PLOS WATER

REVIEW

Virtual water flows in a real world

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Abstract

Virtual water was introduced by John Anthony Allan in 1998 as a measure of the amount of water required for the production of goods and services. Following the initiation of the Sustainable Development Goals in recent years, an intensified focus on environmental sustainability, particularly regarding water sustainability, has emerged. In this context, virtual water, as a crucial tool for water resources management, garnering attention from the academic community. Existing studies on virtual water have made significant contributions on quantifying the virtual water content embedded in commodities, delineating cross-regional patterns of virtual water flows, unveiling the temporal evolution and spatial distribution patterns of virtual water trade, assessing the economic valuation of virtual water through shadow pricing techniques, and analyzing the drivers influencing virtual water flows. However, there are still research gaps in the current literature on virtual water trade forecasting, virtual water accounting in different sectors (such as services and light industry), grey water footprint estimation and water scarcity indices. Moreover, virtual water research involves hydrology, economics and ecology. Multidisciplinary crossover will be an important trend in virtual water research in the future. This article seeks to comprehensively review current dialogues and investigations regarding virtual water and virtual water trade, assessing their impacts on a range of natural, social, and economic dimensions, and help scientists advance the frontiers of the field, as well as help policymakers adapt regional trade patterns and manage water resources more efficiently.

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1. Introduction

Virtual water is a concept that was introduced by Professor John Anthony Allan in his seminal work published in 1998 to help us understand the hidden water resource embedded in the production and trade of various goods and commodities [1]. In another article published in the same year, Allan discussed the idea of "trading" water through the exchange of virtual water embodied in trade [2]. He argues that this concept offers a practical alternative to engineering solutions like large-scale water transfer projects, which can be expensive and environmentally damaging. Trading virtual water allows regions with water abundance to meet the needs of regions facing water scarcity. This concept has since gained prominence as a tool for addressing water scarcity and understanding the global distribution and redistribution of water resources. Building on the concept of virtual water, Hoekstra and Mekonnen (2012) introduced the idea of "water footprint", which can be used to quantify the amount of water used in the life-cycle production of goods and services [3]. The water footprint is a measure of the total volume of freshwater resources used directly and indirectly by a consumer, business, or nation. However, it should be noted that, in a later work, Allan (2003) also acknowledged that while virtual water is a useful concept for understanding the water-food-trade nexus, it can also be seen as a misleading metaphor if not applied carefully [4]. He emphasized that virtual water should be used as a tool for water resource management and policy planning rather than a standalone solution.

Virtual water has received significant academic attention in recent years as an important tool for water management [5–10]. Existing literature reviews mostly focus on specific topics within the field of virtual water, such as virtual water trade [11], crop water footprints [12], the construction of water scarcity indices [13], accounting method of virtual water and the coupling of water resources with other systems (energy-food-water nexus) [14, 15]. Some literature reviews also provide a comprehensive overview of research in the field of virtual water [16, 17]. This review will focus on topics related to virtual water trade and is divided into three parts. The first part addresses the trends and driving factors of virtual water trade. In this part, the paper will reveal the development trends of virtual water trade and summarize the factors affecting virtual water trade identified in existing literature, such as agricultural technological advancements, climate change, and geopolitics. The second part discusses the impact of virtual water trade on water resources. This part will analyze the sustainability of water resources and groundwater security in the context of virtual water trade, covering both global and regional perspectives. The third part reviews other potential economic and social indicators that may influence virtual water trade.

This review is structured in three parts, each delving progressively deeper, from describing phenomena to summarizing impacts, and finally analyzing potential trends. It provides a thorough analysis of existing research in the field of virtual water trade and offers a comprehensive summary of the literature. This review can assist policymakers in understanding the implications of virtual water policies and in adjusting and formulating more effective water resource management policies. Additionally, it can help researchers quickly grasp the frontiers of the field, with the identified research gaps providing direction for future studies.

This paper is structured into four comprehensive sections. The initial section delves into the drivers and prevailing trends within virtual water trade. The subsequent section offers an in-depth analysis of its impacts on surface water, including the impacts of virtual water trade on both global and local water resources, their distant interactions, and the broader implications for water scarcity. The third section is dedicated to examining the consequences of virtual water trade on groundwater, highlighting its unique considerations. The final section turns to the economic and social dimensions of virtual water trading. This includes a discussion of the economic value attributed to virtual water trading, its impact for the security and quality of water resources, and an analysis of the climate and water risks transferred through virtual water trading. This segmented approach aims to furnish a nuanced understanding of virtual water trading and its multifaceted impacts across ecological and societal domains.

2. Drivers and trends of virtual water trade

The global evolution of virtual water trade has been significantly influenced by a complex interplay of drivers and trends revealed through extensive research on this subject. At the forefront of these drivers is the relentless process of globalization, trade liberalization and changes in consumption volume and patterns, generating impacts not only on water quantity but also on water quality [18, 19]. These developments have fostered a surge in cross-border trade, leading to an increased exchange of products embodying virtual water between nations and regions. This globalization of trade has had profound implications for the global virtual water landscape. Simultaneously, the burgeoning global population and rising affluence have created heightened food demand [20, 21]. This surge in demand has had a direct impact on virtual water trade dynamics, as water-scarce regions increasingly rely on importing water-intensive agricultural products to meet their food requirements. Furthermore, agricultural practices have emerged as a critical factor shaping virtual water trade patterns due to their impacts on water use intensity for production [22, 23]. Regions that prioritize water-intensive crops and employ inefficient irrigation practices tend to export more virtual water, further influencing global trade balances. Innovation in agriculture, manufacturing, and water-saving technologies is driving the evolution of the virtual water content of products, potentially altering trade patterns [24]. These innovations have a cascading impact on global trade balances and the movement of virtual water [20]. Deng et al. (2021) employed a multi-regional input-output model to assess the virtual water trade among 19 major global economies from 2006 to 2015 [20, 25]. The study found that the virtual water trade import and export volumes of these 19 major economies showed a growing trend, and the import-export disparities across all industries were increasing. Hekmatnia et al. evaluated the virtual water trade of global wheat from 2002 to 2021. They found no positive correlation between the water richness of virtual water exporting countries and the sustainability of global freshwater resources. Furthermore, 68.3% of the virtual water in global wheat trade is unsustainable [26]. Wang et al. (2023) constructed a network of cross-border and cross-sector virtual water trade in China, identifying the dynamic characteristics and driving factors of virtual water trade [27]. The study found that the total volume of virtual water embodied in China's trade increased by 64% between 2002 and 2017, primarily due to growing demand. However, the total volume of virtual water trade decreased by 4% due to the optimization of production structures and improvements in water use efficiency. Wang et al. (2023) quantified the virtual water flows in both domestic and international trade in China and analyzed the driving factors of net outflows [28]. The study found that production structure is the primary driving factor of virtual water net outflows. China's export scale effect and water use efficiency effect reduced the net outflow of virtual water by 17% and 23%, respectively.

The effects of climate change, including shifts in precipitation patterns and hydrological variability, have also come into play, altering virtual water trade patterns [29]. Water-scarce regions, experiencing changes in local water availability, are increasingly dependent on virtual water imports to mitigate the impacts of these shifts. Investments in water-related infrastructure and technological advancements have not gone unnoticed, affecting the capacity of regions to produce water-intensive goods efficiently [20, 30]. Improved infrastructure and technology can enhance a region's ability to contribute to virtual water exports. Equally important are government policies, trade agreements, and tariff structures, which have the power to either facilitate or hinder virtual water trade, thus influencing the direction and volume of virtual water flows [31, 32]. The ever-present specter of environmental concerns, including water pollution and resource depletion, also shapes virtual water trade dynamics, as countries seek to reduce the environmental impact of their imports [31].

Moreover, geopolitical factors also play a crucial role, introducing uncertainties into the reliability of virtual water imports [24]. Political stability, international relations, and conflicts can disrupt trade dynamics, adding a layer of complexity to the global virtual water trade network. In summary, the dynamic landscape of virtual water trade is a reflection of these multifaceted drivers and trends, each contributing to the intricate global network of water resources and international trade. Understanding and navigating these complexities is essential for crafting effective water resource management strategies and trade policies in a world where water scarcity varies widely.

3. Impacts of virtual water trade on the sustainability of global and local water resources

3.1 Impacts of virtual water trade on global water resources

Several studies have explored the implications of virtual water trade on the sustainability of global water resources from different angles. Liu et al. (2019) conducted a comprehensive review on studies of water savings and losses associated with food trade on different spatial scales and found a complex interplay between savings and losses of water resources [33]. Water-scarce regions benefit from importing water-intensive products, thereby conserving their local water resources. However, water-rich regions exporting such products may experience losses, potentially leading to over-exploitation of their own water resources. Chapagain et al. (2006) highlighted the potential for water savings through international trade of water-intensive agricultural products [34]. Their results show that, compared to a scenario where all agricultural products were produced domestically, global trade is able to save global water resources by 352 Gm^3/yr, amounting to 6 per cent of the global water use in agriculture. Turning to specific bilateral trade relationships, Lamastra et al. (2017) examined virtual water trade between Italy and China, revealing that Italy exports virtual water to China due to lower water productivity in Italian agriculture [35]. This export results in a net loss of water resources for Italy but a gain for China, with a net loss of nearly 130 million m^3 of water.

Liu et al. (2018) further emphasized the interconnectedness of virtual water trade, water conservation, and pollution reduction [36]. They highlighted the potential indirect contributions of virtual water trade to water resources conservation by shifting production to more water-efficient regions. However, this also raises concerns about the associated nitrogen pollution linked to increased agricultural production in water-rich areas. While Greve et al. (2018) did not directly address virtual water trade, their study on global water scarcity and challenges emphasized the importance of integrated water resource management [37]. Virtual water trade can be seen as a strategy to mitigate water scarcity uncertainties by diversifying water sources through trade.

In contrast, Mekonnen and Hoekstra (2020) raised concerns about the sustainability of virtual water trade [38]. They argued that nations relying on virtual water imports may exacerbate their water stress, particularly in terms of blue water footprint, which refers to water consumed from surface and groundwater. This raises questions about the long-term viability of relying on water-intensive agricultural imports for even water-abundant countries. Finally, de Fraiture et al. (2004) questioned the effectiveness of virtual water trade in saving water globally, particularly in the context of international cereal trade [39]. Their assessment suggested that that the role of virtual water trade in global water use is modest. Political and economic considerations —often outweighing water scarcity concerns—limit the potential of trade as a policy tool to mitigate water scarcity.

Analyzing the impact of various types of policy and reality shocks on global virtual water trade is a major current issue in the context of globalization. Using a water-constrained model of the human-land system, Graham et al.(2023) analyzed the impact of trade regimes on global virtual water trade under a low-carbon scenario [40]. The integration of different agricultural markets was found to significantly alter the amount of water withdrawn from each region, presenting a major challenge to global non-renewable groundwater. Debaere and Konar (2022) conducted an analysis of the factors influencing water consumption within a globalized economy [41], elucidating the primary consumers and geographic areas, along with the categories of water utilized. This investigation significantly enhances the comprehension of the interaction between society and water resources, providing valuable insights for policymakers aimed at augmenting water use efficiency and facilitating more judicious allocation of water resources. Furthermore, Dolan et al. (2021) undertook an examination of water scarcity impacts at the global basin level, integrating a human-Earth system model, a global hydrological model, and an indicator quantifying economic surplus loss attributable to resource scarcity [42]. This multidisciplinary approach enables a nuanced understanding of the economic ramifications of water scarcity on a global scale.

In conclusion, the impacts of virtual water trade on global water resources are multifaceted and contingent on various factors. While it can provide benefits to water-scarce regions and contribute to water savings, it also carries the risk of exacerbating water stress in water-rich regions and raising environmental concerns such as nitrogen pollution. However, those considerations are often not prioritized in trade policies and thus meriting further closer attention.

3.2. Impacts of virtual water trade on regional and local water resources

Several studies have explored the impacts of virtual water trade on both the exporting regions and the importing regions. While mixed results are found on the impacts on water stress in the receiving regions, it has generally been concluded that virtual water exports have exacerbated water stress in the exporting regions. Zhao et al. (2015) compiled a full inventory for physical water transfers at a provincial level and mapped out virtual water flows between Chinese provinces in 2007 and 2030 and found that both physical and virtual water flows do not play a major role in mitigating water stress in the water-receiving regions but exacerbate water stress for the water-exporting regions of China [43]. Zhang et al. (2011) analyze the impacts of China's international trade on its water resources and usage [44]. They find that international trade can lead to imbalances in water availability within the country suggesting that China's economic gains from being a world "manufacture factory" have come at a high cost to its water resources. Furthermore, Sun et al. (2016) focused on the effects of virtual water flows, particularly concerning grain production, on regional water resource stress and they found that virtual water trade significantly increased water stress in grain export regions and alleviated water stress in grain import regions [45]. Stress from water shortages is generally severe in export regions. Dalin et al. (2014) investigate water resource transfers through food trade between Chinese provinces and other countries and found that China's dry, irrigation-intensive northern provinces tend to export food commodities to wetter places [46]. Their study highlights that virtual water trade can lead to imbalances in water availability and usage across regions, necessitating coordinated water resource management strategies to address these disparities.

Besides China, El-Sadek (2010) explores the role of virtual water trade as a solution for water scarcity in Egypt [47]. Importing water-intensive products can help alleviate water stress in water-scarce regions, and this research highlights the potential benefits of virtual water trade for countries facing significant water challenges. By examining India's virtual water trade in agricultural and livestock products, SreeVidhya and Elango (2019) found that virtual water export were mainly through rice, maize and buffalo meat, while the imports were through cashews, pulses and wheat [48]. Temporal variations in the export and import of virtual water can significantly affect water availability for local consumption and agriculture. Similarly, Brindha (2017) delves into international virtual water flows from agricultural and livestock products in India [49]. The research sheds light on how India's trade practices impact its own water resources and those of its trading partners. Such insights are crucial for formulating sustainable water management and trade strategies in an increasingly interconnected global economy.

Virtual water trade is not limited to international boundaries; it also plays a significant role within countries or regions. In their 2007 study, Guan and Hubacek examined regional trade and virtual water flows within China. Their findings revealed that North China, a water-scarce region, effectively exports approximately 5% of its total available freshwater resources while accepting substantial volumes of wastewater from other regions for their consumption. In contrast, South China, which possesses abundant water resources, virtually imports water from other regions, but these imports contribute to the pollution of other regions water ecosystems. Dang et al. (2015) investigate agricultural virtual water flows within the United States, which is found to make up 51% of its international flows [50]. The research demonstrates that internal virtual water trade can redistribute water resources and impact regional water availability. It emphasizes the role of virtual water in addressing water resource challenges within a nation. In Europe, Antonelli et al. (2017) explore virtual water flows within the European Union related to agricultural trade and found that intra-regional virtual water trade represents 46% of total imports and 75% of total exports by the region [51].

The trade in virtual water transcends the realm of agricultural commodities, extending its significance into the energy sector, particularly in the context of electricity transportation. Scholars define the water used in energy production and power generation as virtual water [52, 53]. The establishment of water footprints for energy commodities is a foundational element for integrated energy-water research. Chini & Peer (2021) developed a database that includes water footprints of 11 energy commodities, such as fossil fuels, biomass, and electricity [54]. Utilizing this database, they constructed a global virtual water trade network for energy commodities spanning from 2010 to 2018, thereby providing a robust database for future research endeavors. The trade in virtual water associated with the transmission of electricity in Europe experienced a 14% increase from 2010 to 2017, characterized by notable seasonal fluctuations [55]. The virtual water flows within the U.S. grid witnessed a comparable substantial augmentation between 2010 and 2016, with the blue water footprint escalating by 21.7% and the grey water footprint experiencing a 42.8% increase [56]. The water footprint of the power sector is mainly concentrated within population centers [57]. In the future, the total amount of virtual water used for electricity transmission in the U.S. is expected to slightly decline. It is projected that there will be a 3% reduction in virtual water transactions in 2050 compared to 2015 [58]. For specific regions, the Colorado River Basin in the United States plays a crucial role in providing water to adjacent urban areas, with the water footprint associated with the transportation of electricity constituting a significant portion of this supply. Thermal power plants located within the basin are responsible for the annual evaporation of approximately 330,000 acre-feet of water for the purpose of electricity generation, with over half of this electricity being exported to other cities [59]. Numerous scholars have conducted research on the volume and flow patterns of virtual water associated with electricity transmission in China [60]. The estimated volume of virtual water associated with China's electricity trade amounts to approximately 5638.4 million m^3, with negative virtual water transfers constituting roughly a quarter of this total [61]. The West–East Electricity Transmission project in China entails the implication of 2.4 km^3 of virtual water, while the total virtual water loss attributed to the entire transmission system amounts to 100 million m^3 [62].

In conclusion, while virtual water trade can offer opportunities to alleviate water stress and enhance water security, its outcomes depend on various factors, including trade patterns, policies, and regional contexts. Effective water resource management and trade policies taking into the environmental, social, economic and technological contexts of both exporting and importing regions into consideration are critical to harness the benefits of virtual water trade while minimizing its negative consequences and ensuring equitable access to water resources. It is important to consider the natural attributes of each location when formulating policies for virtual water trade. Certain crops cannot be grown in some areas due to climate, land availability, and cost constraints. These factors must be taken into account in virtual water trade policy-making [63, 64].

3.3 Impact of virtual water trade on water scarcity

In addition, some studies have shed light on the relationship between virtual water trade and water scarcity, particularly within the context of China and global agricultural trade. Damkjaer and Taylor (2017) focused on the measurement of water scarcity, providing a foundation for understanding how water scarcity is defined and quantified [65]. Although the article did not explicitly delve into virtual water trade, it lays the groundwork for evaluating the impact of virtual water trade on water-scarce regions by establishing meaningful indicators for water scarcity. It underscores the importance of having robust metrics to assess the effectiveness of strategies like virtual water trade in mitigating water scarcity.

Feng et al. (2014) specifically explored how virtual water flows relate to water scarcity in a country as vast and water-stressed as China, i.e. the flow of virtual scarce water [66]. This investigation helps to illuminate the potential benefits and challenges associated with virtual water trade in alleviating regional water scarcity within a large and diverse nation. Zhao et al. (2018) went one step further looking at the scarce water-saving potential of interregional virtual scarce water flows within China [67]. Their results show that interprovincial trade resulted in 14.2 km^3 of water loss without considering water stress, but only 0.4 km^3 scarce water loss using the scarce water concept. By assessing how virtual water trade can reduce water scarcity within the country, this study provides practical insights into the impact of virtual water trade on water resource management. It underscores the significance of optimizing the distribution of water-intensive goods through virtual water trade as a means of addressing water scarcity at the regional level.

Moving beyond national borders, Wu et al. (2022) delved into the global trade of wheat, maize, and rice and its impact on scarce virtual water resources from 2008 to 2017 [68]. This study highlights that different crops have varying effects on scarce virtual water resources in international trade. They found that trade in corns and wheat has saved scarce water while trade in rice led to scarce water loss at the global level. It raises the essential question of whether virtual water trade contributes to water savings or exacerbates water scarcity, depending on the specific commodities involved.

In conclusion, these studies collectively emphasize the importance of robust measurements, regional considerations, and the specific commodities involved in determining the impact of virtual water trade on scarce water resources. As water scarcity continues to pose challenges globally, these studies provide valuable insights for crafting effective strategies to address this pressing issue through virtual water trade.

4. Impacts of virtual water trade on global and local groundwater overexploitation

The impact of virtual water trade on groundwater resources has emerged as a critical concern in the context of global food and water trade. We live in a telecoupled world where changes in one region can impact multiple other regions [69]. On a national level, Marston et al. (2015) examined virtual groundwater transfers from overexploited aquifers in the United States [70]. They shed light on how regions with overexploited aquifers can inadvertently export their groundwater stress through the trade of water-intensive agricultural goods. Irrigated agriculture is contributing to the depletion of the Central Valley, High Plains, and Mississippi Embayment aquifer systems. Yin et al. (2021) investigated how virtual water trade practices impact groundwater resources within China, and concluded that virtual water import has contributed to alleviating groundwater overexploitation in northern China [71]. The research provides a valuable case study highlighting how virtual water flows can influence both surface water and groundwater in a specific geographical context.

On a global level, Dalin et al. (2017) examined the groundwater depletion embedded in international food trade and found that as countries import water-intensive agricultural products, they also import the groundwater depletion associated with their production [72]. Approximately 11% of non-renewable groundwater use for irrigation is embedded in international food trade, of which two-thirds are exported by Pakistan, the USA and India alone.

Although not centered on virtual water trade, Gleeson et al (2012) defined the groundwater footprint as the area required to sustain groundwater use and groundwater-dependent ecosystem services [73]. Their assessment showd that humans are overexploiting groundwater in many large aquifers, especially in Asia and North America. The size of the global groundwater footprint was estimated at about 3.5 times the actual area of aquifers. Understanding the water footprint of aquifers is crucial for comprehending how virtual water trade may impact groundwater sustainability in various regions and countries. Furthermore, Haqiqi et al. (2022) pointed out that over-reliance on virtual water trade may not offer a sustainable long-term solution if it perpetuates groundwater depletion [74].

It should be noted that while virtual water trade can yield surface water savings and alleviation of surface water stress, it also has the potential to exacerbate groundwater depletion and posing sustainability challenges. Sustainable groundwater management and the consideration of environmental consequences within the framework of virtual water trade are essential aspects of addressing global water scarcity issues effectively.

5. Impacts on other social economic dimensions

5.1 Economic impacts of virtual water trade

The economic implications of virtual water trade have emerged as a significant area of research, given its potential to optimize water use in agriculture and influence international trade dynamics. D'Odorico et al. (2020) provides a foundational understanding by assessing the global value of water in agricultural production [75]. While not directly centered on virtual water trade, this research underscores the economic importance of water in agriculture, highlighting its role as a critical resource with substantial economic implications. For example, they suggest that in some regions, the economic value of water in agriculture can be up to 1,000 times higher than its market price. In contrast, Han et al. (2023) took a more focused approach in their study and explicitly explored the economic gains and losses associated with virtual water trade, offering a comprehensive analysis from both environmental and economic standpoints [76]. Their results show that the virtual water flow in China in 2015 resulted in a loss of 8 billion m3 of scarce water; while generating a net economic gain of 8.5 trillion CNY with economically developed areas receiving large amounts of virtual water from less developed areas. Schwarz et al. (2015) investigated the economic efficiency of virtual water flows within the context of evolving trade patterns [77]. This research delves into how shifts in international trade dynamics affect economic efficiency and resource utilization, highlighting the evolving economic impacts of virtual water trade in the global agri-food sector.

Miglietta and Morrone (2018) provided a case study focusing on the wine trade between Italy and the Balkans by assessing the economic water productivity associated with this trade relationship, offering insights into the economic implications of virtual water flows within a specific sector [78]. Liao et al. (2021) narrows its geographical focus to China's JingJinJi Megalopolis [79]. Through an empirical analysis, it examines how virtual water trade influences economic co-benefits within this specific region. This localized approach highlights the economic impacts of virtual water trade on economic development, job creation, and overall economic performance, underscoring the multifaceted nature of its effects.

5.2 Social impacts of virtual water trade on food security and water resource equality

While virtual water trade can lead to water savings and increased access to food, it may also raise challenges for domestic food security. Yawson et al. (2013) examined food security in a water-scarce world and explored the compatibility of virtual water with crop water use and food trade [80]. They emphasized the necessity of integrated approaches to ensure that virtual water trade aligns with crop water use efficiency and food trade practices. It highlighted the importance of considering both water and food security objectives in virtual water trade policies.

Quantitative findings and policy implications vary across the studies, underscoring the need for region-specific approaches and compensation mechanisms to address potential trade-offs between water resource management and food security in water-scarce regions. Konar and Caylor (2013) investigated the relationship between virtual water trade and development in Africa [81]. They introduced the concept of "virtual water trade openness" and conducted empirical analysis, finding that higher levels of virtual water trade openness are associated with a reduction in the prevalence of malnutrition in Africa. This quantitative insight suggests that participation in virtual water trade can contribute significantly to improving food security in the region. By increasing access to food through trade, virtual water trade can help reduce malnutrition rates, thus underscoring its potential positive impact on food security in water-stressed regions. Wichelns (2001) investigated the role of "virtual water" in achieving food security, with a focus on Egypt [82]. It suggested that importing water-intensive crops can help conserve domestic water resources for other essential uses, contributing to both food security and water management goals.

Wang et al. (2014) delved into the dynamics of virtual water flows of grain within China [83]. They observed that inter-provincial virtual water flows of grain led to water resource savings but had a negative impact on grain security within China. To address such trade-off, the authors proposed compensation mechanisms. They argued that those provinces benefiting from water savings through virtual water trade should provide compensation to regions experiencing negative impacts on food security. This highlights the importance of considering the dual objectives of water resource management and food security in virtual water trade policies.

Antonelli et al. (2017) and Antonelli and Tamea (2015) examined the role of virtual water trade in the Middle East and North Africa (MENA) region [84, 85]. While specific quantitative findings are not provided, these studies emphasized the potential benefits of virtual water trade in water-scarce MENA countries. They highlighted that importing water-intensive goods can help these countries reduce their water footprint and secure food supplies. This underscores the potential positive contribution of virtual water trade to food security in regions facing severe water constraints.

Additionally, some studies also examine the impact of virtual water trade on water resource equality and disparity in water use. Seekell (2011) explored the global trade of virtual water and its potential to reduce inequality in freshwater resource allocation [86]. The quantitative findings in this study may vary based on the specific regions and commodities analyzed, but the research suggests that the global trade of virtual water does not necessarily lead to a significant reduction in inequality in freshwater resource allocation. Seekell et al. (2011) pointed out that most inequality in water use is due to agricultural production and can be attributed to climate and arable land availability, not social development status, while virtual water use is highly unequal and is almost completely explained by social development status [87]. Virtual water transfer is therefore unlikely to reduce water-use inequality primarily because agricultural water use dominates national water needs and cannot be completely compensated by virtual water transfers.

On a national level, Xu et al. (2021) investigated the water-saving efficiency and inequality of virtual water trade in China [88]. Their findings suggest that virtual water trade can contribute to water-saving efficiency in some regions but may not fully address inequality in water distribution. Xin et al. (2022) conducted a study focusing on China's inter-provincial trade to assess the decline of virtual water inequality [89]. They conducted an environmental economic trade-off analysis and found that there has been a decline in virtual water inequality in China's inter-provincial trade. Quantitatively, they found that through trade, provinces with water surpluses may contribute to addressing water scarcity in water-deficient provinces, thus promoting more equitable water resource distribution within the country.

5.3 Transfer of climate and water risks through virtual water trade

While virtual water trade can enhance water efficiency and resilience in some cases, it may also introduce vulnerabilities and risks, especially in the context of long-term dependencies on virtual water imports. However, findings from the existing studies underscore the need for a nuanced understanding of how virtual water trade can either mitigate or exacerbate climate and water shortage risks, depending on regional and temporal factors. D'Odorico et al. (2010) challenged the notion that virtual water trade universally enhances resilience to drought [90]. While previous studies suggested that short-term virtual water trade can improve regional resilience to drought, this article argued that long-term virtual water trade may lead some regions to intensify water use for virtual water exports. Their findings suggested that over time, this intensification could reduce resilience to drought as regions become more dependent on virtual water imports, potentially leaving them vulnerable when droughts occur. Dalin and Conway (2016) investigated water resources transfers through southern African food trade and their implications for water efficiency and climate signals, which suggested that virtual water trade can be a mechanism to efficiently allocate water resources and help deal with climate-related shocks [91].

Qu et al. (2018) conducted a study that evaluated the impacts of local water scarcity risk on the entire global trade system [92]. Their research provides a novel perspective by considering how local water scarcity risk can propagate through the global trade network. Based on the approach developed by Qu et al. (2018), Zhao et al. (2019) examined how climate-induced changes in virtual water availability can affect the resilience of the global trade network based on quantitative assessments of the vulnerability of different regions to climate-induced water scarcity [92, 93]. Regions or commodities that are particularly vulnerable to climate-related virtual water scarcity risks were also identified.

Zhao et al. (2020) quantifies the virtual water scarcity risk across various Chinese provinces and regions and identified which areas are more vulnerable to water scarcity due to virtual water trade [94]. Their research highlighted how virtual water flows can propagate water scarcity risks from one region to another within China. Zhang et al. (2020) conducted a spillover risk analysis of virtual water trade between North China regions and the rest of the country using a multi-regional input-output model [95]. Their study conducted quantitative assessments of how water scarcity risks can propagate and spillover across regions as a result of virtual water trade and identified sectors of Agriculture and Other manufacturing with the highest risk of water use for Northeast China.

6. Conclusion

This article reviews the concept of virtual water and its far-reaching impacts on various dimensions of society, the economy, and the environment. The article reviews the evolution of virtual water trade, highlighting globalization, changing consumption patterns, and agricultural practices as key drivers. The impacts of virtual water trade on surface water resources are complex, with studies showing both water savings and losses in different regions. While water-scarce areas benefit from importing water-intensive products, water-rich regions exporting such products may experience losses, potentially leading to over-exploitation of their own water resources. Furthermore, the article examines the effects of virtual water trade on regional and local water resources, emphasizing the need for region-specific approaches. It discusses how trade can lead to imbalances in water availability and usage across regions, necessitating coordinated water resource management strategies. The impact of virtual water trade on groundwater resources is also examined, noting concerns about groundwater depletion in regions exporting water-intensive goods. Sustainable groundwater management is identified as crucial in addressing this issue.

Economically, virtual water trade can yield both gains and losses, depending on the commodities involved and the regions participating. It underscores the importance of considering economic implications in virtual water trade policies. In terms of social impacts, studies have shown how virtual water trade can affect food security and water resource equality. While it can contribute to food security by increasing access to food through trade, it may also raise challenges for domestic food security. Ensuring that virtual water trade aligns with crop water use efficiency and food trade practices is highlighted as essential. Lastly, the transfer of climate and water risks through virtual water trade is highlighted. Long-term dependencies on virtual water imports may introduce vulnerabilities and risks, particularly in the context of climate change. It is emphasized the need for a nuanced understanding of how virtual water trade can mitigate or exacerbate climate and water shortage risks.

While numerous studies have explored the concept of virtual water, contributing significantly to a scientific foundation and offering policy implications for the management of global and regional water resources, gaps remain in the existing literature that merit attention. The knowledge gaps were identified based on the current state of the literature, recent advancements, and emerging trends. For instance, although there has been extensive investigation into the temporal evolution and spatial distribution of virtual water trade, less emphasis has been placed on forecasting the future trends of global virtual water trade. Existing forecasts are heavily reliant on assumptions, introducing uncertainty into the projections. Moreover, sector-specific analyses of virtual water have mainly focused on industries known for high water use and pollution—such as the power generation and manufacturing sectors—comparatively less attention has been paid to industries with lower water use, including services and light manufacturing. Despite their relatively low water use and pollution, the development of these sectors is closely linked to high water used sectors, i.e., power generation and manufacturing sectors. This interdependency underscores the necessity of examining water footprints within the broader context of entire industrial chains, heralding a major future direction in water footprint research.

Furthermore, the increasing need for corporations to reveal their environmental performance poses new challenges in the field of virtual water, especially in measuring the supply chain's life cycle water footprint within the company. Accurately quantifying the life cycle water footprint within the corporate sphere remains a pressing challenge due to data availability constraints. Innovative methodologies are necessary to enhance data comprehensiveness and accuracy, ensuring that environmental impact assessments reflect the true water usage and sustainability of corporate activities along their supply chains. Additionally, standardizing accounting methods for grey water footprints and water scarcity indices can advance virtual water research. Interdisciplinary collaboration and technological innovations, such as remote sensing and artificial intelligence, can also enhance the efficacy and scope of virtual water studies.

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