WATER FOOTPRINT ROLE IN WATER MANAGEMENT

EL ROLE DE LA HUELLA HIDRICA EN EL MANEJO DEL AGUA

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ABSTRACT

Scientific advancements have greatly improved human life and increased the demand for essential resources, underscoring the need for effective water management strategies. The Water Footprint (WF) is a promising concept that quantifies the total water usage across a product's entire production chain, the water type used (green, blue, or gray), the virtual water flow, and its temporal and space location, offering a comprehensive understanding of water consumption and its effects on natural resources. This research defines the WF concept and presents an overview of its global distribution, focusing on Colombia. Next, recommendations are placed to reduce WF. The document also examines the WF's key limitations, highlighting the absence of an integrated hydrological and economic framework to ensure

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accurate estimates. Despite the challenges, the study concludes that WF holds significant potential for improving water resource management, provided its current shortcomings are addressed.

Keywords: Virtual water, water footprint, water use, water resources management.

RESUMEN

Los avances científicos han mejorado enormemente la vida humana y han aumentado la demanda de recursos esenciales, como el agua. La Huella Hídrica (HH) es un concepto que cuantifica el uso total de agua en toda la cadena de producción, el tipo de agua utilizada (verde, azul o gris), el flujo de agua virtual y su ubicación temporal y espacial, ofreciendo una comprensión integral del consumo de agua y sus efectos sobre los recursos naturales. Esta investigación define el concepto de HH y presenta una descripción general de su distribución global, centrándose en Colombia. A continuación, se formulan recomendaciones para reducir la HH y se examinan las limitaciones de la HH, destacando la ausencia de un marco hidrológico y económico integrado que garantice estimaciones precisas. El estudio concluye que la HH tiene un potencial significativo para mejorar la gestión de los recursos hídricos, siempre que se aborden sus deficiencias actuales.

Palabras clave: Agua virtual, huella hídrica, uso del agua, gestión de recursos hídricos

1 INTRODUCTION

Science has significantly contributed to improving the quality of human life. Scientific knowledge and technological advancements have greatly improved the detection, control, and reduction of previously devastating diseases, significantly increasing human life expectancy. For example, in the United States, life expectancy rose from 69.77 years in 1960 to 78.69 years by 2016 (World Bank Group, 2024). As life expectancy rises, the demand for essential resources, particularly water, also increases. Therefore, researchers in water resource management must develop strategies that promote the efficient use and sustainable management of this limited and dynamic resource.

The water footprint (WF) concept provides a framework for quantifying water consumption at the level of countries, communities, or individuals, aiming to promote the efficient, sustainable, and equitable use of freshwater resources (Water Footprint Network, 2024b). Therefore, this research addresses the following question: How can WF be applied in water resources management?

2 WATER FOOTPRINT DEFINITION

In the early 1990s, Allan introduced the idea of addressing water scarcity in the Middle East by importing food, thereby indirectly importing water in virtual form rather than physical (Water Footprint Network, 2024b). Initially referred to as "virtual water," this concept was expanded to encompass all the water required to produce a good or service. Virtual water can be quantified by the volume of water per product unit or over a specific period, with typical units including m^3/ton, liters/kg, and m^3/year. Hoekstra & Chapagain (2007) demonstrated that the virtual water volumes of the same product differ significantly between countries. These variations can be attributed to three main factors (Water Footprint Network, 2024b). First, the economic value of water frequently falls below its actual market price due to subsidies. Second, unlike other commodities, the price of water is not significantly affected by scarcity. Third, users generally do not incur the costs related to the negative impacts of water extraction and the subsequent return of water at reduced quality.

While the concept of virtual water is significant, it fails to address fundamental questions: Where is virtual water located? What sources are utilized? When is water consumed? Hoekstra & Hung (2002) introduced the WF concept to tackle these queries. WF refers to the total water used throughout the production chain of any good. Specifically, the WF is a multidimensional indicator encompassing four factors (Echavarria et al., 2016; Muthu, 2019): i) The volume of water associated with the product. ii) The types of water employed in its production (green, blue, gray). iii) The virtual water flows. iv)The spatial and temporal location of water consumption. Thus, WF provides insight into how individuals' or communities' lifestyles and consumption patterns impact water resources (Wackernagel & Rees, 1998).

2.1 Types of Water Utilized in the Production of Goods

Water used to produce goods and services can be categorized into green, blue, and gray. Green water is the moisture stored in the soil's root zone, which is absorbed and utilized by plants without contributing to runoff or replenishing surface or groundwater sources (Muthu, 2019; Water Footprint Network, 2024b). In contrast, blue water refers to freshwater from rivers, lakes, and aquifers (Rost et al., 2008). Lastly, gray water refers to the water required to dilute and assimilate pollutants discharged into the environment, effectively representing the contaminated water within the supply chain (Muthu, 2019). Among the three types of water, green water contributes the least to the WF, followed by blue and gray water. For instance, there is a significant distinction between beef produced in extensively grazed grasslands of Botswana, where green water is utilized without alternative uses, and beef produced on industrial livestock farms in the Netherlands, where livestock is partially fed with irrigated crops that rely on blue water (Hoekstra & Chapagain, 2007). On the other hand, environmental degradation occurs when the WF of a specific type of water exceeds its available supply. For example, if the gray WF surpasses the ability of water bodies to assimilate pollutants, this leads to the deterioration of water resources (Water Footprint Network, 2024b).

2.2 Virtual water flow

Virtual water flow represents the volume of water embedded in products exchanged between regions through trade (Muthu, 2019). This flow is depicted in WF maps, illustrating the locations and timeframes of water appropriation. These maps facilitate critical analyses, such as overlaying WF and water stress maps, to identify areas where high virtual water flows should be reduced (Water Footprint Network, 2024b). Figure 1 depicts the virtual water flows from 1996 to 2005.

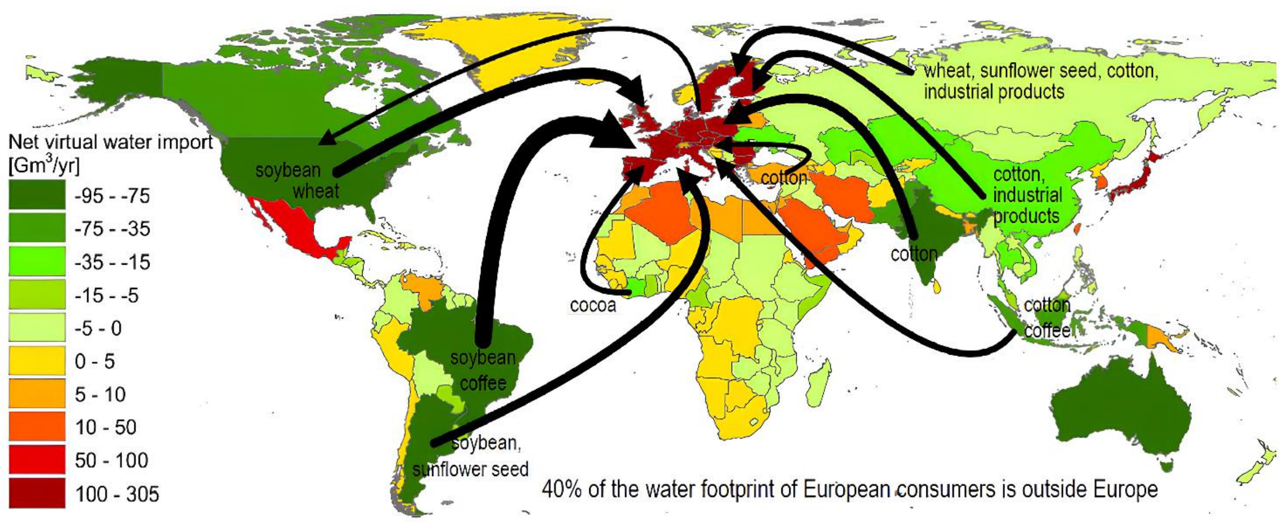

Figure 1. The water footprint of humanity: international dependences over the period 1996-2005 (Hoekstra & Mekonnen, 2012).

3 WORLDWIDE WF

Calculating the internal and external components of the WF is crucial for accurately assessing a country's overall WF. The internal WF refers to the water resources directly consumed within the country, whereas the external WF encompasses the water embedded in goods and services that are imported or exported. According to Hoekstra & Chapagain (2007), the elevated WF of certain countries can be attributed to several factors: the volume and consumption patterns of goods and services, regional climate conditions, and agricultural practices. The following section provides an overview of these factors.

3.1 Consumption Patterns

According to Hoekstra & Chapagain (2007), water consumption in a country tends to increase with its gross income. Generally, higher-income nations demonstrate a more extensive WF among their populations. To evaluate this claim, the authors of this paper assessed their WF by considering two distinct scenarios: as residents of the United States and as residents of Colombia. Utilizing the "Extended Water Footprint Calculator" (Water Footprint Network, 2024b), all parameters except the country of residence were constant. The results indicate an average WF of 982 m^3 per year for an individual in the United States, compared to 798 m^3 per year for a Colombian individual. Data used for the previous analysis can be found in Appendix 1.

3.2 Climate

Crops generally require more water to thrive in regions characterized by high temperatures. Consequently, countries such as Senegal, Mali, Sudan, Chad, Nigeria, and Syria exhibit substantial WFs linked to their agricultural practices (Hoekstra & Chapagain, 2007).

3.3 Agricultural practices

Regions or countries employing inefficient agricultural practices tend to have a larger WF, as these methods require more water for food production. For instance, Hoekstra & Chapagain (2007) note that inadequate rice planting techniques in Thailand resulted in lower yields of 2.5 tons per hectare between 1997 and 2001, in contrast to the global average of 3.9 tons per hectare.

3.4 WF spatial distribution

According to Hoekstra & Mekonnen (2012), the global annual average WF from 1996 to 2005 was approximately 9.087 x 10^12 m³/year, comprising 74% green, 11% blue, and 15% gray water. Nearly a quarter of this total (2.320 x 10^12 m³/year) was attributed to virtual water exports. The countries with the largest WFs were China, India, the United States, and Brazil, with respective WFs of 1.207; 1.182; 1.053; and 0.482 x 10^12 m³/year. Hence, approximately 43% of the global WF is concentrated in just four countries. During the same period, the per capita average WF was as follows: the United States at 2,842 m³/year, China at 1,071 m³/year, India at 1,089 m³/year, Mexico at 1,978 m³/year, and Colombia at 1,375 m³/year. In contrast, the global average consumer's WF was 1,385 m³/year (see Figure 2). Experts indicate that cereals contribute the most to the worldwide WF, accounting for 27%, followed by meat at 22% and dairy products at 7% (Hoekstra & Mekonnen, 2012).

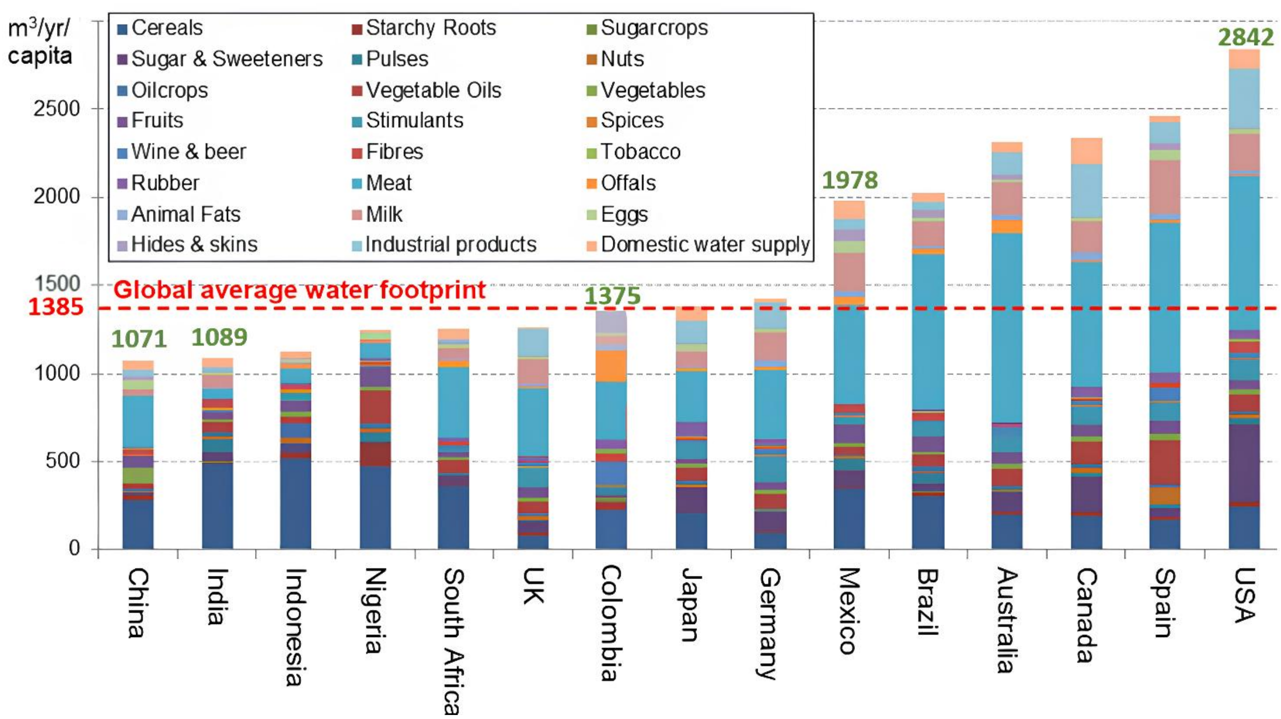

Figure 2. Water footprint for some countries (cubic meter per year per capita) (1996–2005). Adapted from Hoekstra & Mekonnen (2012).

China and India, the two most populous countries, currently have a per capita WF below the global average (see Figure 2). However, this situation could change if their dietary and consumption patterns evolve to resemble those of Western nations. Should this occur, both countries may experience an increase in their WF. Consequently, this shift could prompt them to adopt import policies or pursue land acquisition and leasing in Africa to secure a stable food supply (The Economist Newspaper, 2009).

Although the WF values illustrated in Figure 2 were derived from a spatial resolution of 5 x 5 minutes, there are concerns regarding the accuracy of these results. Accurate estimation of crop water demands requires using irrigation records and detailed water balances that account for various factors, including crop types, climatic conditions, and specific irrigation practices. For instance, in countries like the United States, the prevalence of optimized irrigation systems suggests that WF values reported in Figure 2 may be overestimated.

3.5 Colombia's WF

Since 2010, several studies have been conducted in Colombia to estimate the WF for the country and various products. However, these estimates remain approximate due to significant information gaps. These gaps include incomplete records of domestic water consumption, limited statistical data on crop water demands, and insufficient information on water quality, which prevented the calculation of the gray WF in 2014 (CTA et al., 2015). Despite these limitations—common in many countries—the WF was still calculated, and the results are presented in Table 1.

Table 1. Green and blue WF for different sectors in Colombia (CTA et al., 2015).

Sector	**WF (millions of m3/yr)**	
	Green	**Blue**
Agricultural	54,915	6,976
Livestock	245,538	Not calculated
Domestic	Not calculated	385.8
Industrial	Not calculated	65
Energy generation	Not calculated	297
Mining	Not calculated	6.6
Water transfers	Not calculated	2,200
Total	**300,453**	**9,930.4**

2014, Colombia's green water availability was 1,221,346 million m³ per year, whereas the green WF amounted to 300,453 million m³ annually (CTA et al., 2015). In the same period, blue water availability reached 1,126,905 million m³ yearly, with a corresponding blue WF of 9,930.4 million m³ annually (CTA et al., 2015).

According to CTA et al. (2015), Colombia has the potential to play a crucial role in the global virtual water market due to its agricultural production, which relies not only on irrigation (blue water) but also significantly on rainfall (green water). It is important to note that green water, sourced from precipitation, has the most negligible impact on ecosystems.

4 WF REDUCTION

This section outlines various actions to reduce the WF at the government, business, and consumer levels.

4.1 Recommendations for countries

Several measures have been proposed to mitigate the impacts of WF discussed in section 3. A key recommendation is to decouple economic growth from water use by adopting water-efficient production processes (Hoekstra & Chapagain, 2007). For instance, agriculture in California exemplifies effective water use through conjunctive water management and technologies such as micro-sprinklers, rainwater harvesting, and precision agriculture (Dallman et al., 2016; Joyce et al., 2009). Another effective strategy involves adjusting product pricing by reducing or eliminating water subsidies, encouraging more sustainable water consumption (Hoekstra & Chapagain, 2007). Also, promoting responsible water use through educational campaigns is essential for fostering awareness and best practices. Lastly, countries experiencing water scarcity due to climate variations are encouraged to import water from regions with high water productivity (Chapagain et al., 2005). Collectively, these approaches aim to enhance the overall efficiency of water usage.

4.2 Recommendations for companies

Companies can reduce their WF by minimizing visible and invisible water usage. Implementing treatment and recycling processes for water before disposal is advisable to address the visible WF (Water Footprint Network, 2024b). Conversely, to lower the invisible WF, companies should engage in efficient production chains focused on water management and report the WF associated with each product (Water Footprint Network, 2024b).

4.3 Recommendations for consumers

Consumers can reduce the visible WF by using low-flow devices, turning off the tap while brushing their teeth, showering, and washing dishes by hand. Additionally, reducing the frequency of garden watering and avoiding disposing of pharmaceuticals, paints, oils, and similar substances down the sink is advised (Water Footprint Network, 2024b). Also, individuals can modify their consumption patterns by selecting products with a lower WF, thereby reducing their invisible WF. For instance, they might minimize meat consumption, drink tea instead of coffee, or choose water over other beverages. Opting for artificial fibers rather than cotton can also contribute to this reduction (Water Footprint Network, 2024b). Consumers who wish to sustain their current consumption patterns are advised to choose products with a low WF (Water Footprint Network, 2024b). Nonetheless, this selection process can be problematic due to the absence of labeling indicating the products' WF. In conclusion, a consumer's WF is considered sustainable if it remains below the global average per capita availability and if none of its components harm the environment.

5 WF LIMITATIONS

Thanks to the WF, it is possible to estimate the virtual water volumes associated with numerous products (Hoekstra & Chapagain, 2007) and the virtual water flows (see Figure 1). However, some researchers challenge the mathematical foundations of the WF, arguing that its results are often debatable and challenging to interpret. Below, we present examples that illustrate the limitations of the WF methodology.

First, research has demonstrated that different WF methods yield significantly different results. For instance, a study examining sugar beet production across 59 European regions revealed that the current methodology overestimates blue water usage while underestimating green water contributions. Furthermore, the same study indicated that the final grey WF can vary by a factor of ten or more, depending on the selected water quality standards (Thaler et al., 2012).

Ridoutt et al. (2009) estimated the WF of two products: 250 g of Peanut M&M's and 575 g of Dolmio pasta sauce. This analysis revealed the complexities in relating these products' WFs to their social and environmental impacts. The difficulty in tracing water sources within certain supply chains posed significant challenges. As a result, the authors emphasized that calculating product WFs is essential for establishing a scientifically valid connection between water usage and its associated social and environmental consequences. Without credibility, the WF is unlikely to serve as an effective tool for promoting sustainable consumption. Berger & Finkbeiner (2013) advocate using the WF as an impact indicator rather than a volumetric index. They caution that WF results can be misleading; smaller footprints may sometimes correlate with more significant ecological impacts.

Additionally, the WF concept has several hydrological limitations: i) There are challenges in defining freshwater. ii) Recent studies have questioned the notion that water is generally "lost" from a watershed due to evapotranspiration, highlighting significant continental evaporation recycling rates over short time and length scales. iii) There is no scientific basis for aggregating blue, green, and gray water. iv) The significance of green water consumption is questionable, as soil moisture is primarily accessible to local plants and does not benefit surrounding ecosystems or humans. v) Converting natural land to agricultural use may enhance blue water availability, as this transformation increases surface runoff and aquifer recharge.

Finally, Egan (2012) suggests that while estimating the WF enhances general awareness of responsible water use, it does not address how governments, corporations, and households utilize WF data to inform effective policies and consumption decisions.

6 CONCLUSIONS

This study highlights the significant role of the water footprint (WF) in understanding and managing global water resources. As life expectancy increases, so does water demand, necessitating the adoption of efficient and sustainable management practices. The WF framework provides a method for quantifying water consumption at various levels, fostering a clearer understanding of how lifestyle choices impact water resources.

Key findings indicate that the WF encompasses multiple dimensions, including the types of water used in production—green, blue, and gray—each playing a distinct role in environmental sustainability.

Also, the analysis of virtual water flows emphasizes the importance of trade in shaping global water dynamics. At the same time, regional variations in WF illustrate the effects of consumption patterns, climate, and agricultural practices. However, while current calculations of WF for specific products and locations are feasible, they often yield approximate and sometimes offer questionable results.

The WF is a promising concept for effective water resource management, yet also faces notable limitations. Variability in methodologies and challenges in interpreting results require a careful approach to its application. Involving more scientists to improve WF accounting methods is crucial to ensure that its hydrological and economic foundations are sufficiently robust, leading to reliable estimates that can inform effective reduction strategies.

To ensure that the WF effectively informs policies and consumption decisions, it is essential for stakeholders—including governments, businesses, and consumers—to actively engage in reducing their WFs. This can be achieved through education, adopting efficient practices, and making informed choices. Addressing these challenges is essential for promoting a more equitable and sustainable approach to water resource management.

In conclusion, the current application of the WF promotes responsible water use rather than guiding the design of water management policies.

7 ACKNOWLEDGMENTS

The authors thank Professors Josue Medellin-Azuara and Roger Bales from the University of California, Merced, for their valuable comments and contributions during the research.

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Appendix 1. Data used for the "Extended Water Footprint Calculator".

Variable	Value
Country of residence	United States / Colombia
Food consumption	
Cereal products (wheat, rice, maize, etc.)	0.25 kg per week
Meat products	0.5 kg per week
Dairy products	0.2 kg per week
Eggs	10 number per week
How do you prefer to take your food?	Low fat
How is your sugar and sweets consumption?	Low
Vegetables	1 kg per week

Variable	Value
Fruits	1 kg per week
Starchy roots (potatoes, cassava)	0.1 kg per week
How many cups of coffee do you take per day?	1 cup per day
How many cups of tea do you take per day?	0 cup per day
Domestic water use - indoors	
How many showers do you take each day?	1 number per day
What is the average length of each shower?	5 minute per shower
Do your showers have standard or low-flow showerheads?	Standard shower head
How many baths do you have each week?	7 number per week
How many times per day do you brush your teeth, shave or wash your hand?	6 number per day
Do you leave the tap running when brushing your teeth and shaving?	No
How many loads of laundry do you do in an average week?	0.5 times per week
Do you have a dual flush toilet?	No
If you wash your dishes by hand how many times are dishes washed each day?	3 number per day
How long does the water run during each wash?	5 minute per wash
If you have a dish washer, how many times is it used each week?	0 number per week
Domestic water use - outdoors	
How many times per week do you wash a car?	0.125 number per week
How many times do you water your garden each week?	0 number per week
How long do you water your garden each time?	0 minute per watering
How long per week do you spend rinsing equipment, driveways, or sidewalks each week?	0 minute per week
If you have a swimming pool what is its capacity?	0 cubic meter
How many times per year do you empty your swimming pool?	0 number per year

Variable	Value
Industrial goods consumption	
What is your gross yearly income? (Only that part of income which is consumed by you).	24000 US$ per year