per cent of countries, twenty-seven out of sixty-three, performs as suggested by the Heckscher-Ohlin model. Figure 2.4 shows the result more in the details. All the countries which display “zero” as result are importers as predicted by the model, countries which display “one” do not behave in conformity with what the model predicts, and countries whose result is “two” are exporters and respect the predictions of the model. Despite the result obtained, the author of the study believes that the H-O model does not correctly predict virtual water trade because the two assumptions on which it relies do not hold true in real-world scenarios (Earle, 2001).

Country	Results	Country	Results
Afghanistan	1	Jordan	0
Algeria	0	Kazakhstan	1
Argentina	1	Kenya	0
Australia	1	Korea, Dem. People's Rep.	1
Austria	1	Korea, Republic of	0
Bangladesh	1	Lebanon	1
Belarus	0	Lesotho	1
Belgium-Luxembourg	1	Mexico	0
Botswana	1	Morocco	0
Brazil	1	Myanmar	2
Bulgaria	1	Namibia	1
Canada	2	Pakistan	0
Chile	1	Philippines	1
China	0	Poland	0
Colombia	1	Portugal	1
Czech Republic	1	Romania	1
Denmark	1	Russian Federation	1
Egypt	0	Saudi Arabia	0
Ethiopia	0	South Africa	0
France	1	Sudan	0
Germany	1	Sweden	2
Ghana	1	Syrian Arab Republic	0
Greece	0	Thailand	1
Hungary	1	Turkey	0
India	1	Ukraine	1
Indonesia	1	United Kingdom	1
Iran, Islamic Rep.	0	United States of America	1
Iraq	0	Venezuela, Boliv. Rep. of	1
Ireland	1	Vietnam	2
Israel	0	Yemen	0
Italy	0	Zimbabwe	1
Japan	1		

Figure 2.4, Source: Earle, 2001

In 2004, Ramirez-Vallejo and Rogers applied the Heckscher-Ohlin model in the attempt of deriving a relation between a country's net virtual water trade flows and its freshwater resources. They found no correlation between a net virtual water trade flows and water resource endowments, meaning that agricultural product exchange between countries is not influenced by their national water resources. Furthermore, their analysis identified other variables that have a significantly relevant impact on virtual water trade flows. Some of these variables are population, average income, irrigation, exports measured as a percentage of the country's gross domestic product, etc.

These results may lead to think that there exists a paradox and that the virtual water trade concept is so "economically invisible" that does not contribute at all at determining international food trade paths. This, however, is not the case either. As on one side a number of economists believe the virtual water trade concept fails as it does not find supporting evidence in practice, on the other side, there are scholars who found evidence in favor of a positive relation between imports of virtual water and scarce water resources. In 2009, Novo *et al.* conducted a study analyzing virtual water flows through crop trade in Spain from 1997 to 2005. Their study yielded that Spain virtually imported larger quantities of water during drier years through increased crop imports. In 2002, Yang *et al.* estimated cereal imports in Mediterranean regions, and they found a negative relationship between cereal imports and available water resource endowments. For instance, Libya and Israeli, which are two extremely water-scarce nations, annually import between 90 and 95 per cent of their total domestic cereal supply (Yang *et al.*, 2003).

In 2014, Debaere conducted a study on a sample of 146 countries and 206 sectors to estimate the role of water scarcity in determining international trade in water-intensive commodities. According to his study, empirical evidence actually confirmed that water abundance is a source of comparative advantage which might explain why water-abundant countries tend to export water-intensive commodities. However, despite these encouraging findings, his paper also demonstrates that water shortages play a minor role in determining international trade paths than the traditional production factors, such as labor and capital (Debaere, 2014).

There are different reasons which explain such contradictory findings. First of all, one fundamental assumption for the model to hold is that water constitutes the most critical resource in the production process. However, the reasoning behind the theorem applies to water as well as to all the other inputs involved in the production process. Therefore, considering commodities in accordance with the quantity of virtual water embedded in them provides accurate results only if water is the most relevant input. This, however, is not always the case. A second reason, strictly linked to the previous one, is that all analyses that fail to include other determinants of virtual water flows are very likely to produce biased results. Thirdly, the Heckscher-Ohlin model relies on trade based on relative water scarcity, while many studies imply absolute water scarcity and this bias might lead to such a paradox (Ansik, 2010).

Using data on virtual water trade and water resource availability across regions to test the validity of the Heckscher-Ohlin model may not provide robust results as it does not allow other determinants of virtual water trade to enter in the picture.

2.2.3 The Gravity model of trade

In addition to the Ricardian and the Heckscher-Ohlin models of international trade, the gravity model of trade represents another interesting tool to analyze bilateral virtual water trade flows between nations as it considers also determinants of virtual water flows which do not depend on water endowments. This model predicts that trade flows depend upon the economic size, the physical distance and other distinctive factors of the countries concerned such as trade costs. As a consequence of the wide range of variables included in the analysis, the gravity model of trade provides a more complete idea of what are the forces influencing consumption, production and trade of food products, and thus also the water content of bilateral trade of such goods.

In 2006, Fracasso *et al.* conducted a study on a sample of 145 countries which included both developed and developing nations, with the purpose of estimating the impact of water-related variables on international trade of agricultural products. The results show that mass-related variables, such as population, distance and GDP per capita, are all statistically significant. In particular, there is a negative relationship between imports of virtual water and agricultural tariffs in the importing regions. By contrast, virtual water flows are significantly larger when the countries concerned are adjacent, share the same currency or belong to the same region of trade. As these variables are generally used in all gravity models of trade and are statistically significant also in this specific case, the adoption of the gravity trade model to illustrate bilateral flows of virtual water is definitively compliant. The study yielded also other interesting results about water-related variables. There seems to be a positive (negative) relationship between the portion of land per capita in a country used for agricultural purposes and its exports (imports) of water-intensive food products. Furthermore, variables accounting for water availability for agricultural purposes in a country have a positive coefficient in importing countries and a negative one in exporting countries. A slightly different relationship is found between virtual flows of water and per capita resources of renewable water. Indeed, while the variable accounting for water resources seems to negatively affect water imports, the same cannot be inferred for water exports; this shows that water scarcity has a major impact on a nation's imports than on its exports.

All these results are in line with the intuition behind the virtual water concept according to which water endowments affect the pattern of trade in agricultural products of a country. In addition, the findings of this analysis corroborate the economic intuition of virtual water trade which forecasts that water-scarce countries tend to import water-intensive commodities in order to alleviate their water stress condition (Fracasso *et al.*, 2014).

2.2.4 The New trade theory

Unlike the Ricardian model of trade and the Heckscher-Ohlin model, the New trade theory, proposed by Krugman, assumes imperfect competition and economies of scale, which are both very realistic assumptions. According to this theory, trade between countries is explained mainly by their need to specialize in the production of a good, in order to exploit the advantages of increasing returns of production, rather than by differences in factors of endowments or in the level of productivity. Thus, some countries can benefit from economies of scale realizing some products even if they do not possess comparative advantage on them. In fact, Krugman's new trade theory predicts that, for commodities exhibiting an increasing return to scale, countries gain by producing large quantities of such products and exporting the surpluses abroad.

Two types of economies of scale exist: internal economies of scale- the cost of producing one unit of output decreases as the size of the firm increases- and external economies of scale- the cost of producing one unit of output decreases as the size of the overall industry increases, even if the single firm remains unchanged. The effects of external economies of scale are less intuitive compared to the consequences of internal economies of scale, and thus are often underestimated. However, such gains are remarkably relevant in the case of the agricultural sector as the size of individual firms is relatively small compared to the whole market. The New trade theory does not really seem to be sustained by empirical evidence when it comes to virtual water flows. In fact, most of agricultural trade, and thus the major virtual water flows, is not characterized by economies of scale. Several factors, such as specialized machinery markets, agricultural services, fertilizer market, etc., play a crucial role in the determination of the production site of agricultural products, rather than simple economies of scale. Furthermore, since the production of agricultural food requires substantial quantities of water, trade of such products, as well as virtual water trade which is implicitly included in it, is also influenced by a country's regard for national food security and the maintenance of traditional irrigation-based economies. A country, in order to achieve sustained comparative advantage in the export of virtual water and, in turn, increase economies of scale, needs a non-excessively large population so as domestic food consumption is limited and fertile soil on land is destined to plantations. By contrast, highly urbanized, arid and infertile regions with low agricultural productivity and high opportunity costs of allocating water and land to agricultural exports have comparative disadvantage in the virtual export of water, as predicted by the new trade theory, since they cannot easily achieve economies of scale (Antonelli *et al.*, 2015).

2.3 Definitions of "Water Scarcity"

All the researchers which attempted to apply the virtual water concept to traditional international trade models based their assumptions on the much-discussed issue of *water scarcity*. Water scarcity can be described as the lack of access to adequate water resources for human and environmental purposes that characterizes many areas of the world. Despite the meaning of “water scarcity” seems to be widely understood and, as a consequence, the term is regularly used in contexts of water-stressed conditions, a more precise quantitative and methodological definition is needed since there is no a wide-spread consensus on how water scarcity should be effectively measured. The most logic consequence of the lack of an agreed definition of such a frequently used concept is that researchers might conduct studies using the same world to refer to different measures.

2.3.1 The Water Scarcity Index

One of the most used water-scarcity indicators is the “Falkenmark Indicator” or “Water Scarcity Index” (WSI). This index measures the amount of annual water availability per capita and it was developed in 1989 by the Swedish hydrologist Falkenmark *et al.* which analyzed the effects of shortages of natural water resource endowments on semi-arid countries. Based on annual per capita water usage, they individualized a threshold of 1,700 m^3 of water below which countries can experience different degrees of water shortages. In particular, if the amount of available water per capita is 1,700 m^3 per year, the country falls in the “water stress” category, if the amount of available water is equal or less than 1,000 m^3 per person the country has “water scarcity” problems, and, finally, if annual water resources are below the 500 m^3 per capital threshold the country is said to experience “absolute water scarcity” (Falkenmark *et al.*, 1989). The water scarcity index soon found a wide-spread consensus as it relies on readily available data and, most importantly, because it provides very intuitive and straightforward results.

Despite these evident advantages, this simple indicator has some limitations that might hamper its reliability. Firstly, it only considers water availability at the aggregate level without considering hydric resources distribution differentials within countries. Secondly, it fails to consider water quality or water accessibility despite, in reality, a significant portion of global water resources is either polluted or stored at great depths and, therefore, unavailable to men. Thirdly, it disregards the existence of artificial sources of water such as desalination plants that increase the volume of water available for human consumption. Finally, it treats all the regions of the world homogeneously, ignoring the fact that different countries and different regions within a country might have different water needs.

2.3.2 Basic Human Needs Index

In 1996, the American scientist Peter Gleick developed the “Basic Human Needs Index” to measure the ability of countries to meet water requirements for basic human needs such as drinking, cooking and personal hygiene. This index is based on the assumption that fifty liters of water per day per capita are needed to successfully meet basic human needs given that, under normal circumstances, the minimum daily drinking requirement for human survival is five liters per person, basic requirements for sanitation generally require twenty liters per day depending on social and cultural preferences, fifteen liters per day are needed for adequate bathing, and, finally, the amount of water used for food preparation is about ten liters per day per capita. Based on such data, Gleick proposed a benchmark indicator of 1,000 m^3 per capita per year accepted by the World Bank as a watershed between water scarcity and no-water scarcity conditions.

This index is revolutionary as it does not consider the volume of available water in a country, but rather it focuses on whether domestic water resources of a country are sufficient to satisfy fundamental human rights, such as hygiene and nutrition.

Despite its alternative and innovative approach, the Basic Human Needs Index presents some limitations that might undermine its effectiveness. Just like the Water Scarcity Index, the Basic Human Needs Index assesses water usage on a country scale, without controlling for availability differentials among regions nor for water quality. Furthermore, this water scarcity indicator only takes into account households' water requirements, disregarding water needs for different purposes, such as industrial, environmental or agricultural use.

2.3.3 The Withdrawal-to-Availability ratio

Whilst the Water Scarcity Index measures water availability per capita based on fixed global water demand and the Basic Human Needs Index assumes homogeneous water requirements, a team of researchers at the State Hydrological Institute in St. Petersburg, Russia, focused on annual water availability based on actual water demand when developed the "Withdrawal-to-Availability ratio". This index provides a measure of water scarcity as a ratio of total annual withdrawals to the total amount of available water resources. Water withdrawals are defined as the amount of water subtracted from rivers, streams or groundwater aquifers to satisfy human water requirements (Raskin *et al*., 1997). According to this approach, a country is said to be water scarce if annual water intakes are between 20 and 40 per cent of annual freshwater supply. Similarly, if the Withdrawal-to-Availability ratio exceeds the 40 per cent, the country is said to experience severe water scarcity. This method is widely used by researchers for water scarcity analyses and the 40 per cent threshold is now considered a "criticality ratio", defined as the proportion of water intakes for human consumption purposes to total available hydric resources (Alcamo *et al*., 1997).

Despite this water scarcity indicator considers heterogeneous water demand across the world, it still has some limitations which reduce its effectiveness. Just like the Water Scarcity Index, the Withdrawal-to-Availability ratio does not account for artificial water resources such as desalination plants or water storage facilities that increase water availability. Moreover, this index disregards recycled or reused water as well as a country's ability to implement new technologies or infrastructures to mitigate domestic water shortage issues (Rijsberman *et al*., 2006).

2.3.4 The Social Water Stress Index

The "Social Water Stress Index" (SWSI) builds on the Water Scarcity Index, but it expands its scope taking into consideration also the society's *adaptive capacity*- that is, the society's ability to adapt to water stress conditions through technological, economic or other means. This water scarcity indicator was developed in the year 2000 by the authors Ohlsson and Turton which noticed that political and socioeconomic factors could affect, either positively or negatively, a country's water resources availability inducing a particular type of water scarcity referred to as "social" or "second order water scarcity".

In particular, Ohlsson argued that countries adapt differently to water shortages depending on their income distribution, education opportunities and political participation. He proposed the introduction of the Human Development Index (HDI) that embodies three variables, namely, life expectancy, educational attainment and GDP per capita, in a more complete water scarcity index to control for societal variables and provide, consequently, more reliable estimates.

Thus, combining the Water Scarcity Index with the Human Development Index, the Social Water Stress Index can be easily obtained as

$$SWSI = \frac{WSI}{HDI/2}$$

This ratio allows to measure a country's water scarcity considering also the level of domestic human development and to divide countries into four categories depending on their level of water availability. Countries with a Social Water Scarcity ratio higher than five are considered relatively sufficient in terms of natural water endowments, countries with a ratio between five and ten fall in the category of "water stress", and, finally, countries with a ratio between ten and twenty or higher are considered to be water scarce or absolutely-water scarce, respectively (Sullivan *et al*., 2014).

As would be expected, countries' classification based on water scarcity according to the SWSI will differ from the one derived from the use of the simpler WSI. For instance, according to data from the year 2000, countries such as South Korea, United Kingdom, Iran and Belgium do not qualify anymore as "water-stressed" countries, but rather as "relatively sufficient", due to their higher social capacity to adapt captured by a higher Human Development Index. By contrast, developing countries such as Niger, Eritrea and Nigeria move from "relatively sufficiency" to "water stress" category as a consequence of their limited adaptive capacity.

2.3.5 International Water Management Institute (IWMI) Indicator

A more comprehensive water scarcity indicator was developed by the International Water Management Institute (IWMI) with the aim of addressing the deficiencies of the previous listed measures. This approach considers a greater number of factors which might affect water scarcity conditions in a country such as its infrastructures that might increase domestic water resources, like for example desalination plants; whether the country uses recycled or fresh water by considering water demand to consumptive purposes rather than merely total withdrawals; and, finally, its capacity to adapt to water scarcity through efficiency improvements and infrastructure enhancement.

According to this indicator, countries are divided into two categories based on their level of water scarcity. Countries that are predicted to be incapable of satisfying future water demand even with the development of new infrastructures and efficiency improvements are classified as "physically water scarce". This category includes countries where more than 75 per cent of domestic river flows are withdrawn for human purposes. Countries where more than 60 per cent of river flows are withdrawn are expected to experience water scarcity in the near future, and thus classified in the "approaching physical water scarcity" category. On the other hand, countries that possess adequate natural water resource endowments but would not be able to satisfy domestic water demand without improvements in investments or efficiency are considered "economically water scarce". This category includes countries where less than 25 per cent of domestic river flows are withdrawn for industrial, agricultural or domestic purposes but efficiency or infrastructure improvements are needed to allocate water resources as efficiently as possible. Finally, countries that withdraw less than 25 per cent of river flows for human purposes are considered to experience "little or no water scarcity" (Seckler *et al.*, 1998).

Since the International Water Management Index is a more elaborated water scarcity indicator than the ones previously listed, it logically follows that it involves significant amount of time and of resources to be assessed and that its interpretation is not as intuitive as the other indexes'. However, despite its innovative approach, this index still presents some limitations that compromise its effectiveness. In fact, it disregards the capacity of individuals within countries to adapt to water shortages as well as their economic situation which may affect their adaptive ability by importing food produced abroad or using water saving devices in order to mitigate the pressure on stressed domestic water resources.

The findings of a study conducted by the International Water Management Institute in 2007 on global water scarcity using this approach are shown by Figure 1.5.

2.3.6 Water Poverty Index

In 2003, Sullivan *et al.* developed the "Water Poverty Index" with the aim of creating a nexus between water scarcity and socioeconomic factors. This water scarcity indicator classifies countries according to different levels of water scarcity combining five different variables: (1) access to water resources, (2) physical availability and quality of water resources, (3) effectiveness of people's capacity to manage hydric resources, (4) water uses for domestic, agricultural and industrial purposes and (5) environmental impact of water withdrawals. Hence, the Water Poverty Index is given by the expression

$$WPI = \frac{\sum_{i=1}^{N} w_i X_i}{\sum_{i=1}^{N} w_i}$$

where X_i represents the five components determined, in turn, by many subcomponents and w_i is the weight applied to that component. Each component is standardized and a maximum score of 20 is assigned to each of them, so that the final index score ranges from 0 to 100. A country with a WPI equal to 100 has the lowest possible water scarcity condition, while a score equal to 0 indicates the country occupies a low rank in all five components. The increased complexity of the Water Poverty Index allows to provide a more comprehensive assessment including all the variables ignored by simpler indicators, resulting in a more reliable measure. On the other hand, such complexity might also hamper its popularity as researchers may prefer a more straightforward approach such as the Falkenmark Indicator. Moreover, because this indicator requires a vast amount of data, it is more suited to analyses at a local rather than global level. Despite such drawbacks, the results of this approach provide various advantages as the Water Poverty Index provides an exhaustive means to understand the complexity of water shortage problems by merging economic, environmental and social aspects.

2.4 *Is Virtual Water Trade Actually Driven by Water-Scarcity?*

Ascertained that directly trading water does not make economic sense due to the difficulty of its transportation and its low price per weight, the only profitable solution to water-scarcity problems is the international trade of water-intensive commodities. In particular, international exchange of agricultural products, which embed a substantial amount of water, saves water globally and mitigates local water shortages all over the world through the geographical shift of agricultural products that allows countries not to consume their resources. However, as it might be wrongly inferred, virtual water trade's primary purpose is not to solve the problem of uneven natural resources' distribution on the planet as it does not always involve trade between water-abundant and water-scarce nations. Although the logic argument might conclude that the more a country suffers from water shortages, the more it will become dependent on virtual water imports, this is not always the case. Real world data deny indeed the existence of a positive relationship between a country's water scarcity and water dependency, as shown by Figure 2.5 (Hoekstra *et al.*, 2002).

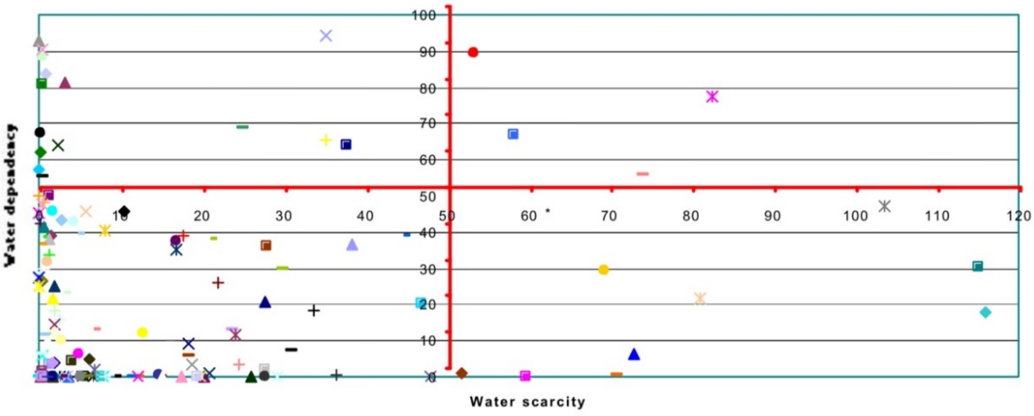


Figure 2.5, Source: Hoekstra *et al.*, 2002

If the two factors analyzed were positively correlated, all points would have lied around the 45° bisector. However, the majority of the countries lies in the left-bottom area of the scatterplot which corresponds to low water dependency and low water scarcity. What might seem odd is the presence of countries in the right-upper and right-bottom areas of the graph which correspond, respectively, to high water dependency but low water scarcity (e.g. Indonesia and Switzerland), and low water dependency but high water scarcity (e.g. Iran and Pakistan).

For instance, more than half of cereal trade involves water-abundant countries as importers, rather than as exporters only, and only 20 per cent of it is water scarcity induced (de Fraiture *et al.*, 2004). There are situations in which water-abundant countries import water-intensive products from water-scarce regions and this happens because it is not unusual that, in some countries, labor costs or land endowments, rather than water, are the binding constraints. A study to show whether a minor natural endowment of water resources influences virtual water trade was conducted on a sample of 131 countries across the globe among which nine have absolute water scarcity, four are characterized by water scarcity, fourteen fall in the water stress category, and the remaining ones are all water abundant. The analysis yielded that there is no a distinct relationship between the volume of food trade of a country and its relative water availability. In fact, of the 131 countries in the sample, sixty-five water-abundant countries are net importer of virtual water and, by contrast, other countries on the verge of water stress, such as Malawi, India and Afghanistan, export water-intensive products such as livestock and food grain (Kumar *et al.*, 2005).

A similar reasoning applies to water flows in China which demonstrate a lack of water allocation efficiency. Here the trade pattern might seem even counter-intuitive: Northern China, which is a water-scarce region, exports about 5% of its available hydric resource while, by contrast, Southern China, which is a water-abundant region, is a net importer of water from other regions, exacerbating their already precarious resources (Chapagain *et al.*, 2006). In India as well trade patterns follow a resembling path. Regions in the northern area of the country export substantial quantities of food to the eastern regions which are characterized by greater water endowments (Verma *et al.*, 2009).

These results confirm the hypothesis that virtual water trade does not entirely mitigate the problem of unequal allocation of water on the planet because water shortage is just one of the numerous drivers of national trade strategies which are mainly influenced by political, historical and economic considerations. In addition, international food trade, although entails a more efficient water resource allocation among nations, does not depend on countries' water resources endowments, contrary to what is stated by the Heckscher-Ohlin Theorem (Ramirez-Vallejo *et al.*, 2004). In fact, decisions about trade patterns are made considering the product's price and characteristics, rather than the quantity of water used during its production process. Thus, water savings through trade are related to productivity differences between traders and are simply a secondary result.

Chapter 3: Does Virtual Water Trade Effectively Optimize the Amount of Water Consumed?

The virtual water concept represents a new paradigm for understanding complex dynamics of hydric resource usage by humans. In particular, the use of such an indicator allows to highlight the role agriculture plays in the consumption of global natural resources and, additionally, it permits the recognition of the importance of hydric resource management which must be carried out on a worldwide scale, rather than on a local scale as often happened in the past. As it has been repeatedly mentioned in this paper, alimentary commodity trade among countries involves a correspondent transfer of large volumes of water from a continent to another, with significant flows which occasionally even exceed the quantity of water used for the production of agri-food products destined to domestic consumption.

When countries import agricultural commodities, they are substantially importing water resources from the exporter. The opposite happens when they export such commodities to other countries which can thus save water they would have otherwise needed to consume. Water-use efficiency is defined as the volume of water used to produce one unit of output. A country can increase its water-use efficiency by decreasing the volume of water to produce the same amount of output. Virtual water trade allows to save water both at national and global level. At the country level, by importing water-intensive commodities, such as cereals, a country can reduce its consumption of water resource by a significant extent. Globally, savings of water through agricultural commodity trade occur if the exporting country has a more efficient production system in terms of water than the importer does. The smaller the productivity gap between the importer and the exporter, the more negligible water savings are, ceteris paribus. If the importing countries improve their productivity in respect to water, the volume of water global savings will reduce. In fact, improved productivity might enable the importing country to produce the same quantity of output as before deploying a smaller volume of water. This, in turn, would reduce the quantity of exports demanded by the importing country, reducing the overall amount of water savings through international trade.

For instance, trade decreases the total amount of water used at a global level if the exporting country cultivates under rain-fed conditions instead of relying on irrigated agriculture, as the importing country would be forced to do. Indeed, if a country produces under rain-fed conditions only green water is consumed, while if it relies on irrigation water, both blue water and green water in the form of rainfalls are consumed.

Several scholars promote the idea that international food trade is a useful policy tool to reduce water-scarcity related problems affecting numerous regions of the world. According to these theories, water-scarce countries should import water-intensive commodities from water-rich countries in order to save as much as water possible and employ it for unavoidable purposes instead.

In 2006, Chapagain *et al.* conducted one of the most comprehensive studies about a country's water savings through international trade of agricultural products. National water savings are computed as the product between the volume of imports and the volume of water that would have been employed if the commodities were produced domestically. Virtual water trade on one hand generates savings for the importing countries, and on the other one it generates losses for the exporting countries as the amount of water required to export products cannot be used domestically for other purposes. Globally, the net effect of virtual water trade will depend on the level of productivity of the exporter relative to importer's. Trade indeed will only be profitable if commodities are produced in high-productive countries and transferred to low-productive regions, otherwise losses in terms of water resource will be incurred.

3.1 Effects of International Cereal Trade on Virtual Water

Despite empirical evidence proves that water scarcity is only one of the numerous drivers of international food trade and that most of this trade occurs between water-abundant countries and does not involve water-scarce countries as importers, several studies have been made to estimate virtual water flows with the purpose of stressing the importance of international trade for the management and preservation of such a precious resource.

According to a study on cereal trade conducted in 2004 by de Fraiture *et al.,* in 1995, 12 per cent of the global cereal production, equal to 1,724 million tons, was traded internationally. The United States, accounting for almost half of the world cereal exports, were the biggest exporting countries, followed by Canada, Argentina, and Europe. In these countries, cereals, which account for the 80 per cent of all cereal exports, are cultivated under rain-fed conditions and 269 km^3 of crop water were used to produce the traded amount. For what concerns the importing countries, among the top ten importers there were China, Japan, Iran, Mexico, Korea, Egypt and Indonesia. These countries would have consumed 433 km^3 of crop water and 179 km^3 of irrigation water to produce domestically the amount they imported instead. The global average amount of crop water needed to produce one kilogram of cereal is 1.70 m^3. Exporters are naturally more efficient than importing countries as, on average, they deploy 1.23 m^3 and 2.05 m^3 of crop water per one kilogram of cereal, respectively.

Figure 3.1 provides a graphical representation of global virtual water flows in 1995, where exporting countries are colored in green and importing countries in red. As it can be inferred from the map, many countries of the sub-Saharan Africa do not import a considerable amount of cereal despite their low hydric resources and agricultural productivity in terms of water. This "paradox" is justified by the countries' inadequate financial resources needed to import food in order to meet domestic consumption demand.

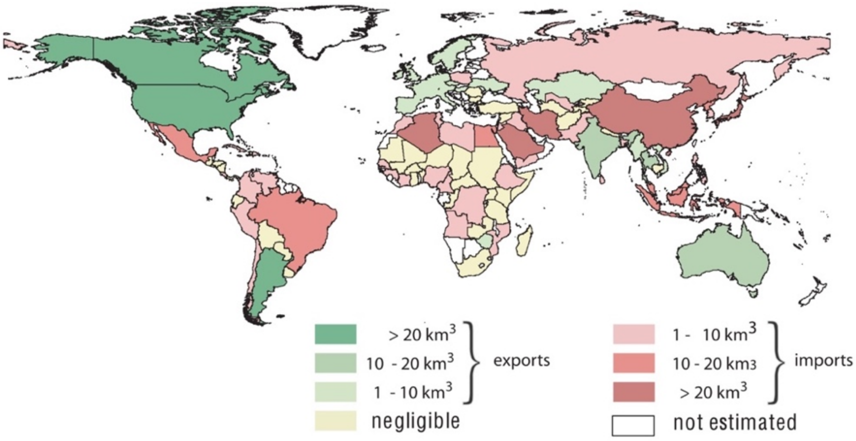


Figure 3.1, Source: de Fraiture *et al.*, 2004

As previously mentioned, a country saves water at a national level by importing a product instead of producing it. This is the case of water-stressed countries, such as Egypt which, in 2000, saved 5.8 billion m^3 of national water by importing maize. Trading one kilogram of maize with France, Egypt would save circa 0.52 m^3 of water because the content of virtual water of maize in France and Egypt is 0.6 m^3/kg and 1.12 m^3/kg, respectively. Globally, a water saving equal to 2.7 billion m^3 of water was generated from productivity differences between the exporting countries and Egypt (Renault, 2003). Likewise, in the same year, Japan imported 27 million tons of grain from Australia, Canada and the United States, saving a total of 37 km^3 of its own water resources, between rain and irrigation, which would have been otherwise required to produce that quantity of grain on Japanese soil (de Fraiture *et al.*, 2004).

At the global level, as long as the exporter is more water efficient than the importer, international trade reduces water use in the importing country. In 1995, Japan imported an equivalent of 16.6 km^3 of crop water from the United States, for which it could have required 28.1 km^3. This is an example of how a country can save global water resources, in this example 11.5 km^3 (28.1 km^3-16.6 km^3), by importing from a more water efficient country. This favorable scenario does not always take place in the real world.

Sometimes, in fact, it might happen that the importer is more water efficient than the exporting country. This is, for example, the case of India which in 1992 exported 2.3 million tons of grain to Indonesia which employed 17.4 km^3 of water. However, if Indonesia decided to produce the same amount of crop domestically, only 16.7 km^3 of water would have been employed, causing therefore a global water loss of 0.7 km^3. A similar scenario resulted from grain imports in Sudan. In 1995, Sudan imported grain from South Africa, the Russian Federation and other countries reducing global crop water consumption by 1.1 km^3. However, since the exporting countries relied primarily on irrigation while Sudan would have produced mainly under rain-fed conditions, the result was a global loss of irrigation water equal to 0.2 km^3 (de Fraiture *et al.*, 2004).

In 1995, without international cereal trade, irrigation water consumption would have been 11 per cent higher, while crop water consumption would have been higher by 6 per cent. Despite such an encouraging result, it has been made clear from previously mentioned analyses that the role of water scarcity in determining international trade paths is limited. According to a study conducted in 2003 by Yang and Zehnder on a sample of Asian and African countries with data from 1980 to 2000, about 20 per cent of cereal trade has water-scarcity as prominent determinant. A result in line with the analysis of Yang and Zehnder is the one of the analysis conducted by de Fraiture *et al.* according to which only 23 per cent of international cereal trade of year 1995 occurred for reasons related to hydric resource scarcity.

All this means that at an aggregate level, the role of water resources shortage in determining food trade flows is negligible. However, its contribution varies at the national level. According to data on world's cereal trade in 1995, no linear relationship between water shortages, water productivity and water savings through trade exists. In fact, among the major importers, Japan and Korea appear even if they do not suffer water-scarcity problems. Furthermore, countries such as Egypt combine high water productivity with a significant lack of water resources which constitutes an important determinant of food imports. Finally, the third category of importing countries consists of those with low water productivity and insufficient water resources, such as Algeria, Pakistan and Saudi Arabia, that constantly face a trade-off between increasing food imports to save water or investing to increase water productivity.

Water savings stemming from virtual water trade are mainly a consequence of differences in water productivity levels among countries than an effect of differences in water resources. Countries such as Australia indeed, despite they do not have excessively abundant hydric resources, allow water savings at a global level by exporting food commodities grown with irrigation water because they employ water in a more efficient way than the countries to which they export. In the light of this assumption, an increase in cereal production and trade does not necessarily result in an increase in water depletion as long as water productivity is improved contextually.

Between 1980 and 2000, the volume of cereal exports increased by almost 30 per cent, while the volume of water consumed by the exporters remained roughly constant, fluctuating around 270 km^3 of crop water per year. This result might seem a paradox but, in practice, it is the direct consequence of improved water productivity in the exporting countries which widened even more the productivity gap between importing and exporting regions, as shown by the scatter plot in Figure 3.2.

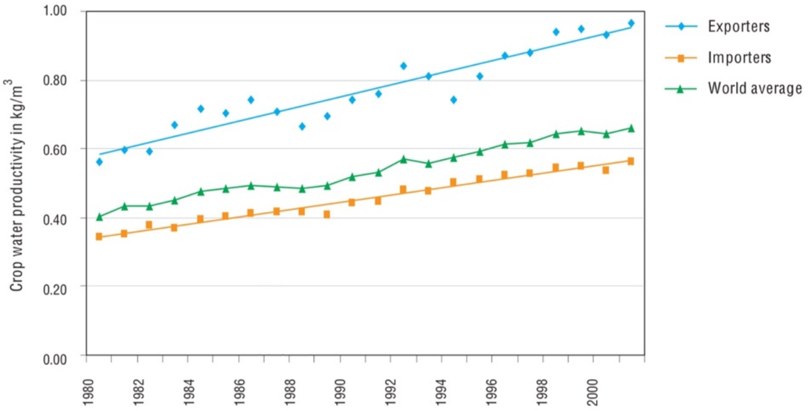


Figure 3.2, Source: de Fraiture *et al*., 2004

Fraiture *et al.* made also some projections for trade and water savings for the year 2025 based on some predictions made by Rosegrant *et al*. in 2002 according to which, by 2025, cereal exports will increase to 343 million tons, employing "only" 336 km^3 of crop water. This total amount of crop water corresponds to a world average of 1.02 m^3 of water per kilogram of cereal which, compared to the 1995 global average of 1.70 m^3 per kilogram, would lead to an improvement of circa 24 per cent (Rosegrant *et al*., 2002).

To provide a complete picture of expectations about virtual water trade volume changes in 2025 as a consequence of an increase in trade by almost 60 per cent compared to 1995, the volume of crop water depleted for cereal production destined to exports is expected to increase by 20 per cent from 269 km^3 to 336 km^3, while irrigation water is expected to remain constant floating around 65 km^3 per year because of forecasted water-productivity improvements in all exporting countries. As a consequence, global water savings through international food trade will increase significantly for both crop and irrigation water, from 164 to 359 km^3 and from 111 to 191 km^3, respectively. Globally, water savings are expected to rise to 19 per cent within 2025 because of commodity exchange between countries, proving an increase in water scarcity's contribution to shaping international trade patterns all around the world (de Fraiture *et al*., 2004).

These results, however, should not mislead the analysis heretofore conducted. Indeed, despite projections of future scenarios might suggest an increase in the role of hydric resources in international exchanges, most water savings stem from improved water productivity in exporting regions. According to Rosegrant's forecasts, in fact, developed countries will increase their water productivity of cereals from 1 to 1.4 kilograms per m^3 of water, while developing countries' water productivity will increase from 0.6 to 1 kilograms/m^3.

3.2 Final Assessment of the Effect of Virtual Water Trade

Virtual water trade can generate water savings at a national and at an aggregate level. In the former case, water savings are equal to the value of imports multiplied by the volume of water which would have been required to produce the good domestically. This, however, is a zero-sum game as a water "gain" of the importing country corresponds to a water "loss" in the exporting country where that amount of water cannot be used for other purposes. At the aggregate level, net water savings depend on the difference between the volume of water used in the exporting country and the volume that would have been depleted to produce the same quantity of output in the importing country. In this context, savings can be realized in two alternatives ways: (1) trading products from high-water productive to low-water productive countries, (2) transferring products from high to low productive periods through food storage.

In 2006, Chapagain, Hoekstra and Savenije conducted a study to estimate national and global net water savings and losses for the years 1997-2001 through trade of all major crop and livestock products. In this study, however, they merely focused on physical savings, rather than on their economic interpretation as the economic efficiency of international trade of water-intensive commodities, as for any other type of products, is determined by more factors than water alone, such as capital, land and labor endowments, import quotas or tariffs and export subsidies.

The analysis yielded results that might have been expected: many countries effectively reduced their domestic water consumption through international trade in agricultural products, as shown by Figure 3.3.

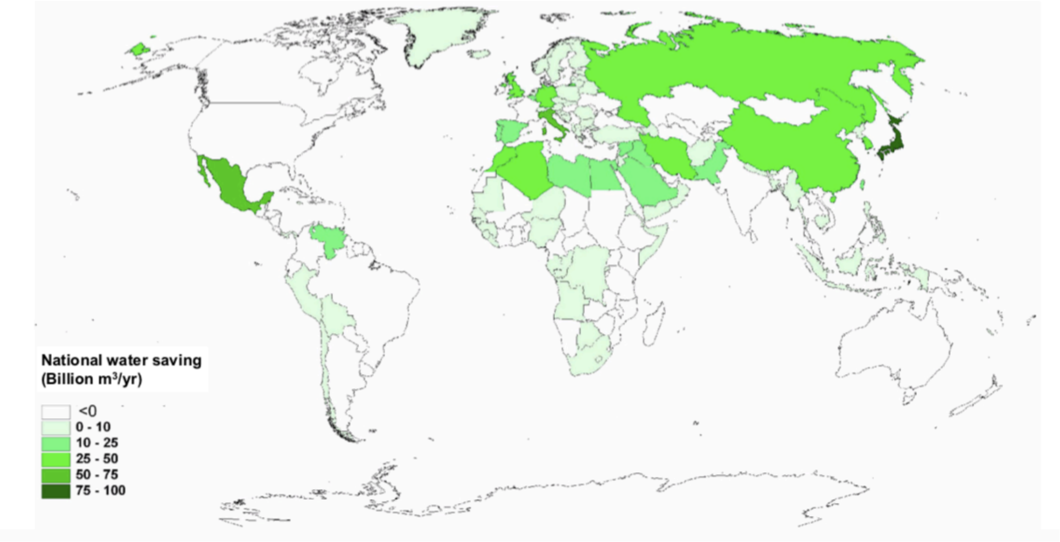
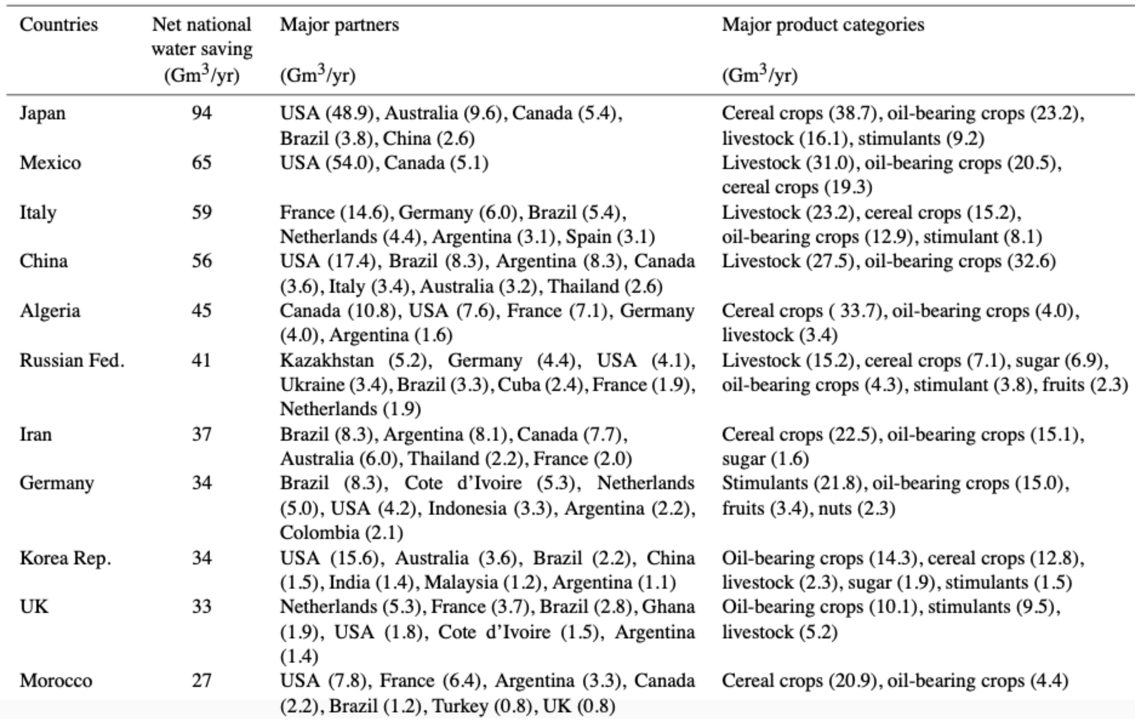


Figure 3.3, Source: Chapagain *et al.*, 2006

From 1997 to 2001, Japan, the world largest net importer of water-intensive commodities, saved 94 billion m^3 per year from its domestic hydric resources, Mexico saved 65 billion m^3, and Italy 59 billion m^3. Figure 3.4 provides an overview of global national savings as a result of international trade in crop and livestock products from the year 1997 until 2001. These data ought to be read bearing in mind that water-scarcity in the importing country is only one of the many determinants of international trade patterns. Thus, these national water savings, even though significant, are only partially induced by water shortage problems. Moreover, national water savings have different implications from country to country.

For instance, Germany saves 34 billion m^3 of water per year through imports of stimulants crops, such as coffee and tea, which it would otherwise not produce itself. Thus, even if the country reduced imports of such products, its hydric resources would not be put under additional stress. By contrast, Morocco, which imports 27 billion m^3 of water per year mainly through cereal crops, would increase domestic water depletion by 21 billion m^3 per year if it decided to produce this commodity domestically (Chapagain *et al*., 2006).



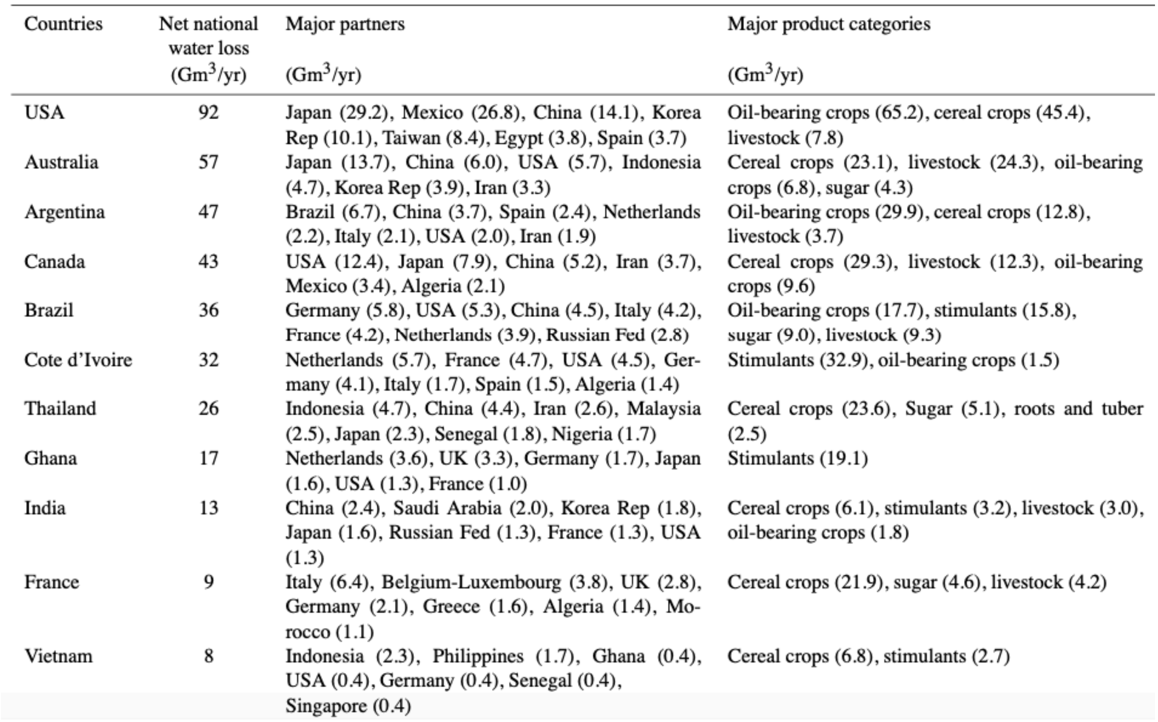
Countries	Net national water saving (Gm^3/yr)	Major partners (Gm^3/yr)	Major product categories (Gm^3/yr)
Japan	94	USA (48.9), Australia (9.6), Canada (5.4), Brazil (3.8), China (2.6)	Cereal crops (38.7), oil-bearing crops (23.2), livestock (16.1), stimulants (9.2)
Mexico	65	USA (54.0), Canada (5.1)	Livestock (31.0), oil-bearing crops (20.5), cereal crops (19.3)
Italy	59	France (14.6), Germany (6.0), Brazil (5.4), Netherlands (4.4), Argentina (3.1), Spain (3.1)	Livestock (23.2), cereal crops (15.2), oil-bearing crops (12.9), stimulant (8.1)
China	56	USA (17.4), Brazil (8.3), Argentina (8.3), Canada (3.6), Italy (3.4), Australia (3.2), Thailand (2.6)	Livestock (27.5), oil-bearing crops (32.6)
Algeria	45	Canada (10.8), USA (7.6), France (7.1), Germany (4.0), Argentina (1.6)	Cereal crops (33.7), oil-bearing crops (4.0), livestock (3.4)
Russian Fed.	41	Kazakhstan (5.2), Germany (4.4), USA (4.1), Ukraine (3.4), Brazil (3.3), Cuba (2.4), France (1.9), Netherlands (1.9)	Livestock (15.2), cereal crops (7.1), sugar (6.9), oil-bearing crops (4.3), stimulant (3.8), fruits (2.3)
Iran	37	Brazil (8.3), Argentina (8.1), Canada (7.7), Australia (6.0), Thailand (2.2), France (2.0)	Cereal crops (22.5), oil-bearing crops (15.1), sugar (1.6)
Germany	34	Brazil (8.3), Cote d'Ivoire (5.3), Netherlands (5.0), USA (4.2), Indonesia (3.3), Argentina (2.2), Colombia (2.1)	Stimulants (21.8), oil-bearing crops (15.0), fruits (3.4), nuts (2.3)
Korea Rep.	34	USA (15.6), Australia (3.6), Brazil (2.2), China (1.5), India (1.4), Malaysia (1.2), Argentina (1.1)	Oil-bearing crops (14.3), cereal crops (12.8), livestock (2.3), sugar (1.9), stimulants (1.5)
UK	33	Netherlands (5.3), France (3.7), Brazil (2.8), Ghana (1.9), USA (1.8), Cote d'Ivoire (1.5), Argentina (1.4)	Oil-bearing crops (10.1), stimulants (9.5), livestock (5.2)
Morocco	27	USA (7.8), France (6.4), Argentina (3.3), Canada (2.2), Brazil (1.2), Turkey (0.8), UK (0.8)	Cereal crops (20.9), oil-bearing crops (4.4)

Figure 3.4, Source: Chapagain *et al*., 2006

International food trade creates winners and losers. On one hand, importing countries save their domestic water resources by purchasing products produced abroad; on the other hand, exporting countries employ their domestic hydric resources to produce goods which are then not consumed by their inhabitants, generating national water losses. The idea behind is that if a country's water resources are depleted to produce commodities consumed by other countries, the volume of water consumed is not available anymore for in-country purposes. From 1997 to 2001, the United States was the country with the largest net water losses as a result of international trade in agricultural and livestock products and its losses amounted to 92 billion m^3 of hydric resources per year. During the same period, Australia's water losses amounted to 57 billion m^3 per year, followed by Argentina and Canada with, respectively, annual losses of 47 and 43 billion m^3 of water. Figure 3.5 provides an overview of water losses of all countries that incurred into losses in terms of water as a result of production for export purposes.

Water losses, however, do not have the same economic nor environmental implications in all countries. Whereas in the United States they are mainly linked to oil-bearing crops and cereal crops exports which are partly irrigated and partly grown under rain-fed conditions, national water losses in countries such as

Cote d’Ivoire and Ghana stem primarily from the exports of stimulants which are produced entirely under rain-fed conditions- that is, using green water resources. This implies that such losses have a negligible impact on national economy and on the environment due to the very low opportunity cost of green water which, moreover, would not be necessarily used for other in-country purposes.



Countries	Net national water loss (Gm^3/yr)	Major partners (Gm^3/yr)	Major product categories (Gm^3/yr)
USA	92	Japan (29.2), Mexico (26.8), China (14.1), Korea Rep (10.1), Taiwan (8.4), Egypt (3.8), Spain (3.7)	Oil-bearing crops (65.2), cereal crops (45.4), livestock (7.8)
Australia	57	Japan (13.7), China (6.0), USA (5.7), Indonesia (4.7), Korea Rep (3.9), Iran (3.3)	Cereal crops (23.1), livestock (24.3), oil-bearing crops (6.8), sugar (4.3)
Argentina	47	Brazil (6.7), China (3.7), Spain (2.4), Netherlands (2.2), Italy (2.1), USA (2.0), Iran (1.9)	Oil-bearing crops (29.9), cereal crops (12.8), livestock (3.7)
Canada	43	USA (12.4), Japan (7.9), China (5.2), Iran (3.7), Mexico (3.4), Algeria (2.1)	Cereal crops (29.3), livestock (12.3), oil-bearing crops (9.6)
Brazil	36	Germany (5.8), USA (5.3), China (4.5), Italy (4.2), France (4.2), Netherlands (3.9), Russian Fed (2.8)	Oil-bearing crops (17.7), stimulants (15.8), sugar (9.0), livestock (9.3)
Cote d’Ivoire	32	Netherlands (5.7), France (4.7), USA (4.5), Germany (4.1), Italy (1.7), Spain (1.5), Algeria (1.4)	Stimulants (32.9), oil-bearing crops (1.5)
Thailand	26	Indonesia (4.7), China (4.4), Iran (2.6), Malaysia (2.5), Japan (2.3), Senegal (1.8), Nigeria (1.7)	Cereal crops (23.6), Sugar (5.1), roots and tuber (2.5)
Ghana	17	Netherlands (3.6), UK (3.3), Germany (1.7), Japan (1.6), USA (1.3), France (1.0)	Stimulants (19.1)
India	13	China (2.4), Saudi Arabia (2.0), Korea Rep (1.8), Japan (1.6), Russian Fed (1.3), France (1.3), USA (1.3)	Cereal crops (6.1), stimulants (3.2), livestock (3.0), oil-bearing crops (1.8)
France	9	Italy (6.4), Belgium-Luxembourg (3.8), UK (2.8), Germany (2.1), Greece (1.6), Algeria (1.4), Morocco (1.1)	Cereal crops (21.9), sugar (4.6), livestock (4.2)
Vietnam	8	Indonesia (2.3), Philippines (1.7), Ghana (0.4), USA (0.4), Germany (0.4), Senegal (0.4), Singapore (0.4)	Cereal crops (6.8), stimulants (2.7)

Figure 3.5, Source: Chapagain *et al*., 2006

Chapagain, Hoekstra and Savenije, by analyzing trade patterns of 285 crop products and 123 livestock products, estimated that global water savings from year 1997 to 2001 as a result of trade in agricultural products amounted to 352 billion m^3 per year, the 6 per cent of the volume of water used for global agricultural production. Furthermore, they quantified the contribution of different categories of products to water savings at the aggregate level throughout the same time frame. The group responsible for the largest water savings was the one of cereal crop products, with a net saving of 222 billion m^3 of water per year. Within the group, wheat trade produced 103 billion m^3 of water savings per year mainly as a result of trade from Western Europe and North America to the Middle East and North Africa, maize trade annually saved 68 billion m^3 of water mainly from exports from the United States, and rice trade saved about 21 billion m^3 per year. Cereals were then followed by oil-bearing crops which contributed to global water savings sparing 68 billion m^3 of water per year, and by livestock products with an annual net water saving of 45 billion m^3. Water savings due to trade of livestock products are less copious than average savings in other agricultural products because there is a smaller variation in the volume of virtual water employed in the production of such commodities.

Thus, on one hand virtual water alleviates water shortage problems in water-poor countries through international trade, and on the other one it might create additional pressure on countries which export water-intensive commodities. In order to obtain a complete evaluation of the global effect of virtual water trade at the aggregate level, an assessment of the type of water used- either blue or green- and of the water productivity of the countries under analysis is therefore needed.

Conclusions

Over the last decades, the interest towards the virtual water concept has been growing substantially as a consequence of the increased concern for global water security.

Daily water depletion by men far exceeds the volume associated with domestic usage; indeed, the greatest portion of consumption of this precious resource is related to the volume embedded in the production process of all goods and services consumed, in particular food. For instance, data on water consumption in Italy suggest that only 4 per cent of the overall daily water depletion is devoted to domestic consumption, leaving the remaining 96 per cent to unconscious consumption. In fact, notwithstanding routine activities deploy substantial amount of water resources, people are not completely aware of their level of water consumption as virtual water is de facto invisible. The virtual water concept represents a fundamental nexus between food security and water security, and this is why it must be properly exploited in order to achieve an efficient management of global natural resource endowments.

Through international trade of water-intensive commodities, countries can employ global water resources more efficiently by producing in more water-abundant countries or in countries with a higher productivity. Nevertheless, despite virtual imports of water through trade of other commodities might seem the most reasonable solution to solve problems caused by the uneven global distribution of natural resource endowments, water scarcity is just one of the many factors influencing trade patterns between countries, determined mainly by political and economic forces.

Even though scarce natural water endowments moderately contribute to the definition of prevailing trade patterns between countries without playing a decisive role and virtual water trade is simply a by-product of international trade, international trade actually does create global water savings that cannot be ignored. In particular, virtual water trade generates water savings at two different levels: (1) at the national level, as importing countries spare domestic water resources by purchasing commodities produced abroad, (2) and at the global level, as long as the exporting country possesses comparative advantage in terms of water relative to the importer. For instance, for what concerns water savings resulting from international trade of agricultural products at the aggregate level for the year 1997 until 2001, they have been estimated to be 352 billion m^3 per year.

The positive impact of trade on the global water use, despite of the forces determining it, is undeniable and this is the reason why a growing number of researchers propose that international food trade could be used as an efficient policy instruments to mitigate water scarcity at the global level.

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