Final Report

Strengths and Limitations of Water Footprints: a Literature Review

REPORT 260

CLIENT	**Netherlands Environmental Assessment Agency (PBL)**
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Executive summary

This report, commissioned by the Netherlands Environmental Assessment Agency (PBL) and conducted by FutureWater, provides a systematic literature review of the strengths and limitations of the water footprint concept. The sample consisted of 15 scientific articles selected by PBL at a previous stage. The water footprint is commonly defined as the total volume of freshwater consumed and polluted at various levels (e.g., national, corporate, or product levels). The review aims to assess the capabilities and challenges associated with the application of water footprint methodologies in different contexts, with a focus on their role in sustainable water management.

It was found that the Water Footprint Assessment (WFA) and Life Cycle Assessment (LCA) are the most utilized methodologies. Water footprint analyses are widely applied in various sectors, with significant focus on agriculture and industry. However, there is a noted geographic and sectoral bias, with most studies focusing on high-income countries and production/manufacturing stages.

Water footprints have proven useful in identifying areas of unsustainable water use, and can guide policy decisions aimed at reducing water stress. They are an effective tool for raising awareness among consumers, producers, and policymakers about the environmental impacts of water use. They can also support strategies for redistributing water resources through virtual water trade. There are, however, several limitations that should be taken into account when performing water footprint assessments and evaluating their outcomes. For example, the lack of standardized methodologies and reliable site-specific data, as well as insufficient consideration of local hydrological and environmental conditions, can hamper interpretation of water footprint values.

The following recommendations were found during the review. Future research and development should focus on addressing these limitations to enhance the utility of the water footprint concept for consumers, producers and policy makers. The literature review shows that there is a need for further research to link water footprint to local water availability, particularly in areas facing increasing water demand and climate change. Also, integrating water footprints assessments with broader concepts like the Water-Food-Energy nexus and improving data availability at higher spatial resolutions are crucial for enhancing the accuracy and usefulness of water footprint applications. Sector-specific methodologies and benchmarks should be developed to address unique challenges in sectors such as wine production and forestry.

Content

1 Introduction

1.1 Background

In support of a scientific background study, the Netherlands Environmental Assessment Agency (PBL) has commissioned FutureWater to conduct a systematic literature review to research the opportunities and limitations related with the application of the *Water Footprint* concept.

This report synthesizes the main results of the literature review and presents a set of conclusions and recommendations based on the consulted literature.

1.2 Approach to the Literature Review

1.2.1 Research Questions

PBL defined the main research question to be answered from the literature review is as follows:

What are the capabilities and limitations of water footprints reported in the selected primary literature?

To this end, the sub-questions listed in Table 1 were formulated by PBL. These were grouped in the categories indicated in the right column of the table, which correspond with the section headings of Chapter 2 of this report.

Table 1: Research questions addressed in this study

ID	Research question	Category
Q1	Which definitions and types of water footprints are mentioned?	Definitions and methodologies
Q2	Which methods are mentioned for calculating water footprints	
Q3	Which methodological challenges are mentioned?	
Q4	What is the scope of the water footprint assessments that are mentioned?	Applications and scope
Q5	Which examples of the use of water footprints to stimulate sustainable water use are mentioned?	
Q6	Which capabilities and limitations of water footprints are discussed, regarding the use of water footprints as an awareness tool?	Capabilities and Limitations
Q7	Which capabilities and limitations of water footprints are discussed, regarding the use of water footprints as an assessment tool?	
Q8	Which challenges and opportunities are discussed regarding linking water footprints to specific locations?	
Q9	Which challenges and opportunities are discussed regarding linking water footprints to other tools or approaches?	
Q10	Which knowledge gaps are mentioned?	Knowledge Gaps and Recommendations
Q11	Which recommendations for future research and practice are mentioned?	

1.2.2 List of references

The list of scientific articles to be consulted was compiled by PBL in a previous stage. Table 2 lists the 15 papers that were investigated. All of these have been published in peer-reviewed journals and they can all be considered review papers, synthesizing and drawing from other articles that zoom in on particular sectors, products and/or geographical regions. For easy reference throughout this report, a unique ID code (“A1”, “A2”, etc.). is assigned to each of the review papers.

Table 2: List of scientific papers consulted in the literature review

ID	Title	Author(s)	Year
A1	A water footprint review of Italian wine: Drivers, barriers, and practices for sustainable stewardship	Aivazidou E.; Tsolakis N.	2020
A2	The emerging role of water footprint in supply chain management: A critical literature synthesis and a hierarchical decision-making framework	Aivazidou E.; Tsolakis N.; Iakovou E.; Vlachos D.	2016
A3	A review on Water Footprint Assessment and Water-Food-Energy nexus for electronic and food products	Bong P.X.H.; Malek M.A.; Noor Z.Z.	2018
A4	Ascertaining and Optimizing the Water Footprint and Sludge Management Practice in Steel Industries	Choudhury A.R.; Singh N.; Veeraraghavan A.; Gupta A.; Palani S.G.; Mehdizadeh M.; Omidi A.; Al-Taey D.K.A.	2023
A5	Volumetric and Impact-Oriented Water Footprint of Agricultural Crops: A Review	Deepa R.; Anandhi A.; Alhashim R.	2021
A6	A quantitative review of water footprint accounting and simulation for crop production based on publications during 2002–2018	Feng B.; Zhuo L.; Xie D.; Mao Y.; Gao J.; Xie P.; Wu P.	2021
A7	The Water Footprint of Diets: A Global Systematic Review and Meta-analysis	Harris F.; Moss C.; Joy E.J.M.; Quinn R.; Scheelbeek P.F.D.; Dangour A.D.; Green R.	2020
A8	Is the water footprint an appropriate tool for forestry and forest products: The Fennoscandian case	Launiainen S.; Futter M.N.; Ellison D.; Clarke N.; Finér L.; Högbom L.; Laurén A.; Ring E.	2014
A9	Comparing the usefulness and applicability of different water footprint methodologies for sustainable water management in agriculture	Le Roux B.; van der Laan M.; Gush M.B.; Bristow K.L.	2018
A10	Savings and losses of global water resources in food-related virtual water trade	Liu W.; Antonelli M.; Kummu M.; Zhao X.; Wu P.; Liu J.; Zhuo L.; Yang H.	2019
A11	The water footprint of global food production	Mekonnen M.M.; Gerbens-Leenes W.	2020
A12	Water Footprint As A Tool of Water Resources Management - Review	Mohamed A.; Abuarab M.E.; Mehawed H.S.; Kasem M.A.	2021
A13	A bibliometrics review of hotspots in water footprint research based on co-words network analysis	Sun Y.; Wang Z.; Lee L.-C.; Li X.; Wang Y.	2022
A14	A review of water stress and water footprint accounting	Wang D.; Hubacek K.; Shan Y.; Gerbens-Leenes W.; Liu J.	2021
A15	Water footprint study review for understanding and resolving water issues in China	Zhuo L.; Feng B.; Wu P.	2020

2 Results

2.1 Overview

For reference, Table 3 visualizes the extent to which each research question (Section 1.2.1) is addressed in the selected scientific articles. Some of the review papers (e.g. Sun et al., 2022 - A13) analyze basic properties of previous research efforts, but only answer a few research questions since they do not provide in-depth observations of implications of water footprint applications, strengths and limitations, or linkages to water management.

Table 3: The extent to which each research question is addressed in the selected scientific articles

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15
Q1	E	E	E	N	E	E	E	E	E	E	E	E	P	E	E
Q2	E	E	E	N	E	E	E	P	E	E	E	E	E	E	E
Q3	E	E	P	P	E	E	E	P	P	E	P	P	P	E	E
Q4	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Q5	E	E	E	N	P	N	N	N	E	N	E	P	P	P	E
Q6	P	E	P	N	N	N	N	E	E	N	P	N	N	N	E
Q7	E	E	E	P	P	P	E	P	E	P	P	P	P	P	E
Q8	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Q9	P	P	N	P	E	N	P	N	N	N	N	N	N	E	P
Q10	E	E	E	N	E	E	E	E	E	E	E	E	N	E	E
Q11	E	E	E	N	E	E	E	E	E	E	E	E	N	E	E

E Explicitly addressed   P Partially addressed   N Not addressed

2.2 Definitions and Methodologies

2.2.1 Definitions Associated with Water Footprints

From the sources consulted, definitions associated with water footprints can be identified across multiple hierarchical levels. The definition of a water footprint is "*the total volume of freshwater consumed and polluted at various levels, including national, corporate, or product levels"* (Aivazidou and Tsolakis, 2020). These **volumetric water footprints** are by now well-established and widely implemented, as evidenced by the bibliographic review of Sun et al. (2022). The concept is closely associated with the term **virtual water**, which has a more narrow definition and refers to the total to the amount of water used along the value chain of goods and services. Virtual water flow analysis is mostly concerned with international and interregional trade (Liu et al., 2019). In addition to the volumetric water footprint, a category of water footprints developed more recently is the **impact-oriented** water footprint, which focuses on the environmental impact of water use (Sun et al., 2022).

All but one[1] of the consulted papers mention the volumetric water footprint and break it down in three main components, which we summarize as follows:

- **Green Water Footprint**: Refers to the absorption of rainwater by plants, which is the proportion of precipitation that infiltrates the soil and is temporarily stored in the soil and vegetation canopy.
- **Blue Water Footprint**: Represents the volume of surface and groundwater consumed during the production of goods and services.
- **Grey Water Footprint**: The volume of freshwater required to assimilate pollutants during farming and manufacturing processes, given specific water quality standards.

These three general concepts are mentioned by all the papers but one (Choudhury et al., 2023), although there are subtle differences in definitions utilized in the different papers. These definitions do not contradict each other, but mostly highlight particular aspects of the water footprint definition. For example, Wang et al. (2021) explicitly mention that both rainwater evapotranspiration and water incorporated into harvested crop or wood are part of the green water footprint definition. Regarding the grey water footprint, Wang et al. (2021) state clearly that it should be calculated with respect to natural background concentrations of the relevant pollutants.

When analyzing water footprints under one or more of the above categories and components, one is concerned with the selection and definition of a set of indicators and parameters related to the hydrological cycle and water quality. Although many of these have clear definitions (e.g. precipitation, soil moisture), it is important to consider differences in definitions that may occur when comparing water footprints between different sources (e.g. water use vs. water consumption, evapotranspiration vs. evaporation).

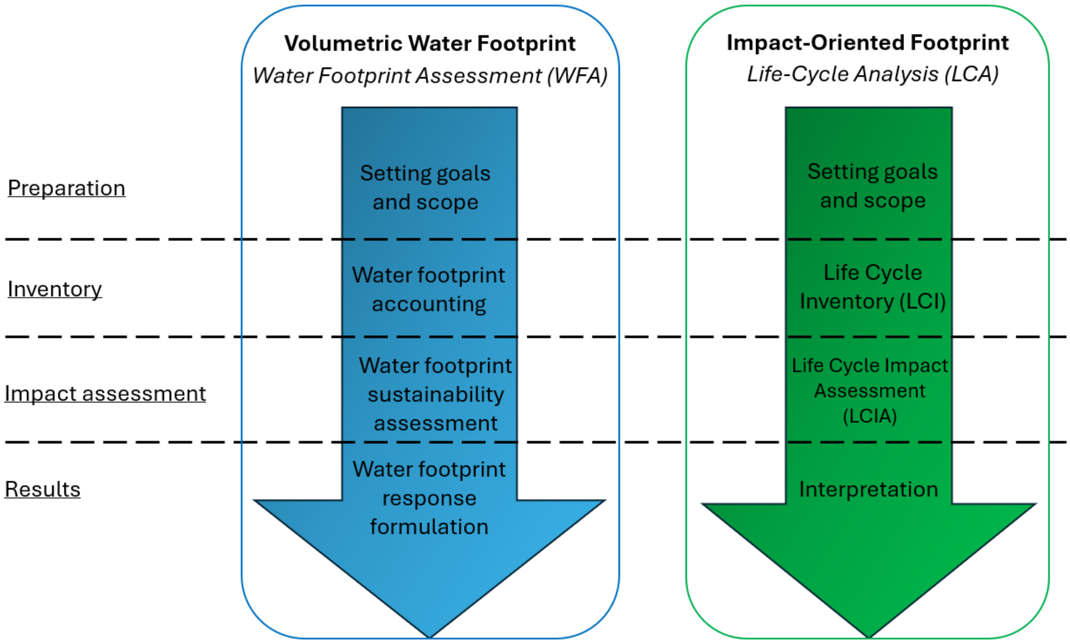

Figure 1: Visual representation of the stages associated with water footprint analyses according to the two main methodologies (based on Vanham et al., 2013[2])

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[1] Choudhury et al. (2023) use the WF concept very loosely, and do not provide a clear definition. While they do not explicitly classify water footprints into types such as green, blue, or grey, they do discuss the water intake (which could be analogous to blue water) and the wastewater generation (which could relate to grey water). Their review discusses water requirements across the different stages of the steel production process.

[2] https://www.sciencedirect.com/science/article/abs/pii/S1470160X1200372X

2.2.2 Methods for Calculating Water Footprints

This section focuses on methods and frameworks for calculating water footprints, rather than techniques for collecting the input data required for water footprint accounting, or for evaluating the impacts of the water footprint on catchment hydrology. Several of the selected review papers discuss such methods, including hydrological models (Deepa et al., 2021), satellite remote sensing (Feng et al., 2021), crop models (Liu et al., 2019), and statistical data (Harris et al., 2020). The strengths and limitations of each of these approaches are considered out of scope for this assignment and therefore not discussed in this report.

The global standard for determining volumetric water footprints is the **Water Footprint Assessment (WFA)** methodology published by Hoekstra et al. (2011)[1]. This method includes four stages: (i) goal and scope setting, (ii) water footprint accounting, (iii) water footprint sustainability assessment, and (iv) water footprint response formulation. Based on the general WFA principles, several tools have been developed which focus on the characteristics of particular sectors. An example is the V.I.V.A. Tool, which was developed specifically for enhancing grey water footprint assessments in the Italian wine industry and accounts for the different varieties of wine (Aivazidou and Tsolakis, 2020).

Life Cycle Assessment (LCA) is the approach commonly followed for determining the impact-oriented water footprint. The international standard developed for this purpose is ISO 14046, which specifies the principles, requirements and guidelines for the quantification, impact assessment and reporting of the water footprint of products, processes and organizations ISO 14046 (Aivazidou et al., 2016).

WFA and LCA have several overlapping features, but differ in purpose and scope. Although they share a generic framework of four stages in the assessment (see Figure 1), LCA is a product-focused method aiming to assess sustainability of products, while WFA focuses on the sustainability of water resources and can be more directly used in catchment to basin water management (Le Roux et al., 2018). LCA is in practice typically limited to blue water use, as applications of this method in many cases leads to negative green water footprints (e.g. for the agrifood sector, strictly speaking only the difference between cropland and natural vegetation - net green water - should be considered). With regards to grey water, the LCA approach prescribes the use of other indicators to evaluate water pollution (Wang et al., 2021). Deepa et al. (2021) identify several studies that are considered ‘hybrid’, i.e. combining elements from the WFA and LCA approaches.

Water footprint assessments can be made more comprehensive by integrating **Input-Output (IO) analysis**; in the sample of articles that was reviewed for this report, this approach that has been pursued particularly in the Chinese context (Sun et al., 2022; Wang et al., 2021; Zhuo et al., 2020). At the core of IO is the use of an input-output table depicting monetary flows of goods and services among different economic sectors through trade, linking the entire supply chain to final consumption using macro-level approaches and concepts to analyse footprints of individuals, companies, sectors or regions. IO is used to extend water footprint accounting across supply chains, particularly in complex economic systems (Wang et al., 2021; Zhuo et al., 2020). IO, as well as the related Multi-Regional Input-Output analysis, have the potential to provide more complete information about supply chains than WFA and LCA, which focus on the most important processes but exclude others. A downside of IO analysis is that economic sectors are aggregated, showing less detailed process information (Wang et al., 2021).

Methodological challenges reported in literature include the following:

1. A common challenge highlighted in many studies relates to limitations in **data availability and quality**. The accuracy of water footprint assessments is often hindered by the lack of reliable,

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[1] https://waterfootprint.org/resources/TheWaterFootprintAssessmentManual_English.pdf

site-specific, and/or up-to-date data (Deepa et al., 2021; Feng et al., 2021; Harris et al., 2020; Mohamed et al., 2021). Especially in the context of multi-regional analyses (e.g. in the case of virtual water trade), the precision of water footprint assessments is limited by significant differences in availability and accuracy of trade and crop yield data (Liu et al., 2019)

2. **Complexities related to grey water footprint accounting***:* grey water footprints in particular can be difficult to assess in practice. Evaluating the grey water footprint can be challenging due to difficulties in quantifying pollutants and integrating these assessments into real water volumes (Mohamed et al., 2021). Also, the grey water footprint may in some cases not accurately represent water pollution, as the range of pollutants can be quite diverse and a certain level of these substances occurs naturally in the water (Deepa et al., 2021).
3. **Scaling and defining system boundaries***:* Aggregating local water use over a product's life cycle can lead to inconsistencies with the principles of the hydrologic cycle (Launiainen et al., 2014). Also, aggregation of data available at varying resolutions can lead to substantial differences depending on aggregation approaches (Liu et al., 2019). System boundaries need to be well defined to compare methods, e.g. which supply chains will be included in the analysis (Aivazidou et al., 2016).

2.3 Applications and Scope

Table 4 presents an overview of the scope of water footprint assessments discussed in the selected literature. As the selected articles are primarily review papers, many have a broad geographical scope and specific example cases are often only briefly highlighted. Some restrict the geography of the review to particular regions or countries. A few of the papers (e.g. Le Roux et al., 2018) present their own water footprint calculations and interpretations in addition to reviewing other sources of information. As can be seen from the table, most of the articles focus on a particular product or category of products, but few explicitly consider different stages of the associated supply chain.

Table 4: Water Footprint applications considered in this report

ID	Scope	Sector / product	Geography of the review
A1	Supply chain	Wine	Italy
A2	Supply chains	Agrifood products	Global
A3	Products	Electronic and food products	Global
A4	Product / industry	Steel	Global
A5	Products (majority of the reviewed studies use planting/sowing and harvesting as boundaries)	Agricultural crops	Global
A6	Products	Agricultural crops	Global
A7	Products (water footprints are obtained from other studies, possibly some include full supply chains, but this is not specified)	Diets (defined at the national scale)	Global
A8	Products	Forest-based products	Fennoscandia
A9	Product	Apples	South Africa

A10	Products (only water savings and losses associated with agricultural production are considered)	Food (crop and livestock products)	Global
A11	Products	Agricultural crops	Global
A12	Products	Agricultural crops (focus on rice, wheat, maize)	Egypt
A13	Water footprint research in the broadest sense	Agriculture, industry, and services sectors.	Global
A14	Various	Not sector-specific	Global
A15	Various	Agriculture, industry, services, forestry sectors, and households.	China

Examples of the use of water footprints to stimulate sustainable water use are provided in the selected literature, especially drawing from case study papers highlighted in the various review papers. In general, water footprint assessments are a potentially helpful tool for **identifying areas of unsustainable water use**, particularly in agriculture, and for **guiding policy decisions** aimed at reducing water stress (Wang et al., 2021). It is considered particularly helpful that water footprints can potentially inform policies and strategies for sustainable water use by pinpointing the particularly **water-intensive stages within supply chain**s (Aivazidou et al., 2016). Although they do not embed their analysis in water footprint concepts, Choudhury et al. (2023) present a review of water requirements, wastewater generation and sludge production across the process of steel production. Based on his information, they propose a "*preferential combination of treatments to balance efficacy and economy*".

Water footprint can help governments understand the extent to which the size of their national water footprint is due to consumption patterns or inefficient production. This can then help to prioritize policy actions such as changing consumption patterns or improving the water efficiency of production (Mohamed et al., 2021). Mekonnen and Gerbens-Leenes (2020) discuss the importance of setting **benchmarks** and caps on water footprints per river basin and per product to stimulate sustainable water use, referencing a study that propose global caps disaggregated per river basin.

One clear example of water footprints informing sustainable water use decisions is provided for the Italian wine industry by Aivazidou and Tsolakis (2020). They performed an extensive review of water footprint assessments in the wine sector to conclude that vine growers and winemaking practitioners should focus on **water management interventions** at three levels, including (i) soil management, (ii) freshwater management, and (iii) wastewater treatment. Specifically, they find that *"the type of irrigation systems and practices to be applied should consider the edaphoclimatic and related infrastructure conditions at each winemaking region to increase the efficiency of water resources appropriation. Regarding wastewater treatment, aerobic processes could offer an efficient and easy-to-use solution compared to anaerobic ones that constitute a more economic option*". Such concrete water footprint mitigation practices can subsequently be integrated into a water stewardship plan for the sector. By expanding a water footprint assessment with a more elaborate analysis of driving factors, Zhuo et al. (2020) derive a set of recommendations that could theoretically lead to more sustainable water use in China: (i) utilizing water-saving technologies in crop fields, (ii) industrial restructuring, (iii) trade network optimization, consumption pattern (diet) adjustments, and (iv) water price reformation.

Using models and other tools for **scenario analyses**, water footprints under different future scenarios can be assessed, which can guide policy makers on water footprint mitigation. For example, the future usage of water in the electrify production sector, was assessed in Turkey via application of the water footprint concept to evaluate water-usage-impacts of future policies of energy development plans developed by the government (study referenced by Bong et al., 2018). The same authors also highlight an example of how water footprints can support spatial planning, by citing a study that shows how water footprints can help to identify appropriate locations of rubber plantations in Southern Thailand. With their example of applying multiple water footprint methodologies to apple production in Western Cape (South Africa), Le Roux et al. (2018) show how a comparison of different methodologies can be used to identify effective approaches for managing water resources in agriculture.

Mekonnen and Gerbens-Leenes (2020) emphasize the role of **virtual water trade analyses** to support strategies for redistributing water resources from water-abundant to water-scarce regions. The idea here is to alleviate water scarcity, where water-scarce regions import water-intensive products from water-abundant regions. An example is the trade between Morocco and France, where importing wheat from France allows Morocco to save blue water resources.(Liu et al., 2019)

2.4 Capabilities and Limitations

2.4.1 Water Footprints as an Awareness Tool

Water footprints have proven successful in raising **awareness** of water use impacts as a result of water consumed to make and distribute products. Several of the selected papers highlight the strengths of water footprints as an awareness tool (Deepa et al., 2021; Le Roux et al., 2018; Liu et al., 2019), in particular for three target groups: consumers, policy makers, and industries / producers. Water footprints can help consumers understand the environmental impact of the consumed goods, such as wine or meat products (Aivazidou et al., 2016). Water footprint assessments can help businesses and policymakers understand the extent of water use and pollution within supply chains, raising awareness of the environmental impacts of their operations. Furthermore, water footprint assessment can raise awareness about the disparities in water use efficiency across regions and the impact of global trade on water resources (Liu et al., 2019).

Le Roux et al. (2018) explain that a limitation of water footprints as an awareness tool is the difficulty to develop a "*method of which the outcome is an undisputed number that can be used on product labels and will indicate 'right' or 'wrong'*"', e.g. to inform consumer decisions. They state that the use of the volumetric water footprint as a product label with the intention to inform customers of sustainability of water use will likely lead to misunderstandings, as the value would be detached from the local environmental and hydrological conditions. Also, risks of oversimplification are quite realistic; effective communication to a broad audience is challenging due to a lack of understanding of blue, green and grey water footprints, and the overall complexities associated with the data, methods and indicators applied (Launiainen et al., 2014).

2.4.2 Water Footprints as an Assessment Tool

As an **assessment** tool, a key strength of water footprints is their ability to provide an understanding of water use associated with the production of goods, for every echelon in the supply chain, helping in the identification of areas needed improvement regarding water management (Aivazidou et al., 2016). An overview of typical management decisions that can be informed by water footprint assessments is presented in Table 5.

Table 5: Hierarchical decision-making framework for water footprint management decisions (adopted from Aivazidou et al., 2016)

Hierarchical level	Water footprint management decision	Supply Chain Echelon						
		Cultivation / Procurement	Processing / Manufacturing	Packaging	Transportation	Retailing	Consumption / Consumer use	Waste management
Strategic	Cultivation of crops requiring less water	✓						
	Alteration of conventional crops into organic crops	✓						
	Selection and collaboration with water-friendly partners		✓			✓		
	Establishment of water auditing and control systems		✓			✓		
	Investment in water-efficient technologies		✓	✓		✓		✓
	Campaigns for raising user awareness					✓	✓	
Tactical	Use of precision techniques of irrigation and agriculture	✓						
	Enhancement of water retention in the soil	✓						
	Change in product composition		✓					
	Reuse and recycling of wastewater		✓	✓				
	Establishment of environmental labelling							
Operational	Prudent use of pesticides and fertilizers	✓						
	Prudent use of toxic chemical substances		✓	✓				✓
	Use of water-efficient packaging			✓				
	Prudent use of biofuels in transport				✓			
	Reduction of food waste	✓	✓		✓	✓		

An issue related with water footprints as an assessment tool relates to a **variability in methods and lack of standardization**. The review papers consulted report a lack of standardized methodologies for water footprint assessments, leading to inconsistencies in results across different studies (e.g. Aivazidou and Tsolakis, 2020; Bong et al., 2018; Harris et al., 2020). A lack of consensus in water footprint tools is evident; depending on the selected methods, assessment results and subsequent interpretation of water use sustainability can differ substantially (Aivazidou et al., 2016). Limitations of water footprint assessments can also be specific to particular water footprint components and sectors: Launiainen et al. (2014) demonstrate how the green water footprint as defined in the WFA methodology does not correctly reflect water use in the forestry sector. The WFA accounts for all water consumption from managed forests as a human appropriation of green water, while in practice there is no demonstrable significant difference between evapotranspiration from managed and unmanaged forests.

Finally, it is important to note that while water footprints clearly hold value as awareness and assessment tools, they do not directly point to operable measures (Zhuo et al., 2020). Additional information needs to be considered to derive actionable insights and make well-informed decisions.

2.4.3 Linking Water Footprints to Specific Locations

Two articles note that, to understand the full impact of a production process on water resources in a particular context, it is important to **link water use to local water availability**, acknowledging the prevailing environmental and hydrological conditions. Harris et al. (2020) note that this is especially relevant in areas "*where water demand is growing and climate change threatens supply*", but they conclude that "*some studies are using water scarcity–weighted footprint metrics for this purpose, but such studies remain relatively rare*." "*Water use and water-related impacts should always be contextualized with local water availability and environmental sensitivity*", however this contextualization is not an integral part of the classical methodology for volumetric water footprint assessment (Launiainen et al., 2014). In many parts of the world, the lack of localized data hamper sound contextualization of water use (see Section 2.2.2).

2.4.4 Linkages with Other Tools and Approaches

Linking water footprints to other tools or approaches can help to paint a more complete and actionable picture of the water resources situation. Several of the reviewed papers highlight the opportunities associated with integrating water footprint assessments with broader concepts, e.g. from a **Water-Food-Energy (WFE) nexus perspective** (Bong et al., 2018; Deepa et al., 2021; Sun et al., 2022). The analysis could be extended to energy and carbon footprints, where a tradeoff is considered of the different indicators for the water, carbon and energy assessments (Deepa et al., 2021). Also, methods for investigating the social and economic effects of water footprints are expected to have added value, as water footprints are generated by social and economic activities (Deepa et al., 2021)..

Wang et al. (2021) state that "*there is a slowly growing recognition that **environmental flow** requirements, need to be considered in the evaluation of water quantity stress.*" Linking water footprint assessments with environmental flow requirements allows for better insights into water scarcity and water stress (Wang et al., 2021). They indicate that by correcting runoff for environmental flows, a more accurate measure of blue water availability can be obtained to put a calculated water footprint into perspective.

Better integration of **return flows** into grey water footprints holds opportunities for improved water footprint assessment in the future (Wang et al., 2021). Reuse of return flows can be quite sizeable, especially in irrigated agriculture, but is now often outside the system boundaries of grey water footprint assessments. Wang et al. (2021) are concerned that the beneficial impacts of enhanced wastewater technologies in reducing water footprints are therefore usually not adequately captured

2.5 Knowledge Gaps and Recommendations

The reviewed literature highlights several important knowledge gaps, often informing recommendations for future research and practices. This section emphasizes in particular the knowledge gaps and recommendations that are put forward by multiple authors.

There is an **unequally distributed number of water footprint applications across different sectors and supply chain stages**. In the context of agrifood products, Aivazidou et al. (2016) note a knowledge gap due to the fact that water footprint accounting is often not supply-chain oriented. Studies cited in their review are strongly biased towards the production and manufacturing stages of the supply chain. To truly support helpful insights and effective decisions, the authors recommend to incorporate the full cradle-to-grave perspective. Another observation is the fact that the application of water footprint theory is much more common in industry and agriculture than in the services sector (Sun et al., 2022). Harris et al., (2020) also note a geographic bias in water footprint literature, leading to limited case studies and evidence from low-income countries.

Related to the points raised in Section 2.4.3 of this report, several authors recommend to dedicate further research to improving and standardizing methods for placing water footprint assessments in perspective of **local water availability** (Harris et al., 2020; Launiainen et al., 2014; Le Roux et al., 2018; Liu et al., 2019). Especially the impact of water use on water pollution, through application of the grey water footprint, is often insufficiently addressed due to a lack of robust methodologies and/or issues with availability and quality of data (Deepa et al., 2021; Liu et al., 2019).

Future studies should explore **integrating water footprint assessments with broader concepts**, e.g. from a water-food-energy nexus perspective. The analysis could be extended to energy and carbon footprints, where a tradeoff is considered of the different indicators for the water, carbon and energy assessments (Deepa et al., 2021). Also, methods for investigating the social and economic effects of water footprints must be further developed, "as water footprints are generated by social and economic activities" (Zhuo et al., 2020). Their recommended next step is to distinguish between the *"green and blue water economic values"* to determine the associated economic effects.

Other recommendations for future research and practices include:

- The need for addressing the current lack of specific **water footprint benchmarks** based on best management practices. Water footprint benchmarks could be set at different levels (product, supply chains, region, river basin) to guide sustainable water use (Deepa et al., 2021; Mekonnen and Gerbens-Leenes, 2020). For industrial sectors, benchmarks can be set according to the optimal production techniques and supply chains (Liu et al., 2019).
- There is a lack of knowledge regarding the **temporal dimension** of water footprints. Bong et al. (2018) mention that "*the challenges in estimating water footprints include […] the understanding of temporal variations*". Future research should look to "*improve the performance of hydrological models during weather extremes*" (Deepa et al., 2021).
- Enhanced accuracy and usefulness of water footprint applications can be achieved by future efforts towards enhanced data availability at **higher spatial resolutions** and development of unified methods for **measuring uncertainties** associated with water footprint values (Harris et al., 2020; Zhuo et al., 2020).

In addition to these general notions, **sector-specific recommendations** also come forward from the literature review .To enhance water footprint assessment and resolve freshwater resource planning and operational problems in the **wine** sector, Aivazidou and Tsolakis (2020) recommend the introduction of advanced technologies, propelling the digitalization of wine supply chain. Future research should look into the economic valuation of the green water footprint of wine, and account for the inter-annual variability of the regional green and blue water footprints to improve the management of grapes' production, supply, and wine trade. Harris et al. (2020) recommend further water footprint research dedicated to **fruits, vegetables, and nuts**, as they are relatively poorly understood crops in terms of water footprint, but are of great importance as constituents of healthy diets globally. Strong recommendations for water footprint applications in the **forestry** sector are provided by Launiainen et al. (2014), based on previous volumetric water footprint applications. In addition to the need for better contextualization of water use with local availability and environmental sensitivity, they recommend future assessments to exclude water consumption of rainfed semi-natural forests from the water footprint, as there is no evidence of substantial differences in evapotranspiration between managed and unmanaged forests. More appropriate water use indicators should be developed that better reflect the environmental impacts and sustainability of forestry.

3 Conclusions and Recommendations

To summarize, the following conclusions and recommendations can be derived from the literature review presented in this report:

- The articles selected for this review are themselves review scientific papers. Therefore, many specific details about locations and studies are not comprehensively covered within the 15 selected articles. *Sections 2.1, 2.3*
- The common definition among the listed papers of a water footprint is “the total volume of freshwater consumed and polluted at various levels, including national, corporate, or product levels”. The volumetric water footprint is further broken down into three main components: *Green Water Footprint* (related to rainwater, *Blue Water Footprint*: (related to surface and groundwater) and *Grey Water Footprint* (water needed for assimilation of pollutants to achieve quality standards). *Section 2.2.1*
- The Water Footprint Assessment (WFA) and Life Cycle Assessment (LCA) methodologies are the most used frameworks, each serving different purposes. WFA focuses on water resource management, while LCA is product-oriented. *Section 2.2.2*
- There is significant variability in Water footprint assessment methods, complicating the inter-comparisons across studies. *Sections 2.2.2, 2.4.2*
- Assessing grey water footprints is particularly challenging due to difficulties in quantifying pollutants and integrating these into real water volumes. *Section 2.2.2*
- A major limitation in water footprint assessments is the lack of reliable, site-specific, and up-to-date data, which affects the accuracy and robustness of the results. *Section 2.2.2*
- Current water footprint assessments often lack consideration of the temporal dimension, such as seasonal and long-term climate variations, which could significantly impact water footprints. *Section 2.5*
- Defining system boundaries is crucial for accurate water footprint assessments, especially when aggregating data over a product’s life cycle or comparing methodologies. *Section 2.2.2*
- There is a geographic and sectoral bias in water footprint literature, with a stronger focus on high-income countries and the production and manufacturing stages of supply chains. The application of water footprint is more common in industry and agriculture, with limited application in the services sector, highlighting a need for further research in this area. *Section 2.5*
- Water footprints are strong in raising awareness among consumers, producers and policy makers about the environmental impacts of goods and services. Water footprints can be used to assess water usage under different future scenarios, helping policymakers in planning and implementing water footprint mitigation strategies. *Section 2.4.1*
- Water footprint analyses can support strategies for redistributing water resources through virtual water trade, potentially alleviating water scarcity in water-stressed regions. *Section 2.3*
- Despite their strengths, it should be noted that water footprints are the result of complex analyses and represent a complex reality, impeding their use as a product label directly informing customer decisions, or their ability to directly inform actionable insights to policy makers. *Section 2.4.1*
- There is a need for further research to link water use to local water availability, especially in regions where water demand is increasing, and climate change is a significant factor. *Sections 2.4.3, 2.5*
- Future research should explore integrating water footprint assessments with broader concepts, such as the water-food-energy nexus, to achieve a more holistic understanding of resource use. *Section 2.5*
- Different sectors, such as wine production and forestry, require tailored water footprint methodologies to address their unique challenges and opportunities for sustainable water use.

- Enhancing the accuracy of water footprint assessments requires better data availability at higher spatial resolutions and the development of unified methods to measure uncertainties associated with water footprint values. *Section 2.5*
- Setting water footprint benchmarks at various levels (product, supply chain, region, river basin) is recommended to guide sustainable water use and improve water management practices. *Section 2.5*