

Conflicting Drivers of Virtual Water Trade: A Review Based on the “Virtual Water Concept”

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The virtual water concept has been largely applied in the study of regional, national, and global water flows with particular emphasis on water endowment. Despite water traditionally being managed locally, certain forces (drivers) influence the local water resource availability and hence virtual water exchanges. This study reviews available literature to determine those drivers and their influence on virtual water exchanges. Studies show that the drivers are numerous, and there exist several available literatures providing controversial results leading to a high level of uncertainty in the determination of their relative significance. Possible reasons for the contradicting results are discussed and suggestions made.

Keywords: Water endowment; virtual water trade; environmental and socioeconomic drivers; trade determinants.

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1. Introduction

Water is an important resource component, responsible for the hydrological, biological, geological, and chemical sustainability of the earth (da Silva *et al.* 2016). However, the availability of this indispensable resource at such amounts to enable sufficient food production is a challenge in several parts of the world today (Adelodun and Choi 2020). Agriculture, which is the leading sector for water consumption, accounts for 69% of the world's water withdrawal, while the industries and municipalities account for 19% and 12%, respectively (FAO 2010; Miglietta and Morrone 2018). The increasing population of the world coupled with the increase in economic and social activities has led to the rise in water consumption (Adelodun *et al.* 2020; Liu *et al.* 2015a), prompting the initiation of technical and managerial actions aimed at establishing rational and sustainable water policies (Hoekstra and Chapagain 2008). Moreover, various nations have collaboratively developed virtual water flow regulations focused on commodity and livestock products using the “virtual water” concept coined by the Geographer Tony Allan in the early 90s. An example of the implementation of these flow regulations is the trade activities of the Middle East and North Africa (MENA) region where more water-intensive products are imported from water-sufficient countries. As a water efficiency metric, virtual water defines the amount of water expended in the course of producing goods or services (Allan 1997). It is categorized into three; namely blue, green, and gray water. Blue water comes from the surface and groundwater sources along the supply chain of a product; green water comes from rainfall and is contained in soils; and gray water refers to the amount of water required to dilute contaminated water to bring it to the same quality as ambient water resources (Lillywhite 2010). Tony Allan suggested the importation of virtual water (linked goods or services) to reduce the pressure on the domestic available water resources (Allan 1996), as cited in Miglietta and Morrone (2018). By importing food from other countries, a nation imports virtual water which is embedded virtually in the products being traded (Hoekstra 2003), as cited in Zhao and Jackson (2016). According to Hoekstra and Hung (2005), there is a shift in local water consumption to other countries when food is imported. Thus, the international trade of food and industrial products can be viewed as a trade of a country's water resources in the virtual form (Hoekstra 2003).

The virtual water concept has been largely applied in the study of regional (Akoto-Danso *et al.* 2019; Chen and Li 2015; Cui *et al.* 2018), national (Bazrafshan *et al.* 2019; Dang *et al.* 2015; Zhang and Anadon 2014), and global (Hoekstra and Chapagain 2008; Hoekstra and Hung 2005; Zhang *et al.* 2016) water flows. The increasing research has prompted an increase in the reviews

conducted over the years. [da Silva et al. \(2016\)](#), [Ali et al. \(2017\)](#), [Lovarelli et al. \(2016\)](#), and [Paterson et al. \(2015\)](#) in their respective reviews, focused on volume, self-sufficiency, and methodologies concerning virtual water flows. [Antonelli and Sartori \(2015\)](#) also conducted a review on virtual water with a primary focus on its critics, applications, and relationship with economic theory. In a broad sense, the majority of the reviews related to virtual water trade (VWT) have mainly focused on the water endowment of nations. Virtual water trade enables the externalization of the impacts of water and countries' dependency rate on foreign water resources to be determined ([Duarte et al. 2019](#)). However, analyzing virtual water trade purely from a water endowment perspective offers a partial judgment ([Hoekstra 2017](#)); hence a multidisciplinary perspective must be utilized. This involves the integration of other natural, socioeconomic, and political indicators that affect local and international economies. These indicators have promoted the awareness of water issues on a global scale, revealing the effects of the different trade options on the products consumed and on where the production of goods and services was carried out. A considerable number of studies have analyzed virtual water trade, considering not only water availability but also other environmental and socioeconomic indicators ([Fracasso et al. 2016](#)). As opined by [Wichelns \(2004\)](#), trade in virtual water can likely come from other factors aside from water endowment. The increasing attention on virtual water is extremely relevant since water is an important factor of sustainable development and plays a non-negligible role in the achievement of the United Nation's Sustainable Development Goals. Identifying the drivers of virtual water trade is of utmost importance for the design and evaluation of any environmental and economic policy ([Duarte et al. 2019](#)). Likewise, analyzing virtual water trade as regards its influencing factors, coupled with the accounting and sustainability analysis of water footprints, may support integrated policy options formulation, addressing climate change issues or efficient use of resources ([Tamea et al. 2014](#)). While reviews exist on the drivers of virtual water trade across regions ([D'Odorico et al. 2019](#)), studies indicating the influence of these drivers on virtual water trade flows, as well as the research challenges faced, are little or non-existent. This review, therefore, seeks to explore this loophole in the face of an existing heated discourse. Specifically, this study identifies the various drivers of virtual water trade as observed from reviewed literature and then discusses the influence of these drivers based on the “virtual water concept”. The study is necessary to further add to the existing and expanding literature on virtual water trade analysis. This is critical, especially as it concerns the relationship between available water in a region and the environmental, social, and economic factors influencing the design of policies.

The rest of this research is organized as follows: Section 2 shows the studies on drivers of virtual water trade. Section 3 discusses the influence of the drivers on virtual water exchanges. Section 4 discusses the challenge of contrasting findings. Section 5 discusses the virtual water concept with respect to observed studies. The conclusions are shown in Sec. 6. The methodological process utilized in this study is elaborated in Appendix A. Also, a summary of the explanatory variables used by different models of virtual water trade is contained in the supplementary material.

2. Studies on the Drivers of Virtual Water Trade

The literature on the main empirical forces or drivers influencing virtual water trade has been developing over the years. This section examines those forces as identified by several studies under different spatio-temporal scales and accounting boundaries.

The drivers influence virtual water flows essentially through the direct or indirect effect on the consumption volume and pattern, as well as the water footprint of consumed products and processes (Chapagain and Hoekstra 2007). Yang et al. (2003) and Yang and Zehnder (2007) conducted their studies on a global scale using the multiple regression model, and found virtual water trade to be significantly influenced by the GDP per capita and water availability. They discovered that during the period of 1980–2000, the GDP significantly explained the variations in the level of cereal imports among countries with similar water resources availability, while the reduction in per capita water resources availability dominantly explained the increase in the import of water-intensive crops. Ramirez-Vallejo and Rogers (2004) and Kumar and Singh (2005), who also conducted a similar study, noted that arable land availability, GDP per capita, population, and Human Development Index (HDI) were important considerations in the assessment of fluxes in virtual water imports. Also, D’Odorico et al. (2012), Fracasso (2014), Tamea et al. (2014), Duarte et al. (2016a, 2019), Fracasso et al. (2016), Wang et al. (2016), Kopnova (2017), Tuninetti et al. (2017), and Qian et al. (2019) conducted similar studies on a global scale using different model analyses [Gravity Model, Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT), Decomposition Analysis (DA), and Logarithmic Mean Divisia Index (LMDI)]. They reported that the virtual water trade between countries was highly influenced by economic, institutional, geographical, and environmental factors. In detail, D’Odorico et al. (2012) reported that geographical distance and water availability could adequately influence virtual water fluxes in their study on *spatial organization and drivers of the virtual water trade*. Fracasso (2014) after conducting an analysis on a *gravity model of virtual water*

trade suggested that all indicators studied significantly influenced virtual water trade (imports and exports), concluding that the flows in virtual water trade were affected by national water endowments, classical trade determinants, and the pressure level on water resources. Duarte *et al.* (2016a) also analyzed global agricultural virtual water flows from an economic perspective where it was reported that the availability of such natural resources as water and land, together with the level of economic development, conditioned the volume and trajectory of virtual water exchanges (imports and exports) among nations. They suggested the need to analyze environmental problems at the global level since the growing integration in international trade of many countries is essential to an understanding of their final water consumption. Similarly, Tuninetti *et al.* (2017) and Duarte *et al.* (2019) reported a significant influence of population, GDP per capita, geographical distance, and water availability on virtual water trade. Tamea *et al.* (2014) and Fracasso *et al.* (2016) in their studies also reported that economic factors and agricultural productivity were the main determining factors of virtual water flows.

Zhao *et al.* (2014), Liu *et al.* (2010, 2015b), Chouchane *et al.* (2018), Schwarz *et al.* (2019), Li *et al.* (2019), and Cai *et al.* (2019) conducted their studies at a national scale. Zhao *et al.* (2014) reported a positive influence of population, demand per capita, technological effect, and income on virtual water flows within the Chinese agricultural sector. Also, Chouchane *et al.* (2018) who conducted a study on the virtual water trade patterns as related to environmental and socio-economic factors reported that population, precipitation, GDP, and irrigated area were explanatory in the determination of the virtual water imports in Tunisia. Cai *et al.* (2019) also reported in their study on *drivers of virtual water flows on regional water scarcity in China*, that virtual water trade changes were mainly explained by water scarcity and demand per capita, suggesting the consideration of the direction changes of virtual water flows and its impact on water scarcity in the target set of future regional water use.

Kong *et al.* (2019), Wang *et al.* (2019), Ye *et al.* (2019), and Garcia and Mejia (2019) conducted their studies on a subnational scale. In their study on *decoupling analysis of water footprint and economic growth in three regions of China*, Kong *et al.* (2019) reported that water availability and GDP were significant decisive factors of virtual water trade. Wang *et al.* (2019) reported a similar result in their study, concluding that virtual water fluxes exist because of the uneven distribution of water resources in time and space and the differences in economic and social development. Also, Garcia and Mejia (2019) in their study on *characterizing and modeling subnational virtual water networks of US agricultural and industrial*

Table 1. Studies on Drivers of Virtual Water Trade

Paper	Spatial Scale	Study Period	Impact Model Utilized	Major Findings
Yang et al. (2003)	Global	1980–2000	Multiple regression	GDP per capita was highly significant in explaining the variations in the level of cereal imports among countries with similar availability of water resources, while the rise in the import of water-intensive crops was largely explained by a decrease in per capita water supply availability.
Ramirez-Vallejo and Rogers (2004)	Global	2000–2001	Multiple regression	Virtual water trade flows are independent of water resource endowments. Variables found to significantly influence virtual water imports were average income, population, irrigated land, value-added agriculture, and exports of goods and services.
Kumar and Singh (2005)	Global	1995–1999	Multiple regression	A country's virtual water trade is not significantly influenced by its water situation.
Yang and Zehnder (2007)	Global	1980–2000	Multiple regression	The variations in the level of cereal imports among countries having similar water resources were significantly explained by GDP per capita, while the decline in per capita water resources availability was a dominant factor in explaining the increase in the import of water-intensive crops.
Liu et al. (2010)	National	1994–2008	Gravity law	The positive factors correlated to agricultural virtual water trade are the endowment of the factors of agricultural labor, technology, the agricultural scale economy, the income of demanders, the exchange rate, and the accession to WTO, while the negative ones are the endowment of agricultural land, water, GDP, the price level, and the regional economic organization.

Table 1. (Continued)

Paper	Spatial Scale	Study Period	Impact Model Utilized	Major Findings
D’Odorico <i>et al.</i> (2012)	Global	1986–2008	Gravity law	Geographical proximity partly explains the community structure of virtual water trade and a Gravity Model based on the availability of and demand for virtual water in different countries has higher explanatory power.
Tamea <i>et al.</i> (2014)	Global	1986–2010	Gravity law	Population, GDP, and geographical distance of both exporter and importer countries were the fundamental controlling factors of virtual water fluxes.
Fracasso (2014)	Global	2006	Gravity law	The bilateral virtual water flows are affected by the classical determinants of trade, by national water endowments, and by the level of pressure on water resources.
Zhao <i>et al.</i> (2014)	National	1990–2009	STIRPAT model	Changes in population size are the largest driving force leading to increases in the Chinese agricultural water footprint.
Liu <i>et al.</i> (2015b)	National	1981–2010	Multiple regression	Cultivated area per capita and total population were the major influencing factors for virtual water export; and consumption and retail price index mainly influenced the volume of virtual water import.
Duarte <i>et al.</i> (2016a)	Global	1965–2010	Structural Decomposition Analysis (SDA)	The availability of such natural resources as water and land, together with the level of economic development, condition the volume and trajectory of virtual water trade flows.
Fracasso <i>et al.</i> (2016)	Global	2004	Gravity law	Larger water endowments do not necessarily lead to larger exports of virtual water.
Wang <i>et al.</i> (2016)	Global	2007	STIRPAT model	Affluence was found to be the most critical driver of virtual water imports.

Table 1. (Continued)

Paper	Spatial Scale	Study Period	Impact Model Utilized	Major Findings
Kopnova (2017)	Global	1996–2012	Multiple regression	The countries with more intense trade flows had a lower rating of ecological sustainability.
Tuninetti et al. (2017)	Global	1986–2011	Gravity law	Population, geographical distance, and fertilizer application rate were the major influencers of virtual water trade.
Chouchane et al. (2018)	National	1981–2010	Multiple regression	Blue water scarcity does not explain the net virtual water import dynamics of any of the selected crops.
Han and Huang (2018)	Subnational	2002–2010	Multiple regression	The impacting factors on external virtual water flows successively include population, arable land, water availability, GDP, and agricultural productivity.
Duarte et al. (2019)	Global	1965–2010	Gravity law	Virtual water trade was significantly influenced by the economic, institutional, geographical, as well as environmental factors.
Kong et al. (2019)	Subnational	2004–2017	LMDI	Water availability and GDP were the major decisive factors of virtual water trade.
Wang et al. (2019)	Subnational	2008–2015	Gini coefficient and imbalance index	Natural, socioeconomic, and environmental conditions influence virtual water trade.
Cai et al. (2019)	National	2002–2012	SDA	The main factors explaining changes in virtual water trade were water scarcity and demand per capita.
Garcia and Mejia (2019)	Subnational	2007	Gravity law	Virtual water trade is highly influenced by geographical distance, agricultural land, GDP, and population.
Ye et al. (2019)	Subnational	1996–2015	Multiple regression	Results indicate that GDP, population, technology update, and demand were the dominant influential factors of virtual water flows.
Qian et al. (2019)	Global	2000–2016	LMDI	Virtual water trade was significantly influenced by water intensity, trade structure, and production structure.

Table 1. (Continued)

Paper	Spatial Scale	Study Period	Impact Model Utilized	Major Findings
Schwarz <i>et al.</i> (2019)	National	1986–2013	Index Decomposition Analysis (IDA)	Increasing trade quantities are the main driver of increasing virtual water volumes.
Li <i>et al.</i> (2019)	National	2002–2015	SDA	Trade scale and urban consumption level are quantified as the key drivers raising China’s industrial water footprints.
Duarte <i>et al.</i> (2014)	National	1849–1935	DA	Trade structure was an essential driving factor of rising virtual water flows.
Zhao <i>et al.</i> (2019)	National	1995–2015	Multivariate Linear Regression Analysis	The regional differences in land productivity between agricultural and non-agricultural sectors are the main forces shaping the pattern of virtual water flows across regions.
Wang <i>et al.</i> (2016)	Global	2007	STIRPAT model	Affluence, not the availability of freshwater resources, was found to be the most critical driver of virtual water imports.
Duarte <i>et al.</i> (2016b)	National	1965–2010	DA	A large increase in virtual water trade was primarily driven by the trade structure.

commodity flows posited that distance, agricultural land, GDP, and population mainly controlled the subnational weighted virtual water trade networks.

Other findings related to the global, national, and subnational scales are reported in Table 1. It is evident that several researchers have studied the relationship between virtual water flows and product trade in an attempt to determine to what extent water endowments among other drivers impact on trade flows. This has resulted in contradictory findings due to certain factors discussed in the sections that follow.

3. Influence of the Drivers on Virtual Water Exchanges

As highlighted earlier, the driving forces influence virtual water flows essentially through the direct or indirect effect on the consumption volume and pattern. Investigations into the association of environmental and socioeconomic factors with virtual water fluxes show that research is ongoing toward the identification and testing of the effect of various possible drivers on virtual water exchanges at all

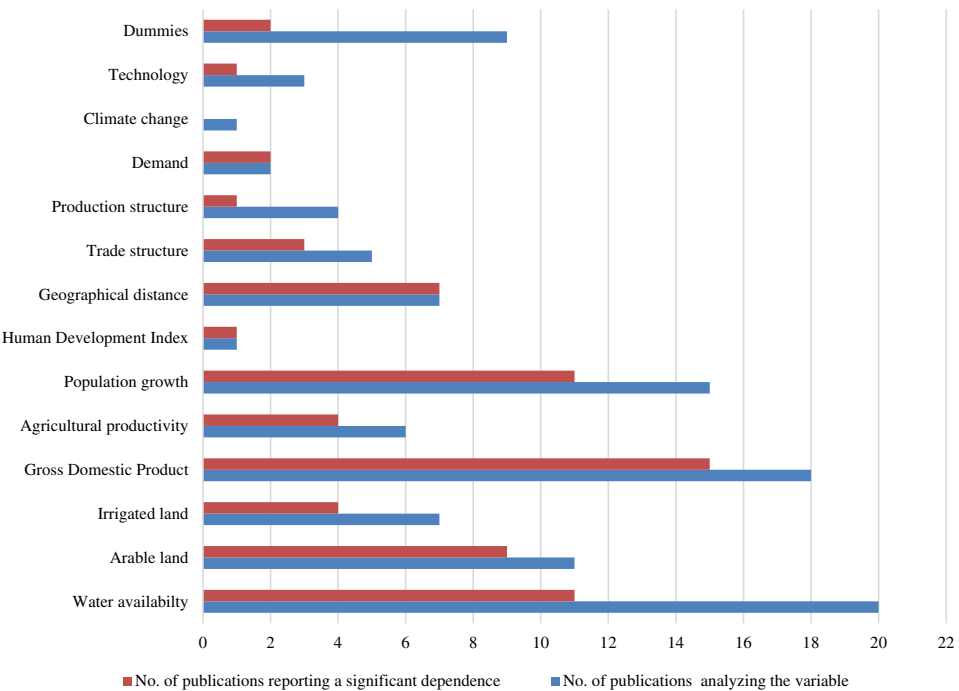


Figure 1. Environmental and Socioeconomic Drivers of Virtual Water Trade Identified from Reviewed Publications

Notes: The red and blue bars show the number of publications reporting a significant relevance of each variable and the number of publications that analyzed each variable, respectively.

spatial levels. As observed from the literature review in Sec. 2, the GDP, water availability, population, arable land, geographical distance, and agricultural productivity were commonly recognized drivers of virtual water trade (Figure 1).

The GDP is a major driver of virtual water fluxes at both local and international levels. Considered as a measure of wealth, the GDP is correlated with the ability to invest in agricultural and industrial production and trade (Dinar *et al.* 2011), hence determining economic development. With continuous economic development, the volume of water utilization increases (Wang *et al.* 2019), suggesting that countries with high economic power (GDP) possess the economic strength of purchasing real/virtual water.

Water availability (including scarcity, intensity, endowment, and precipitation) has received considerable attention and coverage concerning its relationship with the virtual water trade. Though existing empirical results are mixed, there is considerable evidence that the availability of water in a region will significantly influence trade intensity from that region. Based on the findings of Lee *et al.* (2018) and Allan (2003), the pressure on water resources in water-stressed countries may partially be reduced through the importation of water-intensive products from abroad, replacing the use of domestic water for industrial and agricultural production with water that is imported in virtual form, and saving their water resources that are limited for alternative domestic needs thus resulting in local (and global) water savings. It is suggested that as trade occurs from regions with higher water productivity, defined as water use per unit of production, to regions with lower water productivity, there are savings in global water resources (Liu *et al.* 2019). The findings of Reimer (2012), that countries having constrained freshwater resources can consume more water than what is available locally through trade, also justify the inclusivity of water availability as a driver of virtual water flows. However, the arguments against water as a determining factor of virtual water trade stem from the fact that many studies have observed a great negative impact of global trade on water resources, in that several countries with severe water shortages like Egypt and India have exported vast amounts of virtual water, while some (particularly developed) nations with abundant water resources have imported more (Chen *et al.* 2021).

Several studies have also hugely recognized population as a driver of virtual water trade. Population growth is one of the major determinants of increase or decrease, as the case may be, in water demand and per capita availability of water resources. The continuous growth of the world population may increase the number of those living under water stress, leading to an expansion of the demand for food import and thus virtual water exchanges (Yang *et al.* 2003).

Arable land is an essential factor influencing virtual water flows, characterized by the temporary production of crops for food or feed supply purposes. The area of land available for food production will increase or decrease virtual water flows between countries or regions. To understand the relative effect of resource endowments between nations involved in trade, Kumar and Singh (2005) considered the amount of available water resources per hectare of arable land, reasoning that when access to arable land increases, a country's ability to use its water resources and raise livestock or produce crops increases thus influencing virtual water trade. The irrigated land area also plays an important role in virtual water exchanges. There has been a remarkable increase in crop yields on irrigated lands, which has influenced virtual water exchanges especially from the MENA regions characterized by severe droughts.

The distance traveled by goods in the form of virtual water to arrive at the place of consumption is a significant measure of the globalization of virtual water trade. Likewise, the transportation cost (determined by distance and transportation modes) influences the extent of virtual water flows between regions. According to Tamea et al. (2014), the closer the countries, the larger are the exchanged fluxes and vice versa. Luo et al. (2018) in their study on *transfer of virtual water of woody forest products from China*, also reported that virtual water trade among nations was driven by geographical proximity and traffic, bearing in mind the significant effect of transportation cost. For a better quantification of the influence of geographical distance on global, national, and regional virtual water fluxes, the distance value in terms of cost, determined by factors such as the length of travel and mode of transportation, is important.

In terms of food production, agricultural productivity (defined by yield and efficiency) is a major driving factor of virtual water exchanges. As stated by Yang et al. (2006), virtual water flows primarily from nations of high crop water productivity to nations of low crop water productivity, implying that nations with the ability to produce more agricultural products with lower units of water, may have the capacity to supply more to demanding regions.

Additionally, a good number of factors including trade structure, demand, labor, production structure, product price level, climate change, HDI, exchange rate, technology, government policies and international trade agreements, and income have been recognized to influence virtual water flows.

The trade structure defines a country's imports and exports of goods in the total import and export trade share between trading countries in a certain period. To respond to water crises, Qian et al. (2019) posit that more attention should be paid to the risks resulting from water stress and other environmental implications as a result of trade.

Demand here refers to the volume of goods and services consumed by the people in a region or nation. Arguments exist among scholars that virtual water trade is a potential solution for curbing irregularities between available water resources and demand (Antonelli and Sartori 2015; Ma *et al.* 2006). These arguments arise from the fact that some nations have the advantage of high economic efficiency in food production and have surplus water, but still rely on food imports. Hence, demand for goods and services might not be influenced by the available water resources but by the economic state of nations (Kumar and Singh 2005).

The production structure refers to the share of a certain product in the total trade volume between trading countries. A change in production structure can cause a relative change in the total virtual water flows of a country (Cai *et al.* 2019). For example, a production structure restructuring process (involving a reduction in the export of products requiring large amounts of water and stimulating exports of less water-intensive products) can influence internal water consumption (Dietzenbacher and Velázquez 2006). Accordingly, countries with improved resource-use efficiency and less resource-intensive production structure tend to conserve more water resources (Sun *et al.* 2019).

The HDI is a measure of the overall achievement of a country in terms of its economic and social dimensions concerning the health of people, educational attainment, and standard of living. Studies show that countries with relatively high HDI generally have a high dependency on external water resources than countries with low HDI (Allan *et al.* 2017). Since HDI incorporates many factors, it may allow for a significant cross-comparison of the virtual water flows between countries (Carr *et al.* 2013).

Technological advances and the associated improvement in water-use efficiency have played an important role in bringing down the water resources threshold (Yang *et al.* 2003). Technology update influences the efficiency and productivity of water utilization in the industrial and agricultural sectors, hence the nature of virtual water trade.

Climate change is an influential factor in the rise in water demand for domestic, agricultural, and industrial purposes worldwide. Increasing frequencies of climate extremes such as floods and droughts often lead to economic losses, prompting the need for virtual water exchanges across nations. As Lenzen *et al.* (2013) put it, climate change threatens to alter hydrologic cycles in the current face of increasing water demand, thus affecting water availability.

The national income level influences the extent of virtual water trade. Studies show that an increase in income may lead to an increase and a change in the composition of demand for products thus influencing trade patterns (Anderson 2010).

Government policies and international trade agreements govern agricultural production which makes up the bulk of virtual water flows. For instance, since the World Trade Organization (WTO) was established in 1995, there has been an increase of preferential trade agreements that have resulted in various types of trade creation that may not necessarily consider the resource endowments of nations but rather bilateral ties (Saha and Kapuria 2021). These factors influence virtual water trade patterns thus making the examination of their interaction with water endowments a thing of great concern.

The product price level also influences the extent of virtual water trade between trading nations. With lower foreign prices, the demand for imported goods will likely rise, leading to an increase in the virtual water trade volume (Delbourg and Dinar 2020). This is particularly true for countries having strong bilateral trade ties.

4. Suppressing the Challenge of Contrasting Findings

While several works of the literature are of the notion that trade in water-intensive goods and services results in the flows of virtual water from water-endowed (exporting) to water-scarce (importing) regions, e.g., Yang et al. (2003), Yang and Zehnder (2007), Cai et al. (2019), D'Odorico et al. (2012), Duarte et al. (2016a), Fracasso (2014), Kong et al. (2019), and Wang et al. (2019), many other studies have discovered a non-significance of water endowment as a driver of virtual water exchanges, e.g., Fracasso et al. (2016), Garcia and Mejia (2019), Kumar and Singh (2005), Liu et al. (2015b), Schwarz et al. (2019), Tamea et al. (2014), Tuninetti et al. (2017), Wang et al. (2016), Ye et al. (2019), and Zhao et al. (2014). The availability of a large pool of literature providing controversial results leads to a high level of uncertainty in the determination of virtual water flow drivers. The possible reasons for such contrasting findings (Figure 2) as observed from the literature include the following:

- (a) *Existence of several drivers*: There exist several environmental and socio-economic factors that influence goods exchange and in extension, virtual water trade of which water availability is only one. Where several determinants are not included in the empirical estimation of virtual water trade flows, there is a failure in the robustness of the results, often leading to instances of “omitted-variable bias” as the applied model attributes the effects of the missing virtual water flow drivers to the drivers that were included. As opined by Fracasso (2014), one needs to identify as many drivers as possible, to successfully account for the trade dynamics of virtual water flows.

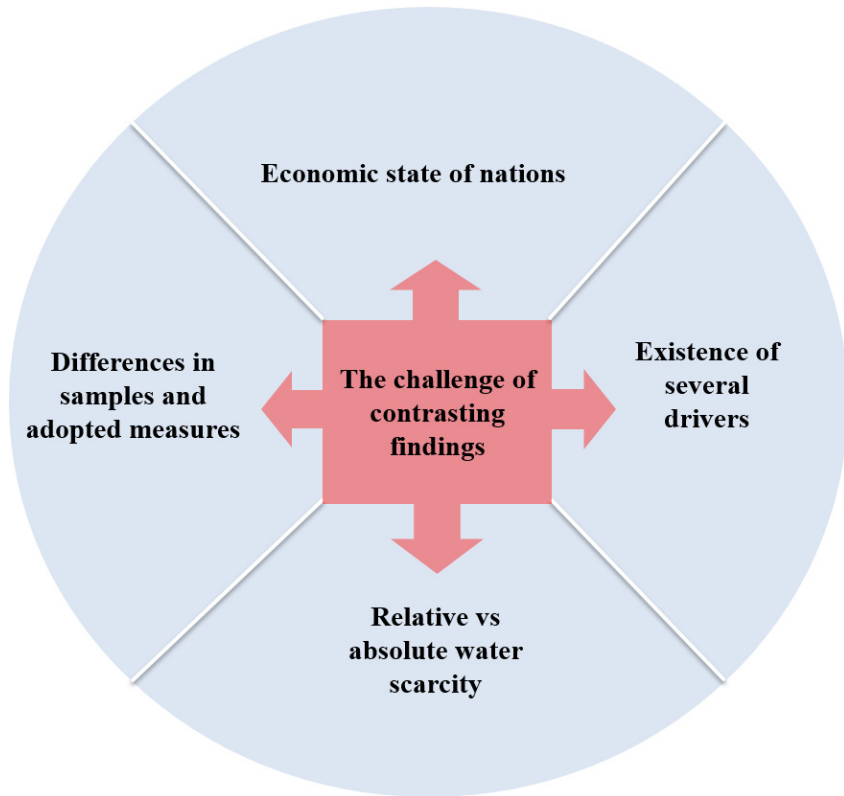


Figure 2. Possible Reasons for Contrasting Findings

- (b) *Differences in samples and adopted measures*: The differences in the samples (subnational, national, and global flows) and adopted measures (export and import flows, bilateral and aggregated flows, and gross and net flows) of countries’ virtual water flows contribute to the observed differences in findings. This is possible because larger nations have higher trade flows as a result of their sheer size, implying that virtual water trade does not rely solely on water endowments. As confirmed by [Kumar and Singh \(2005\)](#), the amount of arable land significantly influences the production of agricultural goods and should be considered in relation to water endowments.
- (c) *Economic state of nations*: The unequal distribution of “factors and goods” prices across nations, as well as the differences in technological prowess, leads to possible variations in observed results. For instance, the cost (scarcity value) of water as a factor of production is sensitive and difficult to account for in agricultural goods in terms of pricing. This is because the majority of

agricultural products are produced using rain (green) water which is *per se* free, and where irrigation (blue) water is applied, the cost is often conditioned by political decisions leading to price variations across nations (Fracasso 2014). This unequal distribution influences the production, consumption, and exchanges of goods and services which, in turn, have an impact on the relative significance of water endowment in the regions or nations involved in trade.

- (d) *Relative versus absolute water scarcity*: The relative and absolute scarcity concepts have been confused in several studies over the years. While the Heckscher–Ohlin (HOV) theory relates net virtual water flows to relative water scarcity, several available works in the literature base their studies on absolute scarcity (Ansink 2010; Fracasso 2014), thus creating contradictory results. The HOV theory of relative factor abundance proposes that the relative endowments and factor intensities of all productive factors and products across countries must be taken into consideration, in order to properly assess the significance of water endowments on virtual water trade flows.

5. The “Virtual Water Concept” and Trade: Discussion from Observed Studies

The virtual water trade is mainly viewed as a water-saving strategy, where countries having water shortages import water-intensive commodities from countries having abundant water resources. However, several studies have shown the non-reflectance of this strategy, especially in the international trade data. de Fraiture et al. (2004) showed that water savings cannot always be reallocated to other beneficial uses to offset water scarcity, hence other environmental, economic, and social considerations can have more impact in deciding the trade strategies. Also, since much focus is put on water resources endowment, trading strategies based on the perspective of virtual water are not consistent with the economic principle of comparative advantage (CA), therefore cannot be used alone as a yardstick for the design and development of satisfactory policies (Wichelns 2010). The CA principle introduces opportunity cost as an analysis factor in choosing between different production options. These production options are influenced by factor endowments thus determining an economy’s ability to produce more of a particular good or service than its trading partners. In other words, the CA principle entails the benefits countries achieve from trade originating from differences in their factor endowments (Deardorff 2011; Hartmann et al. 2017; Hidalgo and Hausmann 2009; Zhao et al. 2019). This principle offers a compelling viewpoint on the forces that drive trade. As also observed from Figure 1 in this study, nearly half of the studies analyzing the influence of water availability on virtual water trade reported its non-

significance, implying that other drivers such as the GDP, population, land availability, and geographical distance are highly relevant to trade and virtual water flows governance. It can also be deduced that irrespective of the spatial scale applied, trade is hugely influenced by socioeconomics and government policies of nations rather than the differences in water endowments. As also stated by Antonelli and Sartori (2015), the ability to engage in trade is asymmetric and is influenced by socioeconomic growth. This implies that water scarcity issues can most likely be solved by the economic capability of regions or nations. Since water endowment is but a factor of production amongst several others, a region’s or nation’s productive efficiency (i.e., total factor productivity) should be a better explanatory factor for trade.

Is the “virtual water concept” thus a helpful perspective in the governing of regional, national, and global trade? The answer is “yes”. Although the impact of water on product trade patterns appears less critical, there is evidence that countries exhibiting greater water availability do export more water-intensive products. Debaere (2014) observed that the higher the water intensity of exported goods, the

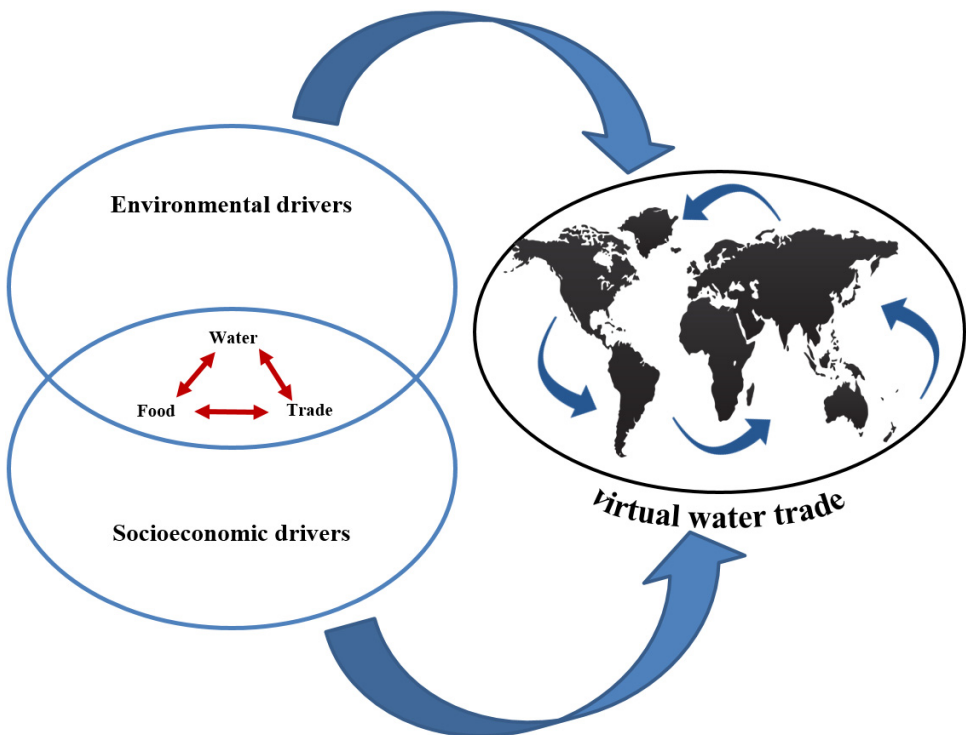


Figure 3. Multifaceted Nature of the Virtual Water Concept

greater the share of world exports of water-rich countries. Also, even though the policy usefulness of the virtual water concept has been a thing of debate, it has attracted the attention of government officials and policymakers, leading to effective monitoring of water allocation patterns and use at the domestic and industrial levels. Furthermore, the “import” of virtual water through trade has provided water and food security to water-scarce regions or nations (Allan 2002b). The MENA region, for example, has been able to cope with water scarcity over the last few decades without significant changes and reforms in water allocation, management, and policy, while avoiding water-related conflicts (Allan 2002a, 2003; Antonelli et al. 2017; Antonelli and Sartori 2015).

Based on the observation from reviewed articles in this study, we consider that the virtual water concept is multifaceted, involving the water–food–trade synergy in the context of environmental and socioeconomic factors in regions and nations (Figure 3). Therefore, to determine the various factors significantly influencing virtual water fluxes from the import and export perspectives, there is a need for a systematic analysis of the interconnections between water resource consumption in one region or nation and another. This can be effectively achieved through the adoption of multidisciplinary approaches involving several disciplines such as environmental science, modeling, hydrology, crop science, agricultural engineering, economics, social science, and mathematics. An analysis of this nature will enable the quantification of the impacts of various interconnected factors associated with, and influencing, virtual water movements across regions or nations.

6. Conclusions

The world is currently facing a water crisis and appropriate policies are necessary to curtail it. An understanding of the networks and controlling factors or drivers of virtual water fluxes will contribute to existing information geared toward establishing effective water regulations. The identification of the significant driving factors of trade flows as observed from the reviewed studies occurred through the modeling of virtual water trade. It is evident that the extent of virtual water trade depends on several drivers. Therefore, to minimize the problem of results inconsistency and to gain a holistic view of significant drivers influencing virtual water flows, it is suggested that a systematic analysis of key production factors that shape the patterns of virtual water trading in an economy is carried out; that is, the different environmental, social, and economic metrics must be considered. This provides complete information on the causes and consequences of trade as well as country resource allocation to assess virtual water trade patterns hence ensuring a more significant and representative outcome. In other words, we believe that

improvement in research through interdisciplinary collaborations will be crucial for informing policy decisions as they relate to the main influencing factors of virtual water trade regionally and globally.

Appendix A

A.1. Methodology

The review included English-written peer-reviewed articles focusing on virtual water trade in terms of its drivers published between 2003 and 2019 at the local and international levels, hence peer-reviewed journals from different parts of the world were considered. Two stages were implemented in the search, classification, and review of related literature, modified from Jiménez *et al.* (2014):

- (i) *Search by keywords (using keywords provided by both us and the database):*
This search was conducted via the Scopus bibliographic database (one of the largest abstract and citation databases of existing peer-reviewed studies). While we provided some of the keywords used in the search, additional

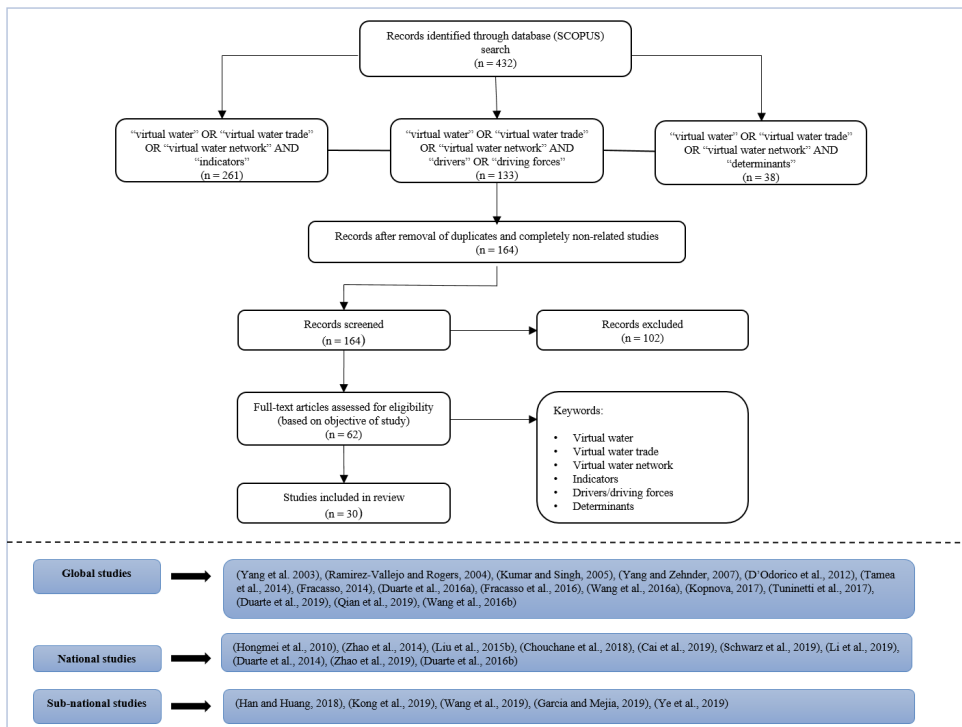


Figure A.1. Methodology and Classification of Reviewed Studies Based on the Specific Categories

keyword suggestions were derived from the Scopus database. The chosen keywords aimed at capturing literature related to the topic and objectives of this study. To achieve this purpose, commonly used keywords were searched in pairs with the Boolean search terms of “OR” and “AND”. For example, *virtual water/virtual water trade/virtual water network* was paired with *indicators, drivers, driving forces, or determinants*.

- (ii) *Review of abstracts and contents to select relevant papers*: The abstracts and contents of the selected papers from (i) were reviewed from which the articles dealing specifically with the study objectives were identified. Figure A.1 describes the step-by-step methodological process adopted.

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Supplementary Material

Table S.1. Summary of Explanatory Variables Used by Different Models of Virtual Water Trade

Drivers of VWT Identified from Reviewed Publications	No. of Publications Analyzing the Variable	No. of Publications Reporting a Significant Dependence
Water availability	20	11
Arable land	11	9
Irrigated land	7	4
GDP	18	15
Agricultural productivity	6	4
Population	15	11
HDI	1	1
Geographical distance	7	7
Trade structure	5	3
Production structure	4	1
Demand	2	2
Climate change	1	0
Technology	3	1
Dummies (religion, language, and government policy)	9	2

Note: VWT: Virtual water trade.