



Water Footprint: A Review Based on Concepts, Methods, and Implications

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Abstract: Water footprint assessment has become a useful method for assessing how much water is used by products and activities related to humans, offering insights into how water resources might be managed sustainably. While agricultural production accounts for the majority of water consumption worldwide, the industrial and residential sectors also use large amounts of water and cause pollution. This review article provides an examination of the approaches and uses of water footprint assessment in a range of industries and geographical areas. The notion of water footprint and its elements green, blue, and grey water footprints as well as the corresponding computation techniques are introduced at the outset of the work. The most recent developments in spatially explicit modelling and life cycle assessment techniques, it examines the development of water footprint assessment procedures. The paper explores the many uses of water footprint assessment, from consumer items and urban water management to industrial operations and agricultural output. It provides case studies and real-world examples that show how water footprint analysis may be applied practically to address issues with pollution, water shortages, and sustainability in various settings. The study also looks at the difficulties and constraints that come with assessing the water footprint, such as methodological uncertainty, data availability, and temporal and geographical variability. It talks about current studies as well as potential paths forward for improving the reliability and usability of water footprint measurement instruments. As a comprehensive and integrated method for measuring and controlling the effects of human-induced water usage on regional and global water resources, this study concludes by highlighting the importance of water footprint assessment. In order to promote sustainable water management practices, it highlights the necessity of multidisciplinary collaboration and stakeholder involvement.

Keyword: Water Footprint, Sustainability, Life Cycle Assessment, Spatial Analysis.

INTRODUCTION

The total amount of freshwater utilised, both directly and indirectly, in the creation of products and services, as well as the environmental effect of this water usage, are measured by a comprehensive indicator called the "water footprint." The notion of water footprint gained popularity as a tool for evaluating water consumption and its related environmental repercussions, and it originated from the work of Arjen Y. Hoekstra and his colleagues in the early 2000s (Hoekstra et al., 2011).

Analysing the water usage along a product or service's whole supply chain is necessary to calculate water footprints. This involves evaluating the amount of water used at various industrial phases, such as extraction of raw materials, manufacture, distribution, and consumption. Water footprint studies offer insights into resource dependencies, environmental consequences, and water usage efficiency at a variety of scales, from individual goods to entire nations or river basins (Mekonnen & Hoekstra, 2011). Water footprint estimates are routinely conducted using the life cycle assessment (LCA) methodology framework. LCA incorporates water consumption into more comprehensive environmental impact evaluations by taking a holistic approach to a product or service's life cycle. Using a comprehensive approach makes it possible to assess how various production and consumption patterns will affect the environment, which will help decision-makers make more sustainable choices (Boulay et al., 2015).

Decisions on how to allocate resources, formulate policies, and implement sustainable water management techniques are all greatly influenced by water footprint assessments. Stakeholders may prioritise mitigation steps and adopt water-saving technology to improve water efficiency and lower hazards associated with water use by identifying hotspots of water use and environmental effect. Additionally, raising consumer and corporate knowledge and educating them about water footprint principles may help them make educated decisions and support initiatives to save water. Water footprint evaluations are being more widely used in a wider range of industries and geographical areas, which emphasises how linked water resources are on a worldwide basis. Research has looked at the water footprints of consumer items, industrial processes, and agricultural products. This has helped to highlight the issues linked to water that various supply chains and businesses are experiencing (Chapagain & Hoekstra, 2008; Vanham et al., 2018). Water footprint evaluations support resource efficiency, environmental conservation, and sustainable water management by measuring water usage and related effects.

The three primary elements of the water footprint framework are the grey, green, and blue water footprints. The amount of surface and groundwater used for irrigation, industrial operations, and residential consumption during production is shown by the blue water footprint. The term "green water footprint" describes how much precipitation is used by plants and crops through evapotranspiration, demonstrating how dependent agriculture is on rainfall. The amount of freshwater needed to dilute pollutants in order to achieve water quality requirements is known as the "grey water footprint," which represents the environmental effect of water pollution (Hoekstra et al., 2011). The process of calculating the total amount of freshwater utilised and contaminated during the creation of products and services is known as water footprint assessment. It sheds light on how water usage affects the ecosystem, including how water resources are depleted, how water bodies are contaminated, and how ecological degradation occurs. Water footprint studies take into account both indirect water usage found in the product supply chain and direct water use, such as irrigation and industrial activities. Blue, green, and grey water footprints are the three primary components of water footprint that are often identified.

1.1 Blue Water Footprint

The amount of surface and groundwater used in manufacturing is shown by the blue water footprint. It includes the water for household, industrial, and agricultural purposes. Quantifying one's "blue water footprint" entails calculating how much water is taken directly from freshwater sources and evaluating its sustainability in relation to the water resources at hand (Mekonnen & Hoekstra, 2011). This element is especially crucial in areas where a shortage of water is an issue since overuse of blue water can cause aquifer depletion and the biological deterioration of water bodies.

1.2 Green Water Footprint

The amount of precipitation that flora and crops evapotranspire and use is known as the "green water footprint." It emphasises the importance of green water to the production of food and fibre and illustrates how agricultural productivity is dependent on rainfall (Mekonnen & Hoekstra, 2011). In order to maximise crop yield while reducing water loss, assessing the green water footprint entails determining potential for sustainable land and water management techniques as well as assessing how well rainfed agriculture uses water.

1.3 Grey Water Footprint

The amount of freshwater needed to dilute contaminants in order to achieve water quality requirements is measured by the grey water footprint. It depicts the effects of water pollution on the ecosystem from a variety of sources, such as home wastewater, agricultural runoff, and industrial discharges (Hoekstra et al., 2011). Assessments of the grey water footprint are useful in locating pollution hotspots and determining how well pollution management strategies reduce negative environmental effects. A thorough picture of water usage and environmental effects across various industries and geographical areas is provided by integrating evaluations of the blue, green, and grey water footprints.

An evaluation of water footprint takes into account both direct and indirect water usage. The term "direct water use" describes the use of water for particular uses, such as household chores, industrial operations, and irrigation. Conversely, indirect water use refers to the use of water that is incorporated into goods and services at all stages of their life cycle, such as manufacturing, shipping, and consumption. The contrast between direct and indirect water usage is explained in studies, emphasising the consequences for sustainability and water resource management (Chapagain & Hoekstra 2004) and (Ridoutt et al. 2010). By calculating the entire amount of freshwater utilised both directly and indirectly in the production and consumption of products and services, water footprint assessment plays a critical role in sustainability. Furthermore, the idea of virtual water commerce makes it possible to evaluate water reliance and scarcity in international supply chains, emphasising the interdependence of water resources on a worldwide scale.

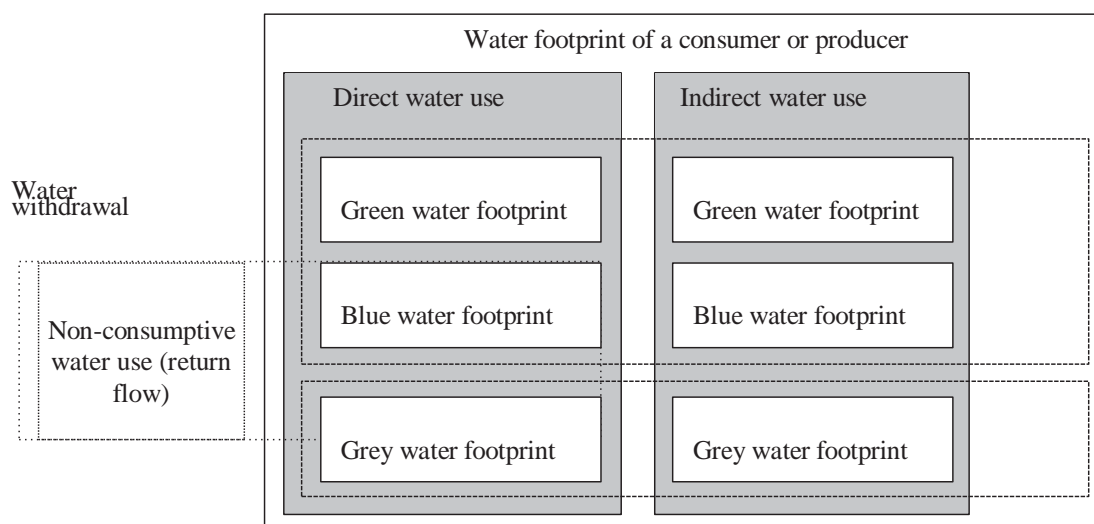


Fig 1: Schematic representation of the components of a water footprint (Source: Aldaya, M. M., Chapagain, A. K., Hoekstra, A. Y., & Mekonnen, M. M. (2011). *The water footprint assessment manual: Setting the global standard*)

II. METHODOLOGY

A variety of approaches are used in water footprint assessment to measure the amount of water used and the environmental effects it has on various sectors. A thorough framework for determining the blue, green, and grey water footprints of goods and processes is offered in Water Footprint Network method (Hoekstra et al. 2011). A comprehensive view of resource consumption and emissions during a product's life cycle is provided by life cycle assessment (LCA), which combines water footprint analysis with other environmental impact categories (Boulay et al., 2018). By analysing the interdependencies across economic sectors, input-output analysis makes it possible to estimate the amount of water used indirectly through supply chains and economic activity (Lenzen et al., 2011). These approaches work well together to provide a thorough evaluation of water footprints at various sizes and degrees of detail, enabling informed decision-making. Case studies demonstrating the application of different water footprint assessment approaches provide insightful information on how to apply these methodologies practically and effectively to guide plans for sustainable water management.

Water Footprint Network technique was used in research to evaluate the water footprint of Australian beef cattle operations (Ridoutt et al. 2010). The study measured the beef cattle's blue, green, and grey water footprints, emphasising the substantial contributions of feed production and animal watering to the overall water consumption. Another example is the life cycle assessment (LCA) of dairy products carried out in France to examine the environmental effects of the goods, including water usage (Boulay et al. 2018). From feed cultivation to milk processing, the research looked at the water footprint of each step in the dairy production chain. It identified hotspots and possible locations where water management techniques may be improved. Additionally, some studies looked at the water usage and environmental impacts of several Australian economic sectors in an input-output study (Lenzen et al. 2011). The study shed light on the interdependence of water consumption across the economy by quantifying the direct and indirect water footprints associated with various sectors using a multi-regional input-output model. The FAO's CROPWAT model is another popular approach for calculating water footprints (Smith, 1992). It evaluates crop production's water needs based on soil, climate, and crop characteristics (FAO, 1992). Furthermore, spatially explicit evaluations of water risk are provided by the Aqueduct Water Risk Atlas, which includes indicators including pollution, variability, and water stress (WRI, 2020). Furthermore, to monitor agricultural water consumption in almost real-time, the AWARE (Agricultural Water Accounting in Real-time) platform combines hydrological modelling with data from remote sensing (FAO, 2020).

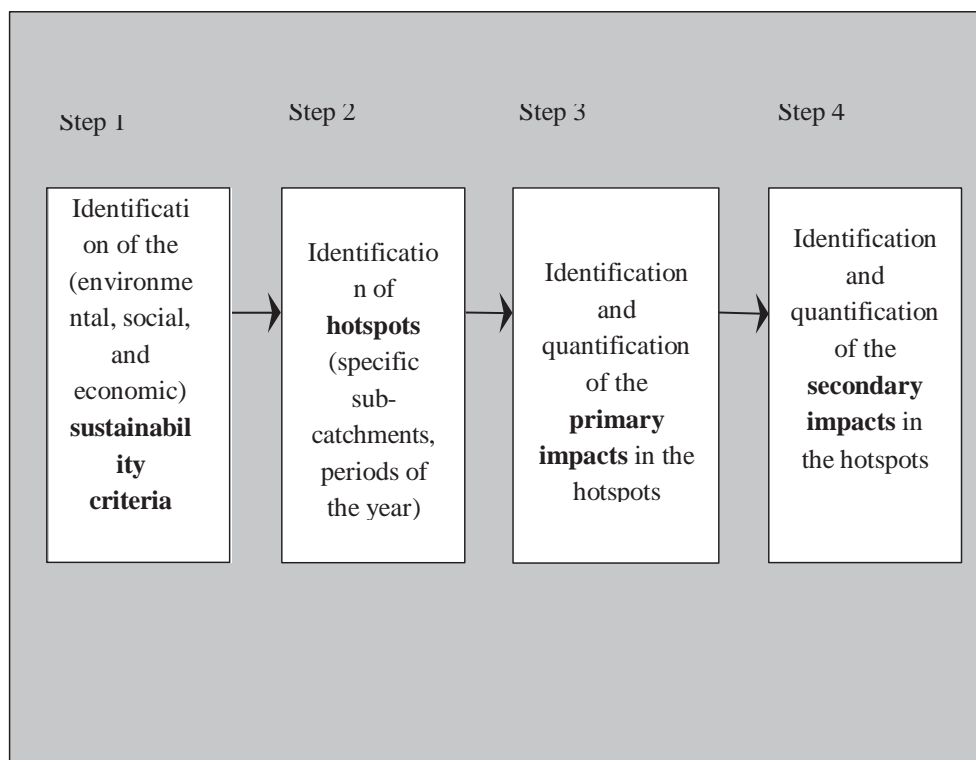


Fig 2: Assessment of the sustainability of the water footprint within a catchment or river basin in four steps (Source: Aldaya, M. M., Chapagain, A. K., Hoekstra, A. Y., & Mekonnen, M. M. (2011). *The water footprint assessment manual: Setting the global standard*)

III. ASSESSMENT OF WATER FOOTPRINT

3.1 Implications

Water consumption in homes, businesses, and agriculture has a big influence on the environment. It causes pollution, water scarcity, and ecological damage. A significant quantity of freshwater withdrawals from agriculture occurs via irrigation, which depletes aquifers and causes salinity in the soil (Mekonnen & Hoekstra, 2011). Furthermore, using water for sanitation and family needs can put a burden on the infrastructure for wastewater treatment and local water supplies, aggravating pollution,

and hygienic problems (Sullivan et al., 2020). The health of ecosystems, biodiversity, and human well-being are all at risk due to these environmental effects, which makes sustainable water management methods and policies across sectors necessary.

A product's water footprint includes the amount of water used in all stages of production, including extraction, manufacture, distribution, and transportation. This includes consumer items and supply chains. According to studies, the complicated supply chains, and resource-intensive production processes of consumer items like food, apparel, and electronics result in sizable water footprints (Mekonnen & Hoekstra, 2011). For instance, the watering of crops frequently necessitates significant water consumption, but the processing and cooling of textile and electronics manufacturing processes demand significant water consumption (Chapagain & Hoekstra, 2004). Recognising possibilities to cut water usage, boost efficiency, and encourage sustainable consumption behaviours requires an understanding of the water footprint of consumer items and supply chains (Mekonnen & Hoekstra, 2011). To ensure sustainability and resilience in the face of growing water shortages and environmental concerns, effective policies for managing water resources are crucial.

3.2 Recent Advances and Challenges

Accurately representing the dynamic nature of water supply and usage requires accounting for both geographical and temporal variability in water footprint estimates. Researchers can now take into consideration differences in climate, land use, and water availability across different locations and time periods because to advancements in remote sensing technologies, hydrological modelling, and spatial analytic approaches (Yang et al., 2020). Water footprint evaluations become more reliable and applicable when high-resolution data and temporal dynamics are added. This helps the assessments guide sustainable water management strategies. The quality and dependability of findings from water footprint analysis are significantly impacted by data restrictions and uncertainty. Inadequate data availability might result in biased estimations of water usage and inadequate evaluations, particularly in developing locations (Mekonnen & Hoekstra, 2011). Uncertainties in water footprint estimations are further compounded by variations in data quality, measurement techniques, and temporal precision (Boulay et al., 2015). To strengthen the validity and comparability of water footprint assessments, addressing these problems calls for enhanced data collection efforts, standardised techniques, and transparent reporting standards (Vanham et al., 2018). Incorporating sensitivity analyses and uncertainty quantification methodologies may also shed light on the dependability of findings and guide policy and management decision-making processes related to water.

IV. DISCUSSION

There are several ways to improve water footprint assessment procedures, which can lead to improvements in the precision, resilience, and usefulness of water footprint evaluations. Water availability and usage can be better understood by the spatially explicit and temporally dynamic integration of remote sensing data, geographic information systems (GIS), and hydrological modelling approaches. To further promote more consistency and comparability among research, multidisciplinary partnerships and stakeholder participation can help build standardised techniques and data sharing protocols. Furthermore, by using developments in machine learning, data analytics, and uncertainty quantification techniques, data constraints and uncertainties may be addressed, enhancing the validity and trustworthiness of water footprint evaluations.

Interdisciplinary methods may provide comprehensive insights into water challenges and guide integrated management plans by bringing together specialists from several domains, including hydrology, ecology, economics, and social sciences. In addition, the inclusion of stakeholders including legislators, business representatives, community leaders, and civil society organisations encourages inclusive water governance and participatory decision-making processes. Hoekstra proposes three pillars under wise water allocation: setting upper limits on WF per river basin, setting WF benchmarks per product, and fair WF shares per community. Improving crop productivity through soil and water management, changing consumption patterns, and reducing food losses and waste are effective measures. Virtual water trade from water-abundant regions to regions with limited resources can also help reduce water scarcity.

V. CONCLUSION

The purpose of the study was to evaluate the existing condition of water resources and the problems, consequences, and suggestions related to sustainable water management. There is an urgent need for coordinated strategies to address inequality, pollution, and water shortage. Water footprint analyses showed considerable temporal and regional variability in water usage, with families, businesses, and agriculture accounting for both direct and indirect water use. Informed decision-making and policy formulation have been found to depend heavily on interdisciplinary cooperation and stakeholder participation. In order to encourage sustainable water usage and management, policy proposals emphasised the significance of integrated water resources management, water price systems, infrastructural improvements, and public awareness initiatives. The findings of the study underscore the pressing need for action to protect water resources and guarantee water security for current and future generations. In order to lessen the negative effects of pollution, water shortages, and climate change on ecosystems and human well-being, sustainable water management techniques are crucial. Prioritising integrated strategies that take into account the social, economic, and environmental aspects of water governance is crucial for policy interventions. To improve water efficiency, conservation, and resilience, investments in water infrastructure, technology, and capacity-building programmes are also required.

The study highlights how crucial it is to carry out further investigation and take action in order to address issues pertaining to water and advance sustainable water management techniques. Longitudinal studies are also necessary to assess the success of policy actions and track changes in water resources over time. To turn research results into workable solutions and promote change, action-oriented projects including public-private partnerships, capacity-building programmes, and community-based initiatives are crucial. Governments, educational institutions, civic society, and the commercial sector may

collaborate to achieve sustainable water management objectives and guarantee everyone has access to water in the future. The importance of research, policy, and group effort in tackling water-related issues and promoting sustainable water management techniques is emphasised in this synopsis. We can create resilient water systems, safeguard ecosystems, and guarantee fair access to clean and secure water resources for future generations by working together and demonstrating a strong commitment.

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