Environmental Science
Water Research & Technology

ROYAL SOCIETY OF CHEMISTRY

CRITICAL REVIEW

View Article Online
View Journal | View Issue

Open Access Article. Published on 16 1403. Downloaded on 07/11/1404 10:48:58 ..
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

Check for updates

Cite this: *Environ. Sci.: Water Res. Technol.*, 2025, **11**, 196

Assessing the environmental impact of freshwater use in LCA: established practices and current methods

Basit A. Mir,[ab] Anissa Nurdiawati[ab] and Sami G. Al-Ghamdi*[ab]

Received 31st July 2024,
Accepted 19th November 2024

DOI: 10.1039/d4ew00641k

rsc.li/es-water

Freshwater, an essential resource for survival, is becoming scarce because of overuse. A reliable and precise assessment approach is necessary to establish a sustainable water system for use in proper decision-making. This paper explores the range of approaches and methods developed over time to evaluate water consumption, considering factors related to scarcity, quality, and volume. These methods are primarily based on volumetric footprint, impact-oriented assessment, or a combination of both. The water footprinting standard defines water footprint as impact-oriented, where volumetric approach serves as an inventory in life cycle assessment (LCA), which is a widely used tool for evaluating the environmental impact of a product or a system throughout its lifetime. The work provides a thorough overview of more than forty different approaches, tools, databases, and water indices related to water use, water footprint and its environmental impact using life cycle assessment tool and compiled from more than sixty reviewed articles. Many approaches focus on availability and shortage while water quality is generally considered separately, with LCA employing specific indicators. To calculate the impact of scarce freshwater supply on the environment, methodologies are being developed to create a connection between water availability, use and impacts. This is accomplished by employing various characterization models that use environmental mechanisms to convert volumetric input flows into impacts. Some models use cause-and-effect chain relationships to evaluate the effects of water scarcity on ecosystems, human health, and natural resources. Water indices, usually focusing on scarcity or quantity, are used as characterization factors in some models. The paper also presents the most recent approaches to water use assessment that emerged from a consensus between the LCA and water scientific groups. Despite substantial progress, challenges are still present within the sector. Continuous improvement is essential for improving current methods. Enhancing environmental mechanisms, measuring uncertainty, resolving temporal and spatial disparities, undertaking regional evaluations, and improving primary or local data are some of the challenges. This study directs future research toward more efficient and comprehensive water use impact assessment techniques by outlining important areas for improvement.

Water impact

Excessive water use causes scarcity, impacting human health, ecosystems, and resources. Several approaches have been developed to assess water-use impacts on the environment within the life cycle assessment methodology. Each model uses specific mechanisms to determine environmental impacts. This review critically evaluates these models, approaches, tools, scope, and applicability, and recommends the most suitable approach, hence facilitating reliable water use impact assessment.

1. Introduction and background

Water is a critical resource on the planet, yet current trends in its usage, fueled by population growth, climate change, and economic development, are heightening the risk of water insecurity.[1–6] As per the UN water report 2023,[3] water use has been increasing at the rate of 1% per year globally and is expected to grow further at the same pace until 2050. Moreover, the effects of climate change have altered the

[a] *Environmental Science and Engineering Program, Biological and Environmental Science and Engineering Division, King Abdullah University of Science and Technology (KAUST), Thuwal 23955-6900, Saudi Arabia. E-mail: sami.alghamdi@kaust.edu.sa*
[b] *KAUST Climate and Livability Initiative, King Abdullah University of Science and Technology (KAUST), Thuwal 23955-6900, Saudi Arabia*

 This journal is © The Royal Society of Chemistry 2025

Open Access Article. Published on 16 1403. Downloaded on 07/11/1404 10:48:58 .. This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

global water cycle, resulting in irregular precipitation trends and thereby causing water scarcity.[7] On the other hand, coupling the freshwater pollution with water stress across regions has resulted in the endemic water scarcity.[8] There is a dire need for a sustainable water system which could prevent further escalation of overexploitation of the resource.

The significance of water becomes apparent as it is virtually integrated in every product of our daily use such as the production of food and energy, socioeconomic growth and sustainable development. The concept of 'virtual water' signifies the water that is 'hidden' or 'embedded' within a product, encompassing both the water directly used in production and that polluted throughout the supply chain.[9,10] Given water's essential role, developing a more robust, reliable assessment method for water use is crucial for guiding decision-making in the water sector along with exploring the current existing methodologies for their applicability and further improvement. This is achieved through data analysis and method development, alongside the creation of indices to provide insights into water use and its impacts on human and environmental health.

Over time, a range of methods and indices have emerged to address water use and its environmental impacts, such as the water footprint (WF), which measures the volume and type of water required for a product or process.[11–14] For instance, the WF of a product is defined as the volume of fresh water used in realizing a product. Both virtual water and water footprint are used interchangeably; however, the latter is a broader term which not only refers to the volume (of water) but also the type of water used.[15–17] Moreover, researchers have developed numerous indicators used in existing methods while at the same time, indicators use variable approaches including water use, consumption, demand, and availability.

As the use of freshwater can generate potential impacts to humans, the ecosystems, and resources, various methods have been developed to evaluate freshwater use in life cycle assessment (LCA). LCA is a widely accepted tool that makes quantifiable measurements of the environmental impacts associated with the product (or system) for the whole of its life cycle, for instance, from cradle to grave, which involves the acquisition of raw material, manufacturing, use, and disposal.[18] LCA is a holistic approach that is used to improve decision-making for enhancing environmental management[19,20] and considered as the best framework for evaluating a product's possible environmental implications.[21–25] Many developed water indicators have been used to facilitate water use impact calculations in LCA. Over time, numerous methods have emerged to address water use assessment within LCA, evaluating environmental impacts by converting water use quantities into specific impact metrics.[26]

Over the years, LCA has increasingly addressed the environmental impact of water use.[27–35] Studies[26,36–38] have reviewed methods and pathways for estimating and evaluating these impacts. Early reviews, such as the work of Berger and Finkbeiner (2010),[26] provided an overview of water accounting and impact assessment methods, recommending approaches for integrating water use into LCA. Later, Kounina *et al.*[38] explored water use in life cycle inventory and impact assessment, detailing pathways to mid- and endpoint levels, while offering recommendations for inventory databases and water indices. In 2016, Berger *et al.*[36] further examined water footprinting methods, databases, and tools, identifying critical methodological challenges and future directions in addition to providing insights about practical applications of various methods. An article by Gerbens-Leenes *et al.*[35] highlighted the scientific disputes, common challenges, and areas of agreement and disagreement between the WF and LCA communities. It called for more methodological contributions, reviews, and case studies to illustrate the complementary strengths of both approaches. While water has become an increasingly prominent focus within LCA research, methods continue to advance and evolve to better address its complexities and impacts. Since the 2016 review, however, literature on newer recommended methods has been limited. Our work aims to bridge this gap, updating the field with recent advancements.

This paper aims to compile and review existing methods for evaluating water use impacts in LCA. Unlike previous reviews, it includes newly developed methods not covered before, offering an updated perspective. It summarizes widely used assessment methods and discusses recommended approaches developed in the past decade, contributing to water research and LCA. The review discusses the most accepted current method and its limitations, exploring the relationship between water use and its impact on various areas of protection like human health, ecosystems, and natural resources. It also touches on indicators of water use, scarcity, and quality, and their applications in environmental modeling. Lastly, it outlines improvements, gaps, method applicability, and potential future work in this field.

This review paper is structured into several sections. Section 1 highlights the importance of water, the issues of overuse, and the need for sustainable water systems and assessment measures. Section 2 presents the methodology employed for searching research articles through databases with related keywords. Section 3 covers approaches to addressing the water footprint, including volumetric and impact-oriented methods and includes ISO guidance. It also briefly mentions water indicators and ratios developed over time. Section 4 outlines widely used methods for water use assessment, categorized by their focus on volumetric or impact-oriented approaches and issues such as water accounting and impact assessment. Section 5 discusses the current evaluation methodology for water use impact assessment, addressing its limitations, challenges, and potential improvements. Finally, section 6 concludes the paper.

2. Methodology

The articles and reports included in this review were collected using a systematic search strategy. Relevant

Open Access Article. Published on 16 1403. Downloaded on 07/11/1404 10:48:58 .. This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

literature was identified through comprehensive searches conducted in academic databases such as Web of Science and Scopus, apart from supplementary search conducted using Google Scholar. The search was performed using keywords and search terms related to the topic of freshwater use and its impact from the perspective of LCA utilizing a combination of keywords. Boolean operators (AND, OR) were employed to narrow down the search and pinpoint pertinent publications. The combination was ("water use" OR "water consumption" OR "water footprint" OR "freshwater use" OR "freshwater consumption") AND ("life cycle analysis" OR "life cycle assessment" OR "LCA" OR "environmental impact" OR "impact assessment" OR "LCIA") for the years of publication 2009 to 2024 in the English language limited to open access. A total of 1666 articles were initially retrieved and screened for relevance, with approximately 60 articles identified as directly relevant to our topic. Many of the initially identified publications did not align with the specific focus of this study and were therefore excluded from further consideration. In addition to the initial database searches, thorough manual searches were conducted on the reference lists of relevant articles. This approach ensured a comprehensive review that encompassed not only LCA studies but also research on topics such as water scarcity, water consumption, and water indices. These additional sources were primarily sourced from the references cited in highly relevant studies, enhancing the depth and breadth of the literature review. Further searches on Google Scholar, along with a snowballing approach, expanded the article count. Keywords extracted through snowballing techniques were rechecked to identify any recent publications that could contribute further relevance to the study. The final selection of publications for analysis was based on their relevance and contribution to the research objectives, encompassing a diverse range of sources including journals, abstracts, conference papers, reports, and key references identified during the literature review process.

This study acknowledges the importance of water indicators for understanding volume, quality, pollution, and related issues, thereby constituting an integral part of comprehensive water management strategies. However, the main focus of the study lies in exploring the impacts of water use on the environment *i.e.*, ecosystems, human health, and resources. Therefore, instead of a detailed discussion and elaboration of various water indicators, we only focus and briefly discuss the commonly used water indicators. Our research will focus exclusively on the methodological aspect of evaluating the effects arising from water use and consumption within the framework of LCA, not on discussing the water indicators critically.

3. Approaches for assessing water use

Different methodologies evolved over time to evaluate water use; the two approaches of the water footprint network[39,40] and LCA community were set up to address it. The WF and LCA communities have been engaged in an ongoing methodological discussion, primarily centered over the issue of considering the WF either as an impact-based or as a volumetric indicator. While the WF community favors volumetric indicator, they assert this resource is not confined to local scale but also to global boundary because it is essentially "traded" globally through commerce and businesses, while the LCA community asserted that volume-based footprints "may have the potential to misinform" and emphasized the need for an impact assessment stage, additionally required by the ISO water footprinting standard. The two approaches and the ISO standard are described below.[41,42] The terminology encompassing "evaluate water use", "water use assessment", "water use impact", "water footprint assessment", or "assess water use" is frequently employed interchangeably within the scholarly discourse. These terms collectively address either a volumetric analysis or an impact-oriented perspective, suggesting their applicability in evaluating various facets including considerations of water scarcity, volume quantification, water quality, and estimations of environmental impacts. However, in this paper, the term "water assessment" pertains specifically to tools used for water accounting.

3.1. Volumetric WF approach

The water community introduced the volumetric water footprint (WF) as a measure to evaluate freshwater use. The term WF, as per the water community, includes the volume of water used throughout the supply chain. Both the water volumes by source and quantities of polluted water with pollution type specified per location and in time are considered, thus, making it a multidimensional indicator.[15,43] The indicator inspects both the indirect and the direct water use by producer or consumer and includes all three components of WF (blue, green and grey), hence differentiating WF from the classical measurement 'water withdrawal' or generally understood as water use. The blue water footprint accounts for surface and groundwater used in activities like irrigation and industrial processes. The green water footprint includes rainwater stored in soil and used by plants, especially in agriculture. The grey water footprint estimates the amount of freshwater required to dilute pollutants, reflecting the impact of water pollution.[13] WF is a measure of consumptive and degradative freshwater. Note that water use (total water withdrawn from sources) is different from water consumption (or consumptive use). Consumptive use is the used freshwater which is not reverted to the same watershed from where it was abstracted due to reasons of evaporation or product integration, or maybe evapotranspiration or release into a different watershed. The consumptive WF included the green and blue component, the where the former refers to consumption of rainfall and latter to consumption from surface or groundwater.[15]

Open Access Article. Published on 16 1403. Downloaded on 07/11/1404 10:48:58 ..
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

In contrast, degradative freshwater use is identified by abstraction and release of freshwater, although with altered quality, into the same watershed. Grey WF, another name for the degradative WF, is the quantity of water needed to assimilate a pollutant load.[10,15,26]

3.2. Impact-oriented WF approach

The impact-oriented approach developed by the LCA community uses LCA methodology to analyze the potential repercussions of water use. LCA attempts to evaluate the regional impacts as well as quantities of water used along the life cycle of a product or system. This means combining the volumetric WF with the life cycle impact assessment (LCIA) models, converting the impacts of water volumes consumed and polluted on human health, ecosystems, and natural resources, hence focusing on both phases, *i.e.*, the accounting (inventory) and the regionalized impact assessment phase.[30] LCA evaluates the material and energy consumed along with the impact (such as emissions) associated with the system over its whole life.

Previously, the attention was focused on the pollution or quality degradation of the freshwater resources by means of toxicity, eutrophication and acidification only, but now methods are developed to consider the potential impacts of depriving humans and ecosystems of water in addition to causing pollution.[36]

LCA methodology consist of four steps: goal and scope, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation of results.[19,20,44] The data are compiled first, then characterized, and finally grouped into various impact categories such as climate change, acidification, eutrophication, abiotic depletion, and many others.[21]

The updated LCIA framework comprises characterization models that connect the LCI results to 17 midpoint impact categories and through damage pathways to end point level reflecting different areas of protection (AoPs), *viz.* human health, ecosystem quality, and natural resources, as can be seen from Fig. 1, adapted from ReCiPe 2016. ReCiPe 2016 is an LCIA method offering an advanced approach to translate life cycle inventories into a select set of impact scores at both midpoint and end point levels.[45] These characterization models generate characterization factors (CF), which serve as weighting metrics to consolidate life cycle emissions into comprehensive scores for assessing impacts on human health and ecosystem well-being.[23,24,39] The distinction between the two levels is that end point uses indicators for assessing AoPs while midpoint lies in between the emission and end point. The environmental impact modeling relies on the cause–effect relationship which links a particular flow to a potential environmental effect.[18] End point has a high environmental relevance compared to midpoint; however, the level of uncertainty is high. The two levels complement each other: midpoint characterization is more directly linked to environmental flows and generally has lower parameter uncertainty, while end point characterization is easier to interpret regarding the significance of these environmental flows. The pathways for the water use have been highlighted in Fig. 1, showcasing the damage pathways associated with water use.

The deprivation of the freshwater resource of specified quality can also affect the ecosystem by changing the biodiversity. The effects on the ecosystem quality are expressed in terms of potentially disappeared fraction (PDF) of species over a given surface (or volume) per cubic meter during a stated time frame.[46,47]

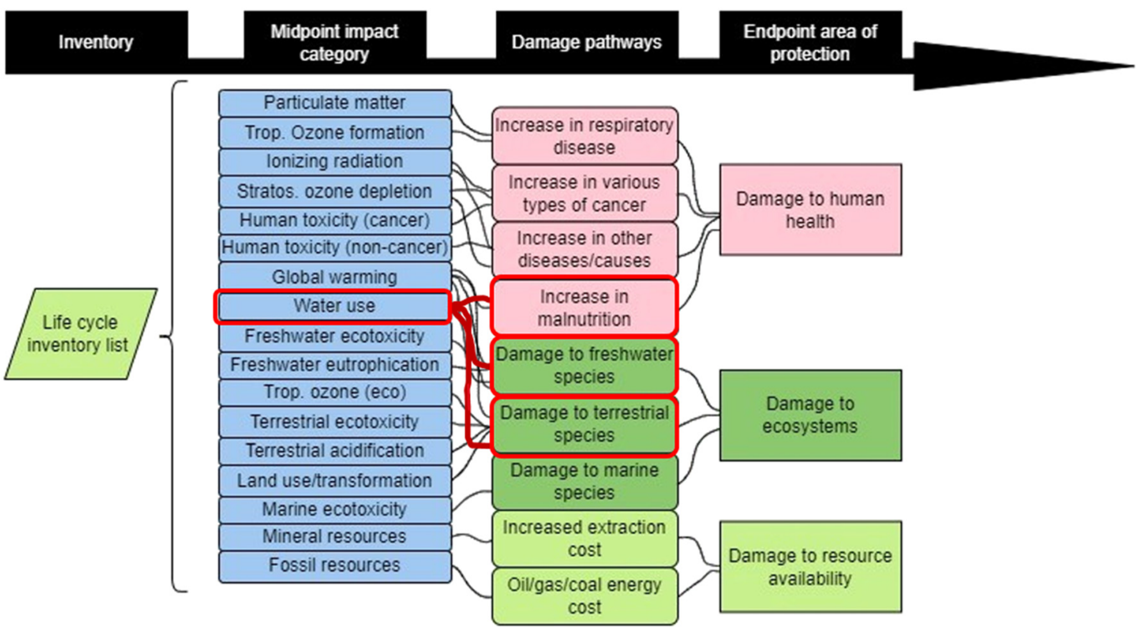

Fig. 1 Structure depicting relationship between life cycle inventory, midpoint and end point in ReCiPe 2016 adapted from Huijbregts *et al.*[45]

Open Access Article. Published on 16 1403. Downloaded on 07/11/1404 10:48:58 ..
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

3.3. ISO guidance

Due to a growing consensus that WF, besides estimating volumes, should also gauge impacts, an international standard on WF was established in 2014 named ISO 14046 (2014)[48] which is based on LCA. It aims at "providing transparency, consistency, and credibility for assessing water footprint and reporting water footprint results of products, processes or organizations". It includes principles, guidelines, and requirements regarding water footprinting. The standard undoubtedly declares that water footprint is an impact-based measure and should comprehensively comprise water availability and water pollution aspects. In line with LCA methodology,[19,20] the WF standard consists of goal and scope, water footprint inventory, water footprint impact assessment, and lastly, interpretation of results. In contrast to water footprint defined by Hoekstra, volumetric water consumption can be reported as water inventory but not termed as water footprint.[15,16,35,49] In a recent publication, the consensus on building water use assessment from FAO livestock environmental assessment and performance (LEAP) partnership recommends using at least two methods for assessment: AWARE and blue water scarcity index.[50]

3.4. Water indices and ratios

The globally emerging water stress and scarcity led to development of various water scarcity indicators and ratios defining them. Including all the indicators in the study would lengthen it and divert our attention from the main study objective; hence some commonly used indicators and ratios defining them are discussed critically. The water resource vulnerability index, or withdrawal-to-availability (WTA) ratio, measures the water scarcity by dividing total annual water intake by total water resources available. It has been applied in many contexts and a greater number of available water scarcity studies use the WTA ratio.[14,51,52] Fig. 2 shows the ratios that have evolved over time with broader scope. Raskin *et al.*[53] introduced the use-to-resource ratio which is explicated as the ratio of water use (withdrawals) to water resources (renewable). These ratios consider only the blue water (BW) withdrawal or consumption. Similarly, SDG indicator 6.4.2,[54] a blue water stress indicator, evaluates the level of water stress by relating water use to availability. Vanham *et al.*[54] suggest possible improvements within the indicator to enhance its effectiveness and relevance in assessing water scarcity.

For a better representation of physical stress of water resource, the consumption-to-availability (CTA) ratio is reliable over the WTA. To tackle the limitations of the WTA ratio, CTA is used.[42,58] CTA is seen as a better ratio for assessing blue water scarcity than WTA.[15] It is argued that using blue water consumption over water withdrawal is more reasonable to assess blue water stress.[13] CTA is employed to measure the blue water scarcity as a ratio of blue water consumption to availability.[13,15] As water use can be interpreted as either water withdrawal or consumption, the work of Munia *et al.*[59] uses withdrawal and consumption as the maximum and minimum levels of water scarcity, respectively.[14,52,60]

An expert discussion within water use in the LCA (WULCA) group recognized the necessity to transit from WTA and CTA to demand-to-availability (DTA) ratio.[34,55] The potential of depriving humans of water use could be understood from WTA or CTA ratios; however, the potential deprivation for another user (either human or ecosystem) is obtained using the DTA ratio which includes both human and ecosystem demands with respect to availability. Still, there were limitations in the DTA in the quantification of the ecosystem demand and the inability to express the absolute water availability, which resulted in loss of information (similar to CTA and WTA).[55] To overcome the limitations, three proposals were put forth: DTA_A, DTAx, and 1/AMD, where the last one is the ratio of availability minus demand (AMD). DTA_A combines the information on arid areas and puts them

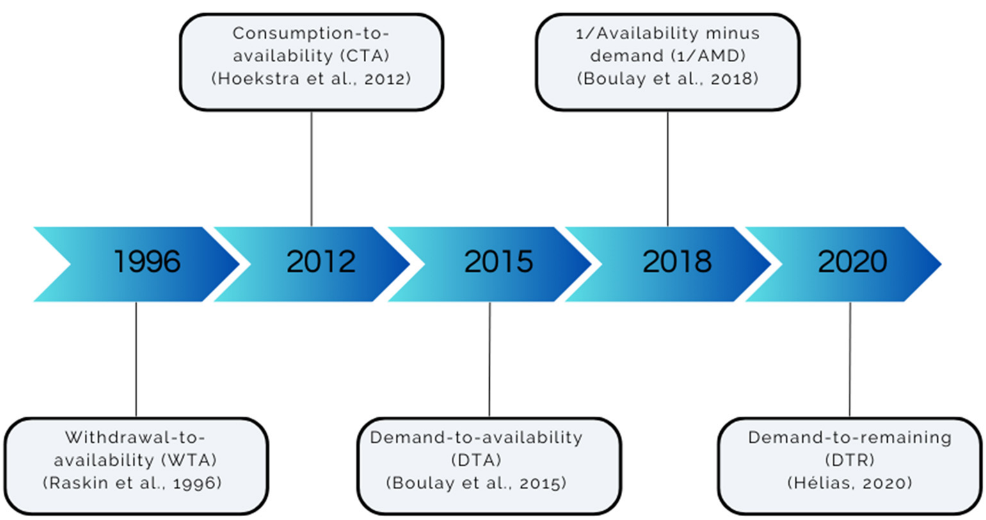

Fig. 2 Evolution of ratios.[32,34,53,55–57]

Open Access Article. Published on 16 1403. Downloaded on 07/11/1404 10:48:58 ..
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

in the DTA indicator; it is based on the DTA ratio with a modification for the arid regions. It was excluded due to its preselection criterion, which applied a maximum value to arid regions with high evapotranspiration. This approach effectively transformed the model into an aridity index, limiting its relevance to water consumption assessment according to expert consensus. DTAx uses a combination of relative availability (DTA) and the absolute availability (AAv) per unit surface, combined using multiplication function, although this approach lacks clear justification, as it imposes an equal weighting on two distinct factors, which may not accurately reflect their real-world impact on deprivation. As a consequence, only the last proposed indicator, 1/AMD, the inverse of availability minus demand, was accepted by the workshop panel. Availability refers to the natural runoff in a region, while demand includes both human and ecosystem water needs. 1/AMD is easy to justify and carries a physical meaning with simple units, hence was recommended by the consensus.[34,55] The limitations and the validity of 1/AMD in characterization methods led to the subsequent improvement of the indicator. A new alternate way suggested by Hélias[56] is the demand-to-remaining (DTR) ratio, which is the ratio of the ecosystem demand to the remaining water after human activities or available water after human appropriation. The DTR model is aligned with the AWARE model features and can guarantee similar outcome behavior to the AWARE model (in terms of CF value) and covers all situations.[56]

The indicators developed recognize the relationship between the water use and freshwater resources, thereby assessing the situation of water scarcity across the globe.[15,61] The terms index, indices, and indicators are used interchangeably throughout the literature and studies. These are defined as the instruments used for summarization of datasets into a simpler and 'easy to understand' form.[62] In addition to these indicators, there is a standard scarcity-based midpoint indicator for assessing impact of water use, which showed up from the LCA community.[55,61] However, the recent investigation by Vanham[63] shows that the scarcity-weighted WF gives an inaccurate water sustainability assessment and suggested using the water stress and water efficiency indicators separately. Another investigation by Vanham[64] criticizes the PEF methodology in sustainable food labelling as it highlights two major flaws in the water scarcity category in the PEF which are (i) not accounting for water efficiency and (ii) spatial resolution too coarse for water stress. This could lead to worsening of the water scarcity globally as well as miscommunicate the results using the labelling system.[64] Therefore, there is a necessity to gain a deeper understanding and identify the most precise method for calculating water scarcity, utilizing it as an indicator to measure the achievement of SDG target 6.4.

Water indices communicate the measurement of human and environmental water requirement (EWR) or the measure of the fraction of available resources to fulfill these requirements. Although they are non-LCA-based indicators, some of them can be used as characterization factors (CFs) in the impact assessment methods either at the midpoint level or at the end point level. The indices, besides water scarcity, may also include water quality aspect.[38,58] But the majority of the indicators in the literature focused solely on one aspect, *i.e.*, water scarcity, and more than 150 indicators have been developed for its estimation. We discuss only the most commonly used in this review.[14,52,65]

The evolution of the indicators along with different aspects are included in Table 1. Various criteria are included to give clarification about these indicators which focus on both green water and blue water. The water use by various sectors is also summarized. The widely used and easily applicable indicator by Falkenmark *et al.*[66] can provide the water scarcity at national scale; however, it considers only the water supply side, excluding the critical drivers of economic growth. It does not reflect the real demand spatially and overlooks the temporal variability. Meanwhile, the basic human needs index has a narrow scope as it includes only the water used for basic human needs like drinking, cooking, and hygiene while ignoring industrial, agricultural, and environmental water needs. Additionally, it truncates the regional variations and water quality.[67]

Rockström *et al.*[69] introduced the first indicator to evaluate water scarcity by incorporating both blue and green water resources. Gerten *et al.*[70] enhanced this model by accounting for regional water requirements to maintain a healthy diet, thus addressing spatial differences in water required for food production across areas. However, assessing water scarcity with green water remains inconsistent. Blue water is often calculated as total runoff, neglecting accessibility, while green water is gauged by evapotranspiration on croplands, undervaluing its total amount since a large portion of evapotranspiration happens on non-croplands. Moreover, EWR was set at 30%, assuming the high-flow season, while the fair condition EWR for freshwater ecosystems ranges between 30% and 60% of pristine flow, depending on seasonal variations (with allocations of 60%, 45%, and 30% for low, intermediate, and high flow seasons, respectively).[35]

Many indicators are based on the criticality ratio, or water use (consumption or withdrawal) to the water availability ratio. It is observed that all of them consider blue water while neglecting green water except the one by Berger *et al.*[42] Also, they do not include the quality aspect except the one by Van Vliet *et al.*[73] Adaptive capacity, recycling, desalination, and the reuse of extracted water are only a few of the technological and societal measures that the criticality ratio ignores, despite its response to fluctuations in demand. Additionally, the national storage capacity is underestimated with water scarcity thresholds being inconsistent.[84] The WF index by Hoekstra *et al.*[15] considers both green water and blue water, but not including quality aspect. However, EWR is estimated at 80% of total water resources across river basins, a level seen as overly simplistic and likely overestimated. This general assumption fails to account for

Open Access Article. Published on 16 1403. Downloaded on 07/11/1404 10:48:58 .. This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

Table 1 List of indicators addressing water-use issues

Indicator name	Water quality	Water availability	Use sectors	Blue water (BW)	Green water (GW)	EWR	Remarks
			Based on per capita water availability				
Falkenmark indicator (1989)[66]	No	Runoff	H	Yes	No	No	Measures water scarcity based on *per capita* water availability per year, comparing regional water availability to population, and assessing it against Falkenmark's threshold
Social water stress indicator (2000)[68]	No	Not stated	H[a]	Yes	No	No	Introduces the society's adaptive capacity in the Falkenmark's indicator. Based on *per capita* water availability and human development index, hence assessing the ability of society to adapt to water stress
Basic human needs index (1996)[67]	No	Not stated	H[b]	Yes	No	No	Assesses the water required to satisfy the basic human needs such as drinking, cooking, and hygiene. The thresholds for basic needs are expressed in *per capita* water availability per day
Green-blue scarcity indicator (2009; 2011)[69,70]	No	Blue and green water sources	A, D, I	Yes	Yes	Yes	Combines both green and blue water, comparing local availability to a global average (1300 m^3 *per capita* per day) needed to produce 3000 kilocalories *per capita* per day of food, identifying areas as water-scarce if they fall below this threshold
			Based on the WTA				
Water stress index by Pfister (2009)[27]	Yes	Renewable freshwater (FW) sources	A, D, I	Yes	No	No	The modification of the WTA ratio by introducing a logistic function to be used as a CF for environmental assessment. Variation factor is used which considers climatic variability and results in a continuous value between 0 and 1
Water stress indicator by Smakhtin (2004)[71]	No	Mean annual runoff	A, D, I	Yes	No	Yes	Considers the EWR of a region and human demand. A certain amount of water is reserved for the environmental use out of the total available surface water. Range given for the WSI to address the level of stress
Water stress index by Vörösmarty (2005)[72]	No	Stream water flow: runoff	A, D, I	Yes	No	No	Ratio of the sum of domestic, industrial and agricultural water withdrawals to the river corridor discharge. If withdrawals cross 10% of discharge, it is assumed that the water stress begins. The classification of water stress index values gives the level of stress
Water scarcity and quality index (2017)[73]	Yes	FW sources	A, D, I	Yes	No	Yes	The ratio of sectoral water withdrawals meeting acceptable quality to total water availability, also factoring in additional withdrawals needed to attain acceptable quality through dilution for each sector
SDG indicator 6.4.2 (2018)[54]	No	Renewable FW sources	All activities	Yes	No	Yes	Level of water stress in a region by computing the ratio of freshwater withdrawals to available freshwater resources (where EWRs are already subtracted). Low level of WS signifies less impact and *vice versa*
Water exploitation index+ (2020)[74]	No	Renewable FW sources	A, D, other	Yes	No	Yes	Includes the possible return flows in addition to freshwater abstraction. It is defined as the ratio of withdrawals minus returns to renewable water resources from where EWR is already subtracted
			Based on CTA				
Blue water sustainability index (2014)[75]	No	Consumptive BW use	A, D, I	Yes	No	Yes	Calculated as a ratio of the sum of non-renewable groundwater and surface water over-abstraction to the consumptive BW use which includes agricultural, industrial and domestic water consumption
Water depletion index (2014)[42]	No	Renewable FW sources	A, D, I[c]	Yes	Yes	No	Indicates the risk of freshwater depletion in an area, considering physical BW scarcity of drainage basins. Includes both surface and groundwater flows
			Based on water footprint				
Blue water scarcity index (2011)[15]	No	FW sources	A, D, I	Yes	No	Yes	Ratio of BW footprint to the available BW resource, where the latter is available natural runoff minus EWR within the river basin. The indicator values of 1 and 2 indicate low and high water stress areas, respectively
Green water scarcity index (2011)[15]	No	GW sources	A	No	Yes	Yes	Ratio of GW footprint to the available GW resource, where the latter is calculated by taking the total evapotranspiration (ET) within a catchment and subtracting the ET reserved for natural vegetation and unproductive ET in crop production
Water debt repayment time indicator (2019)[76]	No	Renewable FW sources	A	Yes	Yes	No	Ratio of the annual water footprint for each source, crop, and location in a 5′ × 5′ cell compared to the average renewable water volume available annually in that cell

Open Access Article. Published on 16 1403. Downloaded on 07/11/1404 10:48:58 .
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

Table 1 *(continued)*

Indicator name	Water quality	Water availability	Use sectors	Blue water (BW)	Green water (GW)	EWR	Remarks
				Composite indices			
Water poverty index (2003)[77,78]	No	FW sources	A, D, I	Yes	No	Yes	Assesses water availability's links to poverty reduction, emphasizing ease of assessment. The water poverty index is primarily intended to evaluate the circumstances around poor water resources and limited ability to adjust
IWMI indicator (1998)[79]	No	FW sources	H	Yes	No	No	It integrates physical and economic water scarcities, assessing a nation's water supply from renewable freshwater for human use and existing water management infrastructure. It considers the country's individual potential to develop water infrastructure and improve irrigational water use efficiencies
Water impact index (2014)[80]	Yes	FW sources	H	Yes	No	No	Combines the issues of water scarcity, volume, and quality into a single indicator using life cycle thinking approach and evaluates volumetric flow per unit process and multiplies it with water quality index and water scarcity index
Water scarcity meter (2013)[81]	Yes	FW sources	A, D, I	Yes	No	No	It communicates water scarcity effectively through a water scarcity meter, considering both quantity and quality. Calculated as the sum of BW scarcity index and grey water scarcity index
QQE water scarcity indicator (2016)[82]	Yes	FW sources	A, D, I	Yes	No	Yes	Estimates water scarcity by considering water quality, water quantity and EWR. This includes considering blue and grey WFs for quantity and quality, respectively. along with total BW availability to achieve the overall water scarcity index
Agricultural water scarcity index (2022)[83]	No	Blue and green water sources	A	Yes	Yes	Yes	The ratio of crop water demand under no water limitations to the combined availability of GW for crop evapotranspiration and BW after accounting for EWR and water needs from other sectors
				Based on 1/AMD			
AWARE index (2018)[34]	No	FW sources	A, D, I[d]	Yes	No	Yes	Water scarcity footprint is the product of water consumption and AWARE CF obtained by the inverse of AMD. It aims at accessing the potential deprivation of water for other users (human or ecosystem)
				Based on DTR			
Water impact by Hélias (2020)[56]	No	FW sources	H	Yes	No	Yes	The DTR (demand-to-remaining) ratio when multiplied by the area gives us the water impact expressed in m^2. Average and marginal CFs divide impact by overall human intervention and use the partial derivative of the impact-inventory flow correlation, respectively

A: agriculture; D: domestic; I: industrial. H: human needs or human water requirements (not specifically mentioning the sector). [a] Not clearly mentioned; however, uses the widely used water scarcity index for computing which considers human water requirement. [b] Only considers human basic needs. [c] WaterGAP2 model includes A, D, I. [d] Also mentions livestock and energy production, which are accounted for in agricultural and industrial sectors, respectively.

the diverse needs and complexity of individual river systems as studies indicate that suitable EWR levels vary significantly across different river regimes.[69] Additionally, the data requirements of the WF approach are high but the availability is low, thereby posing a significant challenge.[14,84] Tuninetti's[76] water debt indicator provides an equitable evaluation of crop production sustainability, but it accounts only for a portion of agricultural production. Future research on sustainability must consider different crops as well as other water-consuming sectors.[76]

Composite indices attempted to integrate the components like green water, blue water, and quality. The international water management institute (IWMI)[79] and poverty index are comprehensive but are complex in their applicability for large regions because of data requirement, factors affecting tedious calculations.[14] The water impact index is calculated based on the most critical pollutant without accounting for the other pollutants in the water flow, hence not capturing the entire environmental impact. Additionally, it does not consider the background pollution data of water bodies, nor differentiating between the water sources.[80] The QQE water scarcity indicator, which stands for quantity–quality–environmental flow requirement, and the water scarcity meter simply calculate the water scarcity but need in-depth knowledge for interpretation of results.[81,82] The agricultural water scarcity index proposed the combination of blue water, green water, and the EWR for the agricultural sector, but it faces uncertainties in the data acquisition and the evaluation of results as water demand may be altered by various factors such as soil quality, varying EWR or nutrient content.[83] Water

Open Access Article. Published on 16 1403. Downloaded on 07/11/1404 10:48:58 .. This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

scarcity can be reduced by improving water quality through better wastewater treatment, reducing pollutants, and increasing water reuse. Comprehensive water scarcity assessments should consider water quality and the cost-effectiveness of adaptation policies.[73]

Most indicators focus on blue water, overlooking green water, although many scholars advocate for including green water in evaluations.[85] A recent guidance from *The Lancet*[86] recommends presenting both blue and green water components separately. However, blue water data are more readily available than green water data, hence takes precedence. Additionally, grey water should be categorized under pollution rather than water consumption.[86] Since green water greatly impacts water scarcity assessments, it must be accurately measured. One of the main challenges that still exists today is effectively combining blue and green water into assessments of water scarcity.[83] Using the green water footprint approach, Schyns *et al.*[87] investigated the issue of green water scarcity and concluded that increasing green water scarcity would be significantly harmful for natural ecosystems. Schyns *et al.*[88] conducted an analysis of 80 distinct green water indicators and explored their significance for effective assessments. Meanwhile, Hussain *et al.*[89] propose a holistic strategy for a thorough assessment of water scarcity. Twelve indicators are examined for their sensitivity to a range of factors in a recent literature review by Hussain *et al.*[84] These factors include blue and green waters, water scarcity caused by quality, environmental flows, data needs, spatial scale, and adaptive capacity. It is crucial to recognize that no single indicator is suitable for all situations or meets all criteria. A variety of water indicators, based on different aspects, criteria, or classifications, should be considered along with expert judgment in determining their applicability.[84]

The study by Vanham *et al.*[54] offers numerous recommendations for the popular water SDG indicator 6.4.2. These include basing the water scarcity indicator on both net and gross water abstraction, incorporating environmental water requirements for individual catchments, and providing annual and monthly estimates, among other suggestions. For further details, please refer to the study by Vanham *et al.*,[54] while other studies[13,14,49,52,84,88–90] critically analyze these indicators and should be consulted for detailed information.

4. Existing methods for assessing water use impact

This section includes the range of methods that emerged over time for accounting and impact assessment of water use. Different methodologies have different scopes in addressing the water management issues of scarcity, pollution, and quality impacts on humans and ecosystems.[26,38,43] They are based on either of the two approaches of water management and are presented collectively. The methods included in this review will only include the consumptive water use and not consider the degradative water use. The effects of degradative water use such as eutrophication, acidification, ecotoxicity or others are not included in this review and LCA proposes different indicators to address the water pollution issues. The inventory level and the impact level assessment are reflected in these methods with a potential to be used in development of new characterization models for LCA. The methods are categorized according to various criteria as shown in Fig. 3 and explained in the following sections. Water inventory methods focus on quantifying water use, providing estimates of the total water consumed in any activity without addressing environmental impacts. In contrast, water impact assessment utilizes inventory data to evaluate impacts through specific characterization methods. Resource consumption methods tailored for water are designed to address water resource use, while impact assessment methods are grouped according to whether they assess impacts at midpoint or endpoint levels. Additional methods that incorporate parameters like water quality, efficiency, and scarcity are classified separately to simplify differentiation. This classification is intended solely to simplify understanding of the methods and does not reflect a strict literature-based structure, allowing for an accessible overview of the different approaches and their respective focuses. Following a concise description of these techniques, specific limitations are also covered.[30,35,91,92]

4.1. Stand-alone methods

Based on the volumetric WF approach, it encompasses methods such as virtual water[10] and water footprint, also called stand-alone methods as they present results on volumetric basis only with some regional consequences. Both the methods evaluate the water used throughout the products' or organizations' supply chains.[40] This involves both indirect and direct water uses along the supply chain.[15] The concept of water footprint and virtual water has already been explained in section 3.1. Various tools and databases are employed to simplify the estimation of volumetric water use. Databases such as WaterStat have been exclusively used for the stand-alone methods.[15,16]

4.2. Water accounting methods

Water accounting is very important in understanding the availability and utilization of water resources. Accounting methods provide results at the volumetric measurement level and serve as a base for any impact assessment pathway. The easiest way to determine the WF of a product or organization is to use its water inventory which means the subtraction of water output (effluents) from freshwater inputs. The detailed accounting of water use is facilitated by water inventory frameworks, databases and tools. This means setting up a water inventory requires backing from frameworks,[23,24,28,93,94] using LCA databases such as Gabi,[95] Ecoinvent,[96] Quantis,[97] FAOSTAT,[98] water footprint network or WaterStat database,

 This journal is © The Royal Society of Chemistry 2025

Open Access Article. Published on 16 1403. Downloaded on 07/11/1404 10:48:58 ..
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

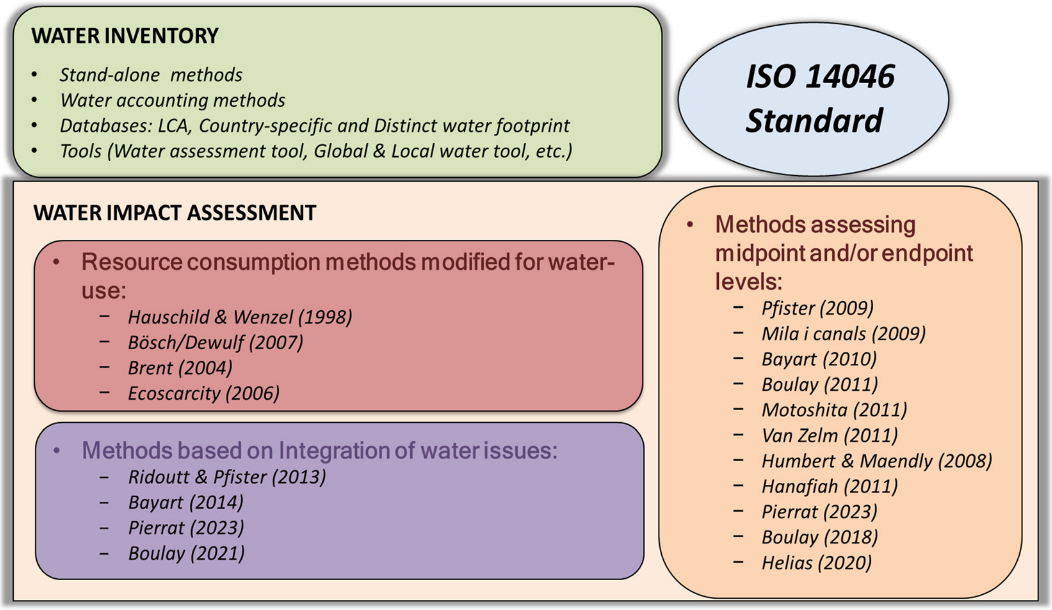

Fig. 3 Classification of water inventories and impact assessment methods obtained from the literature.

$$\text{Normalized water consumption} = \frac{(\text{Water consumption along lifespan})}{(\text{Product lifespan})(\text{Global annual } \textit{per capita} \text{ water availability in reference year})} \quad (1)$$

and employing tools like WBCSD Global and Local water tool, corporate water gauge or water assessment tool.[35,99]

The life cycle inventory (LCI) frameworks proposed above consider the information required for setting up a complete inventory as demanded by the new impact assessment methods. The databases identified for water inventory can be categorized into three groups: life cycle inventory databases (Gabi, Ecoinvent), country-specific databases,[91,98,100,101] and distinct WF databases (Quantis, WF network[40]). The information content of the inventory generated could vary significantly based on the tool, database or framework used.[36,38,102,103]

4.3. Resource consumption methods modified for water use

The modification of the methods points out to the general methods that have been specified or narrowed to water use. The generic methods used for estimating resource consumption in life cycle impact assessment (LCIA) are applied with regard to water use. A brief outline of some methods applied to water use is given below.

Environmental design of industrial product (EDIP) resources. The EDIP resources program includes various impact categories that help to assess the usage of resources (renewable and non-renewable). This helps establish a support to LCIA in LCA. Since the method estimates the consumption of resources, it can be utilized to evaluate water usage as well. The quantity of freshwater consumed along the life cycle of product is normalized as:

To account for water scarcity, the ratio of normalized consumption to time span for which the resource remains available is chosen.[26,104]

Cumulative exergy demand (CExD) and cumulative exergy extraction from the natural environment (CEENE). CExD and CEENE are the proposed indicators in LCIA for resource consumption. The LCIA of water consumption could be estimated by means of exergy by multiplying the resource input (water input) with its exergy content of 50 MJ m^{-3} within a product system. This would indicate the exergy excerpted from the natural environment or signify the price natural environment pays for our product system and society. This method cannot express the water resource depletion in a significant manner as it does not account for local water scarcity or takes into consideration the other implications of water use. Hence, water consumption is analyzed as a type of resource use within these methods.[26,105,106]

Ecological scarcity method. The method uses eco-factors for a variety of substances indicating their environmental impact. The estimation of environmental impact is simple; just multiply the elementary flows in the life cycle inventory with their corresponding eco-factors. This yields the results in eco-points which are combined to obtain a single score indicator for determining the total environmental impact of products studied.[107] Eco-factors are also calculated for the water use by this method. The input water flows are multiplied by their eco-factors to achieve the environmental impact of water use. Here the water use implies the total freshwater inputs into a product system unlike consumption which considers only the water lost due to either evaporation

Open Access Article. Published on 16 1403. Downloaded on 07/11/1404 10:48:58 ..
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

or product embedding. This raises concerns for a reliable assessment as water use does not reflect the actual situation rather than water consumption.[20,107,108]

LCIA method for South Africa. Brent[109] introduced an impact assessment method, which is specifically designed for regions or sites, in this case for South Africa. The method evaluates the use and pollution of resources like water, land, air and mined resources. Implementing this method for water use involves the aggregation of sub-resource groups, water quantity and water quality, within the main resource group 'water'. The aggregation of groundwater and surface water within the sub-resource group 'water quantity' is done simply without characterization, while the normalization of different impact categories such as eutrophication, acidification, and toxicity (human/eco) are performed to denote pollution of water within the sub-resource group 'water quality'. Normalization and weighting are specific (for South African regions) for realizing actual effects. This method also considers water use, not consumption.[26,109]

4.4. Methods assessing midpoint or end point level

A brief introduction to the two levels is given in section 3.2. under impact-oriented WF approach. Below are the different LCIA methods that exist for two levels. The modelling of the midpoint factors is based on robust modelling, while endpoint level is modelled with the best available route but with a high level of uncertainty.[18]

Freshwater consumption impact assessment by Pfister and colleagues. The method established by Pfister *et al.*[27] allows us to perform an exhaustive impact assessment of consuming freshwater at the midpoint and at endpoint levels which enables the damage assessment for all areas of protection (AoPs). Pfister *et al.*[101] also established a database which could facilitate and revise the data collection for performing regionalized LCAs. The water consumption (specific) and land use was calculated for 160 crops and crop groups, which covered most of the globally harvested cropland mass. The impact assessment method considers only the blue water consumption (consumption from ground and surface water) which pertains to the water that is temporarily absent from the hydrological systems.[27] Water stress index is proposed as the CF for the impact category 'water deprivation'. This should not be confused with WSI by Milà i Canals,[29] which is a water stress indicator. The water stress index developed by Pfister advances the concept of the WTA ratio by calculating modified WTA, denoted as WTA*, which is non-linear due to introduction of a variation factor. For calculating the water stress index, the global WaterGAP2 model which provided the WTA for more than 10 000 watersheds is used.[60] Pfister modified the WTA ratio by employing a logistic function and used as a CF to calculate environmental impacts of water consumption. The amounts of blue water consumption are multiplied with the region-specific water stress indexes to obtain the results at the midpoint for the impact category, named 'water deprivation'. These results, also called characterized water footprints, were pointed out as a necessity by Ridoutt and Pfister[103] in addressing and interpreting the water footprint. The revised method involved incorporating the stress CFs to calculate the stress-weighted water footprint expressed in H_2O equivalents. However, the water management community disagreed with the approach, arguing that the characterized water footprint might affect the water management system's stance on water and will mislead the results because of insufficient pathways to impact assessment methods.[13,26,27,103]

The endpoint assessment follows the eco-indicator 99 framework[37] to quantify the potential damage for the three AoPs. The impact pathways followed in human health are (i) diseases arising because of a lack of freshwater for ingestion and hygiene and (ii) malnutrition because of lack of irrigation water for agricultural activities.[27] However, Pfister used only the second pathway for estimating CFs, pointing out the difficulty to assess in the LCA. The quantification of damage to human health arising from malnutrition in a particular region is calculated considering the water shortage for agricultural purposes, effect factor incorporating *per capita* water need to avert malnutrition, health effects due to malnourished people and water consumption. For assessing the damage to ecosystem quality because of water consumption, the ecological cause–effect chain model assumes that the excess abstraction of blue water may lower the green water availability, hence shrinking the terrestrial biodiversity.[27] As per the eco-indicator 99 framework,[37] the ecosystem damage measurement is expressed in potentially disappeared fraction (PDF) of species. The vegetation damage associated with the water shortage is assessed based on net primary production (NPP) which represents the water-shortage vulnerability of ecosystem. The ecosystem damage is quantified by multiplying the NPP with the ratio between the water consumption and precipitation. The last endpoint indicator, enabling damage assessment of the natural resources, evaluates the water resource depletion.[37] Weighting and normalization can be used to derive a single-score indicator which represents the complete damage caused due to consumption of freshwater. The weighting factors are derived from the eco-indicator 99 framework.[26,37,38]

LCI and LCIA modelling according to Milà i Canals. The method developed by Milà i Canals *et al.*[29] proposes to assess the impact of freshwater use in LCA and facilitates both in LCI modelling and proposing midpoint LCIA categories. In LCI modelling, the method works on differentiation between the different water types such as fossil blue water (non-renewable green water stock), green, blue, and water use arising from land use change. Further, the categorization of evaporative and non-evaporative is also done. The proposed ways for quantification of water use impacts in LCIA are given by two midpoint impact categories: freshwater water depletion (FD) and freshwater ecosystem impacts (FEI). The FD assesses the depletion in the water resources due to excess withdrawal of water rather than the natural renewal

Open Access Article. Published on 16 1403. Downloaded on 07/11/1404 10:48:58 ..
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

rate of a water body and it assumes that only consumptive use from aquifers and both evaporative and non-evaporative water from fossil aquifers contribute to this category. The CFs for this category are calculated using the abiotic resource depletion potential (ADP) formula. The Guinee method used for determining the loss of abiotic resources is adjusted to water use by Milà i Canals *et al.*[29]

The second category, FEI, looks at the ecological implications of water use in an area. It examines only the evaporative use of blue water which means the water lost from that watershed or area due to evaporation, or water discharge into another watershed. It also considers the land use changes (infiltration and runoff) which affect freshwater availability for proper functioning of ecosystems (thereby affecting the ecosystem quality) and excludes the fossil groundwater which contributes minimally to ecosystem functions. The CFs are provided by the water stress indicators (WSIs) proposed by Smakhtin *et al.*[71] which include the environmental water requirement of the region. In this way the indicator reserves a certain portion of freshwater necessary for ecosystem stability and functioning.[29,38,71]

Freshwater deprivation for human uses. Bayart *et al.*[28] developed a method in accordance with the recommendations of the framework put forth by the UNEP/SETAC life cycle initiative, which includes both impact assessment and water accounting. The link between the LCI and the LCIA was structured to provide guidance on AoPs for impact pathway modelling. This method overcomes the research gap of Milà i Canals[29] by proposing an impact category, at midpoint level, called 'freshwater deprivation for human uses', which assesses the implications of freshwater consumption on human health. On the inventory level, the freshwater inputs and outputs are grouped based on quality and type of resource. Also, based on type of freshwater consumed, CFs are calculated so that each freshwater type consumed will have its own CF expressed in m^3 water equivalent unavailable per m^3 water consumed.[110] Parameters like scarcity, ecological value and functionality are considered for impact characterization. Based on this procedure, various characterization factors are set up for different countries and freshwater types are determined.[26,28,31,38]

Human health assessment by Bouley. This method identifies and assesses the effects of low water availability or functionality for humans, which may result in potential human health impacts.[32] The model proposed consists of a midpoint, an endpoint, and a compensation assessment which is used to satisfy the water demand, provided the area is economically stable to do it. The modelled impact pathway leads to direct human health impacts due to malnutrition and diseases. They are interconnected and can have an aggregated impact on human health. The impact is characterized at the midpoint level considering local water scarcity, quality, and the resource type and is expressed by estimation of the water stress indicator (WSI).[31] The CF used at the midpoint level, called stress index, expresses competition between users due to physical water scarcity. For endpoint assessment modelling, the potential human health impact is based on the difference in the extraction of water resource and emission into the environment, expressed in disability adjusted life years (DALYs), which is a unit of health indicator developed by the World Health Organization. It quantifies the total amount of health lost due to premature death and disability resulting from illness and injuries. The CF (DALY per m^3) used in the case of endpoint modelling represents local water stress, degree to which user(s) will be influenced by varied water availability and user(s) capability to adhere to this variation and effects water deficiency can have on human health.[58] The midpoint and endpoint levels for human health impact are tested by Boulay *et al.*[32] for their consistency and variability with present models to allow comparison and deeper understanding.[31,36,38,58]

Human health damage assessment by Motoshita. The possible damage on human health due to water consumption is examined using the cause–effect chain on human health models. Motoshita *et al.*[33,111] developed two endpoint-oriented methods that quantify the damage to human health emerging from infectious diseases and malnutrition, which were bought about because of lack of water for agriculture and drinkable clean water, respectively. The first modelled cause–effect chain resulting in undernourishment from lack of agricultural water comprises (i) low agricultural productivity and (ii) subsequent human damage (assessed in DALYs) due to undernourishment from decreased agricultural yield.[33] The second cause–effect chain is associated with the arising of infectious diseases from domestic water utilization or the lack of clean drinking water, thereby causing damage to human health.[111] This pathway also considers the socio-economic parameters as infectious diseases are usually an implication of poverty rather than the physical water scarcity. Motoshita's group estimated the country-specific CFs as well as the damage factors for both cause–effect chains affecting the human health area of protection.[26,32,36,112,113]

Ecological damage of groundwater extraction. The method is an endpoint impact assessment method expressing the damage caused to the ecosystem quality by groundwater extraction. The method uses the fate and effect factor to calculate the CF. The cause–effect chain included by Zelm *et al.*[47] is the disappearance of the species richness of terrestrial vegetation because of excess groundwater use and falling water table which ultimately lead to ecosystem damage, in the context of the Netherlands. The CF (m^2 year per m^3) defines the change in the count of plant species due to the change in groundwater extraction in a particular area.[26,47]

Impact of water consumption on freshwater ecosystems

• *Damage to aquatic ecosystems due to damming.* The method developed by Humbert and Maendly[114] proposes to develop the CFs that ascertain the damage done to aquatic biodiversity due to damming of water especially for hydropower production (non-consumptive use). Hydropower

Open Access Article. Published on 16 1403. Downloaded on 07/11/1404 10:48:58 ..
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

is usually considered as an eco-friendly source of electrical energy; nonetheless, damming of water affects the ecosystem of an area through regulation of river flow and fragmentation of rivers, thereby causing fish species loss per power production.[115,116] This end point impact assessment method develops the specific CFs to assess the effects on aquatic biodiversity, expressed in PDF per m^3 or kWh in the upstream and downstream zones.[26,114]

• *Reduction in freshwater fish species.* The overuse of water by humans has affected the freshwater ecosystem quality. The method proposed by Hanafiah *et al.*[46] derives the CFs for possible depletion of freshwater fish populations because of water consumption and assesses the freshwater ecosystem damage. The basin-specific CFs are calculated by the fate and effect factors and expressed in PDF m^3 year per m^3.[26,46]

The latest model formulated by Pierrat *et al.*[2] also calculates the CFs for impact on freshwater ecosystem quality. It is based upon the regionalized species-discharge relationship which models the riverine fish species biodiversity losses. The CFs for regional and global levels are calculated based on fate and effect factors, which represent how water consumption causes reduction in water levels and leads to habitat reduction of species and their survival. The regional CFs are multiplied by a weighting factor known as global extinction probability which converts the regional impacts to global impacts. The global CF represents the impact of water consumption on global biodiversity.[2,117]

Summarizing for fish losses, the earlier approaches considered only marginal regional impacts; the new regionalized CFs allow for additionally accurate impact assessment by distinguishing between average and marginal impacts as well as damage to regional, *i.e.*, river basin-level, and global biodiversity.[2,117]

AWARE water model. Disputes between the two communities over water footprint assessment being either volumetric or impact-oriented led to the development of an ISO guidance which formulated the water footprinting to be impact-oriented. In this regard, a consensus based on a new characterization model was set up by the Water Use in Life Cycle Assessment (WULCA) group in accordance with the framework ISO 14046 (2014)[48] to evaluate water scarcity footprints. The model assesses the water consumption impacts based on the available water remaining (AWARE),[34,48] focusing on discovering a consensus-based indicator for water use impact assessment (at midpoint level). This method was accepted and recommended by the UNEP-SETAC[93] life cycle initiative, European commission program (PEF/OEF)[110] and the International Environmental Product Declaration (EPD)[118] system.[23,24,55,119] The recommended model, AWARE, considers both human and ecosystem (aquatic) water demand, thereby assessing their probable deprivation at the midpoint level in that area and hence provides the route for calculating the water scarcity footprint in accordance with ISO 14046 (2014).[48] It answers all the questions posed during the earlier consensus building workshops by WULCA.[55] As discussed above in section 2 about the development of different ratios and their use, AWARE is based on the inverse of the availability minus demand ratio (1/AMD). Although the consensus was based on using the 1/AMD ratio, some members recommended employing a different parallel method to check and improve the method's resilience.

The AWARE characterization model developed by Boulay *et al.*[34] sets its basis upon the available water remaining per unit area in a particular watershed relative to the world average after the human and freshwater ecosystem demand is fulfilled. The water scarcity footprint is computed by taking the product of water inventory and AWARE characterization factor, CF_{AWARE}, or in other words, the possible deprivation of water for another user is inversely proportional to the 'amount of water available per unit of surface and time in a region' and directly proportional to the quantity of water consumed (or inventory). Eqn (2) is shown below:

$$\text{Water scarcity footprint} = \text{Water consumption (inventory)} \times CF_{AWARE} \quad (2)$$

where CF_{AWARE} is calculated based on AMD as shown below:

$$\text{AMDi} = \frac{(\text{Availability} - \text{HWC} - \text{EWR})}{\text{Area}} \quad (3)$$

where HWC and EWR are the human water consumption and the environmental water requirement, respectively, and represent the demand of region 'i'. The inverse of AMDi, understood as the surface–time equivalent needed to produce one cubic meter of unused water, STei, is given in eqn (4) below:

$$\text{STei} = \frac{1}{\text{AMDi}} \quad (4)$$

The characterization factor is obtained by dividing local AMDi, expressed in $m^3\ m^{-2}$ per month, to the consumption-weighted AMDi of the world *i.e.*, $AMD_{worldavg}$ with value equal to 0.0136 $m^3\ m^{-2}$ per month, as shown in eqn (5):

$$CF_{AWARE} = \frac{\text{STei}}{\text{STe}_{worldavg}} \text{ OR } \frac{\text{AMD}_{worldavg}}{\text{AMDi}}, \text{ for Demand} < \text{Availability} \quad (5)$$

However, when the demand ≥ availability, a range of values is applied to keep the equation continuous. The cut-offs for the CF are set as maximum and minimum with values of 100 and 0.1, respectively. CF_{AWARE} is dimensionless, expressed in $m^3{}_{world\ eq.}\ m^{-3}{}_i$. The parameters present in the AMD calculations are presented below.

Freshwater availability, as defined by the AWARE model, represents the natural freshwater runoff essential for both human and ecosystem needs. Variations in water availability are influenced by geographical and temporal factors, with data derived from the WaterGAP 2.2 model,[60] which assesses global water resources. Human water consumption (HWC) data, also modeled through WaterGAP, includes demands from domestic, agricultural, and industrial sectors.

This journal is © The Royal Society of Chemistry 2025

Open Access Article. Published on 16 1403. Downloaded on 07/11/1404 10:48:58 ..
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

Ecosystem demand, modeled *via* the environmental water requirement (EWR), accounts for minimal water needs to sustain freshwater ecosystems under "fair" conditions. EWR relies on pristine flow, allocating percentages to maintain habitat health across seasonal flows. For a detailed description, consult the supplementary materials provided by Boulay *et al.*[34]

4.5. Methods based on integration of water-related issues

Water footprint integrating consumptive and degradative water use. There are two ways of using water: consumptive water use (CWU) and degradative water use (DWU); the former is the removal of water from the source and the latter is related to emissions affecting water quality. Various environmental mechanisms involved in LCA report water use, CWU and DWU, in a diverse range of impact category results.[102] The profile of detailed results is rich in explanations and interpretations; however, communicating them becomes inappropriate for a non-technical audience. In this regard, the approach proposed here for LCA-based WF integrates both CWU and DWU in a singular score reflecting the analogy similar to carbon footprinting. The result is expressed in a reference unit H_2O equivalent. CWU is assessed by balancing the water inputs and outputs while using CFs from Pfister's water stress index site-specific values.[120] On the other hand, DWU is obtained by using the critical dilution approach in terms of theoretical volume to express degradative emission. The results from both the water uses are added and reported as a single stand-alone value.[27,28,102,103]

Water impact index. Water footprinting methods have evolved over time but very few integrate the issues like scarcity, quality, and volume. The index presented here assesses the shortage of available water as well as combines the concerns of volume used, local water scarcity, and change in water quality in a single indicator. The water impact index follows the principles of life cycle thinking and water flows within the boundary are multiplied by water scarcity and water quality index and is expressed in 'volume unit water impact index equivalent'. This enhancement in the water footprint represents the step towards enhancing the understanding and evaluation of environmental impacts of water use by users. This method focuses only on the ecosystem quality. This method has been applied on a municipal wastewater management in Milano, Italy.[80] This is a very simplified approach which intends to assess the water deprivation cause–effect chain model described in Bayart *et al.*[28] for water use.[80]

Water footprint impact assessment. The most recent WF impact assessment involved the integration of water scarcity and pollution. This index models two regional indicators, water biodiversity footprint (WBF) and water resource footprint (WRF) that are developed to combine the effects due to scarcity and pollution. The former denotes the consequences on freshwater ecosystems, while the latter models the freshwater resource competition and its effects on the availability of freshwater. The method draws inspiration from the concept of harmonized water footprint assessment by Lathuillière *et al.*,[121] which is based on stages mentioned in the ISO 14046 (2014)[48] standard. Analyzing and reassessing the harmonized WF framework for an enhanced WF impact and sustainability assessment is achieved by developing regional environmental indicators, providing sustainability limits and testing this upgradation on a case study. The outcome of this method highlighted the importance of inclusion of pollution dimension in water footprinting because of its relevance. The findings depict that the impacts of pollution are higher in biodiversity compared to scarcity and reduction of water availability to systems or sectors which require high-quality water input. The integration of water-related parameters forms the basis for future water footprinting and this is a step forward in achieving those water-related sustainable development goals (SDGs).[122]

FAO LEAP partnership. A technical advisory group constituted by the FAO livestock environmental assessment and performance (LEAP)[123] partnership was set up to establish guidelines and protocol on WF estimation for livestock-producing systems. The guidelines set up for livestock water use considers both the impact assessment and water productivity (water use efficiency). A comprehensive picture of possible gains in water productivity and reductions in potential environmental effects associated with water scarcity can be obtained by combining water productivity and water scarcity footprint indicators consistently. Although livestock production systems and feed were the primary focus of this LEAP technical advisory group, many other agriculture sectors can potentially benefit from its findings. By using these guidelines, the LEAP initiative supports sustainable water management practices across sectors, contributing to broader environmental goals, including those outlined in the SDGs.[50,123]

5. Discussion

In this section, we discuss the practical application, limitations, and necessary improvements for the methodologies discussed earlier. This section critically analyzes these methods by highlighting their strengths and areas where they fall short. Additionally, we introduce some case studies that have utilized these methodologies, providing brief insights into their implementation and outcomes. These case studies serve to illustrate the practical relevance and effectiveness of the discussed methodologies in addressing water-related challenges.

5.1. Stand-alone water accounting and resource consumption methods

The water inventory encompassing the stand-alone and accounting methods along with the databases and tools is

Open Access Article. Published on 16 1403. Downloaded on 07/11/1404 10:48:58 .. This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

the most straightforward approach for WF estimation; however, there are numerous discrepancies within. Hoekstra's method of virtual water and WF is an improvement as it considers different types of water like green and gray, not just blue water.[16] Additionally, it also includes information about where water is taken from. However, it can be complicated to use due to challenges in data management and interpretation and lacks clear definitions for water quality standards. This can make it tricky to measure gray water consumption accurately. Another issue is that it might count pollutants twice.[10,15,16,26,36] Accounting methods rely on databases for their operation, but these databases often have limited reliability in data quality. The doubts surrounding data accuracy are amplified by significant discrepancies, sometimes up to a factor of 10, between water use and consumption data.[103] Due to lack of better databases, the Gabi[95] and Ecoinvent[96] databases are among the most utilized and applied ones. Besides inventory-based methods, there are approaches that facilitate assessing the impact of water consumption. It is important to highlight that many of these methods were developed in recent years and there is limited practical experience derived from applying them in case studies, leading to discussions primarily on a theoretical basis.[26,36,38,102,124]

Starting with the resource consumption methods modified for water use, EDIP[104] and CExD/CEENE[105,106] assess only water consumption within the framework of typical resource consumption practices, which means they cannot effectively be used to estimate the water resource depletion. The results from EDIP assesses only the local water depletion, while CExD/CEENE cannot express the water resource depletion in a significant manner as it does not account for local water scarcity. Moreover, none of the methods considers the other effects (human health and ecosystem) related to water consumption. On the other hand, the ecological scarcity method employs eco-factors for water use that are based on the WTA ratio, which raises concerns for a reliable assessment as water use does not reflect the actual situation rather than water consumption. This method is adapted from the Swiss local conditions and can be tailored to different countries' hydrological conditions, providing a site-specific assessment of water consumption.[107] However, it relies on subjective political value choices for weighting which makes it unsuitable for use in LCA studies intended for publication with comparative assertions, as per ISO 14040-44[19,20] standards. Similarly, another method developed specifically for South African regions by Brent[109] shares the same drawbacks, including subjective weighting based on political choices and focusing on water use rather than water consumption.[26,36,38,102,124]

5.2. Methods assessing midpoint or endpoint level

The methods assessing the midpoint and/or endpoint level cover most of the portion of this study. As water inventory cannot provide a reliable assessment of impact because low WF in regions with water scarcity can be more environmentally significant than high WF in areas with ample water resources, characterized WF was developed by Ridoutt and Pfister.[103] However, the water management community disagreed with the approach, arguing that the characterized water footprint might affect the water management system's stance on water and will mislead the results because of insufficient pathways to impact assessment methods.[103] For the end point assessment, Pfister *et al.*[27] used the eco-indicator 99 framework to estimate damage to three AoPs.[37] For human health, only the second pathway was followed, neglecting the first one, which considers the unavailability of drinking water possibly arising from catastrophic events not accounted for in LCA. Moreover, the neglect of health impacts caused by disease transmission due to poor hygiene is justified by arguing that assessing such effects is challenging due to their dependence on local variables.[27] For ecosystem and resource categories, the proxies used within the assessment are net primary production and energy required for desalination, respectively, which can be improved further. Finally, the single aggregate scoring is based on political or subjective weighting, hence cannot be used for publication with comparative assertions similar to the ecological scarcity method.

Milà i Canals's[29] method estimated damage only at the midpoint level for ecosystem and resource depletion without addressing for human health. Also, the unavailability of CF for FEI restricts its application globally and the recommendation to consider green water separately does not reflect in its impact assessment. While Bayart's[28] method addressed the issue of including human health considerations within Milà i Canals's[29] method, it runs the risk of double-counting values due to the interdependence of parameters such as functionality and quality used in Bayart's method. Bouley's human health assessment includes both the functionality and the consumption-based scarcity indicators yet shows inability in different places and does not provide an exact result as it looks at a linear link between water use and impact in LCA.[31] The model's default factors are good for exploring water impacts, but comparison with other models is important to know how reliable it is. Improving life cycle inventory databases and including compensation scenarios can help integrate the method into everyday assessments.

Motoshita's[33,111] estimation of damage to human health showed that absence of hygienic conditions results in damage that is significantly higher than those caused by malnutrition, yet the approach interlinking water use and disease is somewhat contradictory and needs to be understood critically. The following methods focus only on the ecological damage. Zelm *et al.*[47] focuses only on green water extraction and its impact on the ecosystem for the Netherlands and cannot be applied elsewhere. Humbert and Maendly[114] look only into aquatic biodiversity loss, only considering the damming within a particular area, whereas Hanafiah *et al.*[46] and Pierrat *et al.*[2] also solely address the

 This journal is © The Royal Society of Chemistry 2025

Open Access Article. Published on 16 1403. Downloaded on 07/11/1404 10:48:58 .. This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

freshwater ecosystem quality without accounting for terrestrial ecosystem damage.

The widely accepted recommended model AWARE[34] is the result of consensus but still needs further development and improvement. The broad parameters listed by the AWARE authors could potentially be used for determination of the national water scarcity footprint of water consumption. Alternatively, they offer a couple of sector-specific variables, agri and non-agri, in situations when watershed-level factors cannot be employed. These factors give more reliable weighted average because they more accurately reflect the temporal and geographic distribution of water utilization in the nation for an agribusiness or non-agribusiness activity.[34] It already succeeded in providing a consensual, operational, and recommended indicator but faces challenges such as limitations, variability, and uncertainty.[34,55,125] The model considers only the blue water consumption for its evaluation and also does not differentiate between the surface waters and groundwater resources, hence providing one generic indicator.[126,127] The ecosystem demand is only focusing on the aquatic or freshwater ecosystem demand without a focus on the terrestrial ecosystem demand.[34,47,128,129] The ecosystem demand in the model uses the Pastor's approach to retrieve the EWRs which does not account for other environmental dimensions in a specific region as it is based on a global algorithm scale, which is a limitation. Also, the management of hydrological infrastructure could help in satisfying the EWRs of the region; however, the routes are uncertain and variable.[129] Moreover, this model does not provide any damage assessments at the end point level.

The data derived from the WaterGAP model are based on a global scale and do not accurately reflect the specific conditions of individual local regions. The uncertainties inherent in the global hydrological model can impact the reliability of its results. Several studies from Brazil and Australia have highlighted its limited ability to differentiate between varying levels of water scarcity in areas where water availability is insufficient to meet the demand.[126,130–133] Until now, the quantification of CF uncertainty has received little attention; the correlation between CFs, if ignored, could result in misinterpretation of cumulative uncertainty in LCA.[55] At the watershed scale, a significant difference is seen between annual and monthly values.[34,55,125] The factors provided are based on the country scale and does not reflect the actual situation of the watersheds or basins or the local regions. The analysis of the spatial variability was performed by comparison of the annual values of the watershed with annual the value of the same country.[131,134]

The applied cut-offs to the AWARE CF range of 0.1 and 100 have associated limitations as discovered by Hélias.[56] The AWARE model is valid only when the humans have left enough water for the ecosystem to be in fair condition; however, if there is less water available for the ecosystem to meet its needs, the model loses its validity, hence leading to introduction of cut-offs. Due to these limits, the CF is used only for 87% of the world area and only takes into consideration only 62% of the world water consumption.[56] The limitation could be addressed by proposing a methodology that could maintain the validity of the CF over the entire world water consumption.[34,56]

• **Developments and improvements in the model.** The limitations described above were addressed by various authors in their studies. The uncertainty analysis performed in paddy rice production in Korea considering the temporal variations suggested the use of the Block bootstrap method for analyzing uncertainty in AWARE.[135] Similarly, Boulay *et al.*[125] assessed and estimated the uncertainty of the AWARE model by using statistics, dispersion analysis, and distribution best fit and parameters. Another step in the development was to bridge the data gaps by introducing the crop-specific AWARE factors. The 26 crop-specific CFs were developed, validated, and recommended as better proxy for estimating water scarcity footprint.[119] A study also proposed to calculate the groundwater CFs and hence differentiate between surface water and groundwater, which otherwise is not considered in AWARE. The groundwater stress has been included in LCA by a new method called "AGWaRe" standing for available groundwater remaining which reflects green water availability based on available groundwater remaining.[126,127] Regarding the ecosystem system which accounts only for the aquatic ecosystem demand, an interdisciplinary study presented a strategy to resolve the difficulty of including terrestrial ecosystems in the freshwater use impact category.[62]

The modifications in the AWARE model came from two authors, Kaewmai *et al.*[130] recommended a novel approach by modifying the AWARE for individual water scarcity assessments. It was established to highlight and clearly identify the hotspots of water users and the months of scarce water availability. The modification from Hélias[56] addressed the cut-off ranges and the ecosystem demand of the AWARE model. The DTR model, which uses the DTR ratio, improves the AWARE model by defining the relationship involving human intervention and using approaches such as marginal, average/linear to determine the CFs. The upgrade also proposes to maintain the validity over the entire world's water consumption, not limited to 62%. Finally, the most important challenge in improvement of the model is the use of primary local data, not the average world generic datasets. This leads to the development of the regional CFs for reliable, precise, and accurate results to be used for decision-making at local levels. Regionalization is still a challenge and is addressed below.[34]

• **Case studies.** Research has been conducted in Brazil,[132,133] Thailand,[130,136,137] Peru,[126] and Australia[131] where they have computed the CFs at country and watershed level using the local data as AWARE CFs cannot accurately describe the water scarcity conditions at a local region in a country. Ansorge and Beránková[138] demonstrated that regionalized AWARE CFs computed with actual hydrological data differed significantly from WULCA's AWARE CFs computed at the national and watershed levels. The study

Open Access Article. Published on 16 1403. Downloaded on 07/11/1404 10:48:58 ..
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

from Thailand used the local data from the hydrological irrigation center to estimate the new CFs. Another study from Brazil estimated the CFs in the water scarce regions using the data from the National Water Agency. It was observed that the WaterGAP model overestimated the availability while it underestimated the demand in different basins in comparison to hydrological data from the National Water Agency, suggesting replacement of the WaterGAP data with local hydrological data in future regionalization studies as CFs calculated were inaccurate. In Australian basins, data obtained mainly from the Australian Bureau of Statistics and Meteorology for CF calculation showed that the AWARE CFs significantly overestimated the water consumption, and the average Australian CF was 35% lower than WULCA's estimate.[131]

A study in Peru also developed regional CFs for the eight watersheds along the Peruvian coast.[126] The data were obtained from the official reports and national database of the country, using the Water Evaluation and Planning System model.[12,139] The results from this study revealed that the updated annual CFs were 1.1- to 257-fold higher than the original CFs. This could be attributed to the fact that water availability from the national database is 465-fold greater than indicated by WaterGAP. The variations between the original one and the updated CFs are primarily associated with variations in data sources concerning demand and availability. In conclusion, AWARE CFs should be calculated based on the local data for providing a more accurate water scarcity assessment in the area.[126]

5.3. Methods based on integration of water-related issues

Lastly, the methods that are based on integration of various dimensions of water use, quality, and quantity are discussed for their shortcomings. The consumptive water use and degradative water use integration by Ridoutt and Pfister[102] presents an effective way for simple communication to the public; however, it is too simple to reflect the reality as it focuses on only a few LCA impact categories. Also, it cannot be used in LCA because of the possibility of double counting as it already considers few impact categories within its evaluation. Moreover, the water units are not agreed upon by the water community, while the ReCiPe method has its own uncertainties and limitations concerning inventory and assessment. The water impact index is another approach developed by Bayart *et al.*[80] to integrate the scarcity, quality, and quantity of water, but it is considered a very simplified approach and cannot be used for comprehensive assessment as it only focuses on the ecosystem quality. The distinction between green water and surface water sources as well as the

Table 2 Summary of the water use impact assessment methods for life cycle impact assessment, level, and damage

Methods	LCI to LCIA conversion	Level (midpoint/endpoint)	Area of protection (AoP)
EDIP resources (1998)[104]	Using weighted water consumption	Midpoint	Resources
CExD/CEENE (2007)[105,106]	Chemical exergy content of water	Midpoint	Resources
Ecological scarcity (2006)[37]	Eco-factor for water use	Midpoint	Resources
Brent (2004)[109]	Distance-to-target weighting	Midpoint	Ecosystem and resources
Pfister's method (2009)[27,37]	CF: water stress index by Pfister	Midpoint	Human health, ecosystem and resources
	Eco-indicator 99 framework	Endpoint	Human health, ecosystem and resources
Milà i Canals *et al.* (2009)[29]	CF for FD: abiotic depletion potential CF for FEI: WSI by Smakhtin	Midpoint	Resources Ecosystem
Bayart *et al.* (2010)[28]	CF: calculated using WTA, functionality, quality, and compensation ability factors	Midpoint	Human health
Boulay *et al.* (2011)[31]	CF: water stress index	Midpoint	Human health, ecosystem and resources
	CF: fate, exposure and effect	Endpoint	Human health
Motoshita *et al.* (2011, 2018)[33,111]	Regression models to report damage in DALYs	Endpoint	Human health
Zelm *et al.* (2011)[47]	CF: fate and effect factor	Endpoint	Ecosystem
Humbert and Maendly (2008)[114]	CF: based on PDF, electricity generated, and area	Endpoint	Ecosystem
Hanafiah *et al.* (2011)[46]	CF: based on water consumption, PDF, and volume of river basin	Endpoint	Ecosystem
Pierrat *et al.* (2023)[2]	CF: fate and effect factors	Endpoint	Ecosystem
AWARE (2018)[34]	CF: inverse of AMD	Midpoint	—
Hélias (2020)[56]	CF: DTR	Midpoint	—
Ridoutt and Pfister (2013)[102]	CF for CWU: Pfister's water stress index CF for DWU: ReCiPe	—	—
Bayart *et al.* (2014)[80]	Water scarcity index and water quality index	Midpoint	Ecosystem
Boulay *et al.* (2021)[50]	Water productivity and scarcity	—	—
Pierrat *et al.* (2023)[122]	WBF: CFs related to various parameters WRF: pollution and scarcity deprivation potential and pollution weighting factor	Endpoint	Human health, ecosystem and resources

Open Access Article. Published on 16 1403. Downloaded on 07/11/1404 10:48:58 ..
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

seasonal water data could possibly improve the index. The recent WF impact assessment by Pierrat *et al.*[122] tries to put together the effects of scarcity and pollution; however, this approach is data-intensive and shows poor results for spatial and temporal resolutions. Significant LCI data and the CFs lacked involvement in the assessment and hence the results are highly underestimated. Green water consumption and its impacts are also not quantified. However, Quinteiro *et al.*[140] developed a characterization model that addresses the environmental impact of green water flows but has high uncertainty. Finally, the consensus-building process for assessing water use in livestock production and supply chains gives key recommendations covering goal and scope, data, inventory, water scarcity footprint, water productivity, and reporting. It emphasizes the importance of international consensus in water use assessment, combining LCA and water management metrics for efficiency and environmental impact improvements.[50,123]

Table 2 outlines diverse LCA methodologies and their pathways to impact assessment outcomes, including CFs, weighting, or other approaches. It also assesses the level of assessment (midpoint or endpoint) and areas of protection addressed. Applying different methods in water and environmental assessments can lead to varied results due to differences in approaches and methodologies. This diversity underscores the importance of selecting scientifically validated methods as recommended by consensus within the scientific community. Using multiple methods in parallel, as suggested by FAO LEAP, can provide a more comprehensive perspective, allowing for a comparison of results across approaches. The reliability and relevance of a method become evident when it is applied across a range of studies globally, producing consistent and applicable results. Ultimately, only methods validated through widespread application and consensus should be prioritized, as these offer the most credible insights for policy and practice.

5.4. Comparing WF assessment methods: case studies

The term WF assessment is used here to encompass both the water footprint (WF) and the impact assessment of water use. Several comparative studies have been carried out within these WF assessment methods, some of which are discussed in this paper. García-Herrero *et al.*[141] carried out a study to evaluate the WF of European food consumption using two distinct methods, the blue WF assessment and the AWARE model. The former focuses on the evaluation of pressure on water resources, while the latter is the scarcity-weighted WF method quantifying impact. The blue WF method resulted in a narrow scope compared to AWARE because of the absence of background processes and inapplicability of including the full supply chain, hence depicting AWARE as a better approach. Moreover, it considers factors like environmental water requirement (EWR), offers a midpoint indicator with less uncertainty, covers a broader scope, and provides an estimate of potential deprivation of water resources compared to the world average.

Another study estimated the environmental impacts of coffee processing using LCA, where two methods, AWARE and ReCiPe,[45] were compared for water consumption. The AWARE model supplemented the results from RECIPE for a broader evaluation of WF.[142] A study by Usva *et al.*[143] assessed the water use impact of a classic Finnish milk production system, including both midpoint and endpoint level, where the former was evaluated for water scarcity using the water stress index and stress-weighted water footprint index by Pfister[13,26,27,124] and AWARE, while the latter was evaluated for damage assessment using the eco-indicator 99 framework.[37] The comparison between the methods depicted the suitability of using AWARE over other methods as it recognizes hotspots along with their magnitudes with a strong reasoning.[143] Another similar study by Villanueva-Rey *et al.*[144] assessed the WF of a wine appellation in Galicia, Spain, using AWARE for blue water scarcity in addition to using Pfister's water stress index and ReCiPe water depletion for mere comparison. Impact findings from AWARE, water stress index, and ReCiPe water depletion methods showed similar patterns, with water consumption contributing to 30–40% of total impacts. Yet, there were variations in blue water scarcity impacts, emphasizing substantial impact variability depending on CFs across different spatial and temporal scales.[144] Similarly, Borsato *et al.*[145] did a comparative study for wine production using two methods, Pfister's water stress index and AWARE, that evaluated the freshwater use. The study found that the WF of the irrigation process exhibits a comparable percentage contribution across the water stress index and AWARE methodologies. Combining the two methodologies synergistically can enhance the breadth of the assessment of environmental sustainability aimed at reducing freshwater usage and water pollution.[145]

Apart from being used in regionalization and comparison studies, AWARE has been employed in various studies to estimate water use impacts such as an LCA study on fuel types for the Formula 1 Mercedes engine that estimated the impact using AWARE.[146] Similarly, the effect of water consumption on energy systems was analyzed in the United States.[147] AWARE was also used to calculate the water scarcity footprint in a study considering lithium mining for batteries.[148] Also, the use of this model in addressing the future water scarcity is reflected in the work of Baustert *et al.*,[149] who attempted to couple water scarcity and electricity supply in prospective LCA. Due to water consumption, the physical habitat change potential in rivers was modelled using a high-resolution LCIA model employing AWARE.[116] Recently, LCA has been used to evaluate the alternatives of industrial water management using AWARE, where a combined cycle power plant is chosen for analyzing the WF.[150] Other methods such as Pfister's WF assessment of biofuels as well as water consumption and impact assessment of European passenger cars using various assessment models (ecological scarcity) have also been

Open Access Article. Published on 16 1403. Downloaded on 07/11/1404 10:48:58 .. This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

carried out.[43] While these case studies employ the AWARE method or Pfister's WF assessment, they do not extensively explore the method itself.

6. Conclusion and outlook

This study has methodically summarized the diverse approaches used to assess water use and its consequences from the life cycle assessment (LCA) perspective. The review highlights the evolution of WF methodologies, the need for contextual adaptation, and the balance between global models and local precision. Comprehensive assessment of water-related consequences and measurements has been made easier by a collection of databases, tools, and indices. The long-running issues in the water and LCA communities have been somewhat resolved since the ISO standard was established. This results from water footprinting being categorized by the ISO as an impact-oriented approach rather than a volumetric approach. Still, the volumetric method is essential to the assessment of the former. Many approaches have been developed to identify the effects of water use in areas of protection, such as human health, ecosystems, and resources. Current cause–effect relationships, developed across time periods, require additional improvement to impart increased accuracy in the prediction of results at the endpoint level. This need for improvement derives from the complexities involved in identifying the interactions between variables that define the impact pathways of water use in complex systems. Therefore, improvements in the fine-tuning of cause–effect linkages have the potential to improve the robustness and granularity of impact evaluations related to water management and usage.

Several methodologies have emerged, aiming to comprehensively address multifaceted water issues encompassing quality, scarcity, and volume. The techniques, while potentially useful, are limited for widespread adoption. The AWARE model, highly recommended for assessing the impacts of water use on potential deprivation for both human and ecosystem users, stands out. As seen from different case studies, this model has been performing better than other approaches. This model has been globally applied for evaluating the region-specific characterization factors. The AWARE model is known for using generic global data to determine components across many locations; nonetheless, it is acknowledged that these estimations have difficulties in fully expressing regional variations. Regionalization offers significant room for improvement as original AWARE factors can be unreliable and incorrect as they rely on the global databases built from inappropriate information. This review underscores the importance of adapting water footprint (WF) methodologies to local contexts, particularly in regions where national- or watershed-level data diverge significantly from global models, by showcasing case studies from the literature that illustrate the improvements in assessment accuracy achieved through localized approaches. Developing and recalculating local characterization factors using regional data from national departments would enhance the robustness and accuracy of AWARE impact assessments. Moreover, the inclusion of evaluations at the monthly level is recommended as it provides information on changing conditions all year long.

The suggested improvement, which involves switching from the ratio 1/AMD (availability minus demand) to DTR (demand to remaining), should be thoughtfully planned out, especially in the context of case studies intended to evaluate the viability of the DTR plan. As per the DTR, the ecosystem demand metric is currently inaccurate since it does not accurately reflect the true demand; instead, it indicates the residual water remaining after meeting human water requirements. Moreover, the evaluation only considers the demand on aquatic ecosystems, ignoring the terrestrial component. This review points out that better understanding of the complex relationships between terrestrial and aquatic ecosystems and their individual water requirements is necessary in addition to inclusion of green water consumption. Refinement of the model that addresses the demand on aquatic ecosystems is necessary, especially when assessing rivers with conditions classified as ‘less than fair’, where the model evaluates them as poor without accounting for the level of degradation. Building connections is necessary to properly address the use of surface water and groundwater simultaneously. This will ultimately lead to the computation of separate characterization factors (CFs) for surface water and groundwater, which resembles one of the previous approaches.

Future enhancements should prioritize the development of sector-specific characterization factors to more accurately assess variations between existing and new models. This approach would facilitate a clearer identification of gaps between historical and updated values, thereby supporting more precise model improvements for any upgrades or adjustments. Additionally, the aim to create time-sensitive characterization factors would contribute to achieving precise annual results, aligning each factor with the specific year it represents. Such advancements could be instrumental in updating the current methodology with the most recent data, actively contributing to the ongoing global effort to refine and advance impact assessment methodologies. Because water use impact assessment methods are evolving so quickly, it is critical to maintain a consistent updating strategy in order to align with new research and developments particularly in the context of climate change. Rising global temperatures and unpredictable weather patterns are exacerbating water scarcity and placing increased stress on regional water supplies, intensifying the need for accurate and adaptive water resource assessments. These shifts underscore the need to develop reliable, region-specific assessment methods that can adequately account for the diverse and evolving impacts of climate variability on water availability. Properly addressing these climate-driven fluctuations in water resources will support adaptive management strategies, essential for safeguarding human

Open Access Article. Published on 16 1403. Downloaded on 07/11/1404 10:48:58 ..
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

health, ecosystems, and resources in the face of escalating climate challenges. The dynamic character of water use and assessment and its responsiveness to changing scientific insights are fundamental for new developments.

Glossary

1/AMD (inverse of availability minus demand)	An indicator used in water stress measurement, representing the inverse of remaining water after accounting for human and ecosystem demands
AWARE (available water remaining)	A model designed for assessing water scarcity by determining how much water remains after meeting human and ecosystem needs in LCA
Blue water (BW)	Freshwater found in rivers, lakes, and aquifers, often extracted for use in agriculture, industry, and households
Characterization factor (CF)	Value that quantifies the potential environmental impact of a unit of resource or emission, used in LCIA. Characterization factors convert environmental interventions, such as emissions and resource extractions, into measurable outcomes within specific environmental impact categories
Criticality ratio	A ratio assessing water consumption or withdrawal against available resources, commonly used to gauge water stress levels
Demand to availability (DTA)	A ratio that compares the demand for water with the availability in a specific area, offering insights into regional water scarcity
Demand to remaining (DTR)	A proposed ratio in water impact assessment that compares ecosystem water demand to the remaining water after human usage
Ecological scarcity method	An LCIA method that applies eco-factors to evaluate the environmental impact of substances, including water
Endpoint	Endpoint indicators represent environmental impacts at three broader levels: human health effects, ecosystem, and resource depletion. Translating midpoints into endpoints enhances the clarity and interpretability of LCIA results through various damage pathways but has a high uncertainty than midpoint
Green water (GW)	Rainwater stored in soil, used by plants, primarily in agriculture, impacting calculations of water use in food production
Life cycle assessment (LCA)	A method that examines the environmental impact of a product throughout its life cycle, from raw materials to disposal
LCI (life cycle inventory)	Is the data collection phase within LCA. It involves a comprehensive accounting of all inputs and outputs associated with the system under study. This inventory includes detailed tracking of material and resource flows
Life cycle impact assessment (LCIA)	This phase of LCA, the inventory data, which includes raw materials, energy inputs, emissions, and waste outputs, is analyzed to understand the potential environmental impacts of a product or process
Water footprint (WF)	Total freshwater used, directly and indirectly, in a product's life cycle, including consumption and pollution effects
Water stress indicator (WSI)	A measure evaluating regional stress on water resources due to consumption, considering both availability and demand
Withdrawal to availability (WTA)	A ratio that assesses the proportion of available water withdrawn, indicating regional water scarcity levels

List of acronyms

AoP	Area of protection
AWARE	Available water remaining
BW	Blue water
CF	Characterization factors
CTA	Consumption to availability
CWU	Consumptive water use
DALY	Disability-adjusted life year
DTA	Demand to availability
DTR	Demand to remaining

Open Access Article. Published on 16 1403. Downloaded on 07/11/1404 10:48:58 ..
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

DWU	Degradative water use
EWR	Environmental water requirement
FAO	Food and Agriculture Organization
FD	Freshwater depletion
FEI	Freshwater ecosystem impacts
FAOLEAP	FAO livestock environmental assessment and performance
GW	Green water
ISO	International Organization for Standardization
IWMI	International Water Management Institute
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
NPP	Net primary production
PDF	Potentially disappeared fraction
PEF	Product environmental footprint
SDG	Sustainable development goal
WTA	Withdrawal to availability
WSI	Water stress indicator
WF	Water footprint
WULCA	Water use in LCA

Data availability

No new data were created or analysed in this study. Data sharing is not applicable to this article.

Author contributions

Basit A. Mir: conceptualization, methodology, visualization, writing – original draft, writing – review & editing, investigation. Anissa Nurdiawati: conceptualization, writing – review & editing. Sami G. Al-Ghamdi: conceptualization, writing – review & editing, supervision, project administration, funding acquisition.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This research was supported by a scholarship from King Abdullah University of Science and Technology (KAUST). We would like to express our sincere gratitude to Dr. Yoshihide Wada, Professor, BESE division, KAUST for his invaluable guidance and providing useful feedback for this research work.

References

1 M. Piesse, Global water supply and demand trends point towards rising water insecurity, 2020 May.
2 E. Pierrat, V. Barbarossa, M. Núñez, L. Scherer, A. Link and M. Damiani, *et al.*, Global water consumption impacts on riverine fish species richness in Life Cycle Assessment, *Sci. Total Environ.*, 2023, **854**, 158702.
3 Water report UN, Partnerships and cooperation for water The United Nations World Water Development Report 2023 Executive Summary, 2023.
4 M. Mannan and S. G. Al-Ghamdi, Environmental impact of water-use in buildings: Latest developments from a life-cycle assessment perspective, *J. Environ. Manage.*, 2020, **261**, 110198.
5 S. Sbahieh, M. Z. Serdar and S. G. Al-Ghamdi, Decarbonization strategies of building materials used in the construction industry, *Mater. Today: Proc.*, 2023, S2214785323046163.
6 F. Tahir, A. A. B. Baloch and H. Ali, Resilience of Desalination Plants for Sustainable Water Supply in Middle East, in *Sustainability Perspectives: Science, Policy and Practice*, ed. P. A. Khaiter and M. G. Erechtchoukova, Strategies for Sustainability, Springer International Publishing, Cham, 2020, pp. 303–329, DOI: 10.1007/978-3-030-19550-2_15.
7 S. B. Ajjur and S. G. Al-Ghamdi, Evapotranspiration and water availability response to climate change in the Middle East and North Africa, *Clim. Change*, 2021, **166**(3–4), 28.
8 M. S. Afzal, F. Tahir and S. G. Al-Ghamdi, Impact of Onshore Construction Activities on Sea Water Turbidity, in *Environment and Sustainable Development*, ed. K. Ujikawa, M. Ishiwatari and E. V. Hullebusch, Environmental Science and Engineering, Springer Nature Singapore, Singapore, 2023, pp. 17–24, DOI: 10.1007/978-981-99-4101-8_2.
9 C. Ray, D. McInnes and M. Sanderson, Virtual water: its implications on agriculture and trade, *Water Int.*, 2018, **43**(6), 717–730.
10 T. Allan, *Virtual Water: Tackling the Threat to Our Planet's Most Precious Resource*, 2011, available from: https://books.google.com.sa/books?hl=en&lr=&id=BBCMDwAAQBAJ&oi=fnd&pg=PP1&ots=f-xGhWV7Ag&sig=BZH0m8L53qtYC17s_2kaQWsT02I&redir_esc=y#v=onepage&q&f=false.
11 D. Vanham, L. Alfieri, M. Flörke, S. Grimaldi, V. Lorini and A. D. Roo, *et al.*, The number of people exposed to water stress in relation to how much water is reserved for the environment: a global modelling study, 2021, available from: https://www.thelancet.com/journals/lanplh/article/PIIS2542-5196(21)00234-5/fulltext.
12 A. B. Yao, O. M. J. Mangoua, E. S. Georges, A. Kane and B. T. A. Goula, Using "Water Evaluation and Planning" (WEAP) Model to Simulate Water Demand in Lobo Watershed (Central-Western Cote d'Ivoire), *J. Water Resour. Prot.*, 2021, **13**(03), 216–235.
13 D. Wang, K. Hubacek, Y. Shan, W. Gerbens-Leenes and J. Liu, A review of water stress and water footprint accounting, *Water*, 2021, **13**(2), 201.
14 J. Liu, H. Yang, S. N. Gosling, M. Kummu, M. Flörke and S. Pfister, *et al.*, Water scarcity assessments in the past, present, and future, *Earth's Future*, 2017, **5**(6), 545–559.
15 A. Y. Hoekstra, A. K. Chapagain, M. M. Aldaya and M. M. Mekonnen, *The Water Footprint Assessment Manual: Setting the Global Standard*, 2011, available from: https://www.earthscan.co.uk.
16 A. Y. Hoekstra, Water Footprint Assessment: Evolvement of a New Research Field, *Water Resour. Manag.*, 2017, **31**(10), 3061–3081.

This journal is © The Royal Society of Chemistry 2025

Open Access Article. Published on 16 1403. Downloaded on 07/11/1404 10:48:58 ..
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

17 F. Greco, M. Keulertz and D. Dent, Virtual Water, in *Oxford Research Encyclopedia of Environmental Science*, Oxford University Press, 2023.
18 G. Finnveden and J. Potting, Life Cycle Assessment, in *Encyclopedia of Toxicology*, Elsevier, 3rd edn, 2014, pp. 74–77.
19 14040 ISO, ISO 14040:2006 - Environmental management — Life cycle assessment — Principles and framework, 2006, available from: **https://www.iso.org/standard/37456.html**.
20 14044 ISO, ISO 14044:2006 - Environmental management — Life cycle assessment — Requirements and guidelines, 2006, available from: **https://www.iso.org/standard/38498.html**.
21 JRC, European Commission - Joint Research Centre - Institute for Environment and Sustainability: International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance, First edition March 2010, EUR 24708 EN, Publications Office of the European Union, Luxembourg, 2010.
22 B. A. Mir, Comparative life cycle assessment (LCA) of different waste treatment scenarios for plastic fraction of e-waste, 2023, available from: **https://www.politesi.polimi.it/handle/10589/191716**.
23 O. Jolliet and R. Frischknecht, Global Guidance on Environmental Life Cycle Impact Assessment Indicators-Vol 2, 2019, available from: **https://www.lifecycleinitiative.org**.
24 O. Jolliet and R. Frischknecht, Global Guidance for Life Cycle Impact Assessment Indicators-Vol 1, 2016, available from: **https://www.lifecycleinitiative.org**.
25 M. Alhaj, F. Tahir and S. G. Al-Ghamdi, Life-cycle environmental assessment of solar-driven Multi-Effect Desalination (MED) plant, *Desalination*, 2022, **524**, 115451.
26 M. Berger and M. Finkbeiner, Water footprinting: How to address water use in life cycle assessment?, *Sustainability*, 2010, **2**(4), 919–944.
27 S. Pfister, A. Koehler and S. Hellweg, Assessing the environmental impacts of freshwater consumption in LCA, *Environ. Sci. Technol.*, 2009, **43**(11), 4098–4104.
28 J. B. Bayart, C. Bulle, L. Deschênes, M. Margni, S. Pfister and F. Vince, *et al.*, A framework for assessing off-stream freshwater use in LCA, *Int. J. Life Cycle Assess.*, 2010, **15**(5), 439–453.
29 L. Milà i Canals, J. Chenoweth, A. Chapagain, S. Orr, A. Antón and R. Clift, Assessing freshwater use impacts in LCA: Part I—inventory modelling and characterisation factors for the main impact pathways, *Int. J. Life Cycle Assess.*, 2009, **14**(1), 28–42.
30 A. M. Boulay, A. Y. Hoekstra and S. Vionnet, Complementarities of water-focused life cycle assessment and water footprint assessment, *Environ. Sci. Technol.*, 2013, **47**(21), 11926–11927.
31 A. M. Boulay, C. Bulle, J. B. Bayart, L. Deschênes and M. Margni, Regional characterization of freshwater use in LCA: Modeling direct impacts on human health, *Environ. Sci. Technol.*, 2011, **45**(20), 8948–8957.
32 A. M. Boulay, M. Motoshita, S. Pfister, C. Bulle, I. Muñoz and H. Franceschini, *et al.*, Analysis of water use impact assessment methods (part A): evaluation of modeling choices based on a quantitative comparison of scarcity and human health indicators, *Int. J. Life Cycle Assess.*, 2015, **20**(1), 139–160.
33 M. Motoshita, Y. Ono, S. Pfister, A. M. Boulay, M. Berger and K. Nansai, *et al.*, Consistent characterisation factors at midpoint and endpoint relevant to agricultural water scarcity arising from freshwater consumption, *Int. J. Life Cycle Assess.*, 2018, **23**(12), 2276–2287.
34 A. M. Boulay, J. Bare, L. Benini, M. Berger, M. J. Lathuillière and A. Manzardo, *et al.*, The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE), *Int. J. Life Cycle Assess.*, 2018, **23**(2), 368–378.
35 W. Gerbens-Leenes, M. Berger and J. Allan, Water Footprint and Life Cycle Assessment: The Complementary Strengths of Analyzing Global Freshwater Appropriation and Resulting Local Impacts, *Water*, 2021, **13**(6), 803.
36 M. Berger, S. Pfister and M. Motoshita, Water Footprinting in Life Cycle Assessment: How to Count the Drops and Assess the Impacts?, in *Special Types of Life Cycle Assessment*, ed. M. Finkbeiner, LCA Compendium – The Complete World of Life Cycle Assessment, Springer Netherlands, Dordrecht, 2016, pp. 73–114, DOI: **10.1007/978-94-017-7610-3_3**.
37 M. Goedkoop, The Eco-indicator 99 Methodology, *Journal of Life Cycle Assessment, Japan*, 2007, **3**(1), 32–38.
38 A. Kounina, M. Margni, J. B. Bayart, A. M. Boulay, M. Berger and C. Bulle, *et al.*, Review of methods addressing freshwater use in life cycle inventory and impact assessment, *Int. J. Life Cycle Assess.*, 2013, **18**(3), 707–721.
39 O. Jolliet, A. Antón, A. M. Boulay, F. Cherubini, P. Fantke and A. Levasseur, *et al.*, Global guidance on environmental life cycle impact assessment indicators: impacts of climate change, fine particulate matter formation, water consumption and land use, *Int. J. Life Cycle Assess.*, 2018, **23**(11), 2189–2207.
40 WFN, Water Footprint Network, 2023, available from: **https://www.waterfootprint.org/**.
41 B. G. Ridoutt and J. Huang, Environmental relevance - The key to understanding water footprints, *Proc. Natl. Acad. Sci. U. S. A.*, 2012, **109**(22), E1424.
42 M. Berger, R. V. D. Ent, S. Eisner, V. Bach and M. Finkbeiner, Water accounting and vulnerability evaluation (WAVE): Considering atmospheric evaporation recycling and the risk of freshwater depletion in water footprinting, *Environ. Sci. Technol.*, 2014, **48**(8), 4521–4528.
43 A. Y. Hoekstra, A critique on the water-scarcity weighted water footprint in LCA, *Ecol. Indic.*, 2016, **66**, 564–573.
44 *Handbook on Life Cycle Assessment, Operational Guide to the ISO Standards*, ed. J. B. Guinée, M. Gorrée, R. Heijungs, G. Huppes, R. Kleijn, A. de Koning, L. van Oers, A. Wegener Sleeswijk, S. Suh, H. A. Udo de Haes, H. de Bruijn, R. van

Open Access Article. Published on 16 1403. Downloaded on 07/11/1404 10:48:58 .. This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

Duin, M. A. J. Huijbregts, E. Lindeijer, A. A. H. Roorda, B. L. van der Ven and B. P. Weidema, Institute for Environmental Sciences, Leiden University, Leiden, 2002.
45 M. A. J. Huijbregts, Z. J. N. Steinmann, P. M. F. Elshout, G. Stam, F. Verones and M. Vieira, *et al.*, ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level, *Int. J. Life Cycle Assess.*, 2017, **22**(2), 138–147.
46 M. M. Hanafiah, M. A. Xenopoulos, S. Pfister, R. S. E. W. Leuven and M. A. J. Huijbregts, Characterization factors for water consumption and greenhouse gas emissions based on freshwater fish species extinction, *Environ. Sci. Technol.*, 2011, **45**(12), 5272–5278.
47 R. V. Zelm, A. M. Schipper, M. Rombouts, J. Snepvangers and M. A. J. Huijbregts, Implementing groundwater extraction in life cycle impact assessment: Characterization factors based on plant species richness for the Netherlands, *Environ. Sci. Technol.*, 2011, **45**(2), 629–635.
48 14046 ISO, ISO 14046:2014 - Environmental management — Water footprint — Principles, requirements and guidelines, 2014, available from: **https://www.iso.org/standard/43263.html**.
49 D. Nepomilueva, Water scarcity indexes: water availability to satisfy human needs, 2017, available from: **https://core.ac.uk/download/pdf/84797448.pdf**.
50 A. M. Boulay, K. Drastig, Amanullah, A. Chapagain, V. Charlon and B. Civit, *et al.*, Building consensus on water use assessment of livestock production systems and supply chains: Outcome and recommendations from the FAO LEAP Partnership, *Ecol. Indic.*, 2021, **124**, 107391.
51 F. R. Rijsberman, Water scarcity: Fact or fiction?, *Agric. Water Manag.*, 2006, **80**(1–3), 5–22.
52 S. Damkjaer and R. Taylor, The measurement of water scarcity: Defining a meaningful indicator, *Ambio*, 2017, **46**(5), 513–531.
53 P. D. Raskin, E. Hansen and R. M. Margolis, Water and sustainability: Global patterns and long-range problems, *Nat. Resour. Forum*, 1996, **20**(1), 1–15.
54 D. Vanham, A. Y. Hoekstra, Y. Wada, F. Bouraoui, A. de Roo and M. M. Mekonnen, *et al.*, Physical water scarcity metrics for monitoring progress towards SDG target 6.4: An evaluation of indicator 6.4.2 "Level of water stress", *Sci. Total Environ.*, 2018, **613–614**, 218–232.
55 A. M. Boulay, J. Bare, L. Benini, M. Berger, I. Klemmayer and M. Lathuilliere, *et al.*, Building consensus on a generic water scarcity indicator for LCA-based water footprint: preliminary results from WULCA, 2014.
56 A. Hélias, Comments on the international consensus model for the water scarcity footprint (AWARE) and proposal for an improvement, *Sci. Total Environ.*, 2020, **709**, 136189.
57 A. Y. Hoekstra, M. M. Mekonnen, A. K. Chapagain, R. E. Mathews and B. D. Richter, Global monthly water scarcity: Blue water footprints versus blue water availability, *PLoS One*, 2012, **7**(2), e32688.
58 A. M. Boulay, C. Bulle, L. Deschênes and M. Margni, LCA Characterisation of Freshwater Use on Human Health and Through Compensation, in *Towards Life Cycle Sustainability Management*, Springer Netherlands, 2011, pp. 193–204.
59 H. Munia, J. H. A. Guillaume, N. Mirumachi, M. Porkka, Y. Wada and M. Kummu, Water stress in global transboundary river basins: significance of upstream water use on downstream stress, *Environ. Res. Lett.*, 2016, **11**(1), 14002.
60 J. Alcamo, P. Döll, T. Henrichs, F. Kaspar, B. Lehner and T. Rösch, *et al.*, Development and testing of the WaterGAP 2 global model of water use and availability, *Hydrol. Sci. J.*, 2003, **48**(3), 317–337.
61 H. Xu and M. Wu, Water Availability Indices-A Literature Review Energy Systems Division, 2017, available from: **https://www.anl.gov**.
62 A. Smart and B. Sc, Life Cycle Assessment Of Freshwater Use In The Semi-Arid Okanagan: Building The Framework For New LCIA Impact Pathways Of Freshwater Use For Terrestrial Ecosystems And Modeling Irrigation Water Infrastructure And Use In Horticulture, *Master of science*, University of British Columbia, 2023.
63 D. Vanham and M. M. Mekonnen, The scarcity-weighted water footprint provides unreliable water sustainability scoring, *Sci. Total Environ.*, 2021, **756**, 143992.
64 D. Vanham, Envisaged methodologies for sustainable food labelling policies might worsen water scarcity, *Sci. Total Environ.*, 2023, **905**, 167021.
65 WWAP, *United Nations World Water Development Report*, UNESCO, 2003, available from: **https://www.unesco.org/en/wwap/wwdr**.
66 M. Falkenmark, J. Lundqvist and C. Widstrand, Macro-scale water scarcity requires micro-scale approaches, *Nat. Resour. Forum*, 1989, **13**(4), 258–267.
67 P. H. Gleick, Basic Water Requirements for Human Activities: Meeting Basic Needs, *Water Int.*, 1996, **21**(2), 83–92.
68 L. OhIsson, Water conflicts and social resource scarcity, *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere*, 2000, **25**(3), 213–220.
69 J. Rockström, M. Falkenmark, L. Karlberg, H. Hoff, S. Rost and D. Gerten, Future water availability for global food production: The potential of green water for increasing resilience to global change, *Water Resour. Res.*, 2009, **45**(7), 2007WR006767.
70 D. Gerten, J. Heinke, H. Hoff, H. Biemans, M. Fader and K. Waha, Global Water Availability and Requirements for Future Food Production, *J. Hydrometeorol.*, 2011, **12**(5), 885–899.
71 V. Smakhtin, C. Revenga, P. Döll and Institute IWM, *Taking into account environmental water requirements in global-scale water resources assessments*, International Water Management Institute, 2004, p. 24.
72 C. J. Vörösmarty, E. M. Douglas, P. A. Green and C. Revenga, Geospatial Indicators of Emerging Water Stress: An Application to Africa. AMBIO: A Journal of the Human, *Environment*, 2005, **34**(3), 230–236.
73 M. T. H. van Vliet, M. Flörke and Y. Wada, Quality matters for water scarcity, *Nat. Geosci.*, 2017, **10**(11), 800–802.

 This journal is © The Royal Society of Chemistry 2025

Open Access Article. Published on 16 1403. Downloaded on 07/11/1404 10:48:58 ..
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

74 S. Casadei, F. Peppoloni and A. Pierleoni, A new approach to calculate the water exploitation index (WEI+), *Water*, 2020, **12**(11), 1–16.
75 Y. Wada and M. F. P. Bierkens, Sustainability of global water use: past reconstruction and future projections, *Environ. Res. Lett.*, 2014, **9**(10), 104003–104003.
76 M. Tuninetti, S. Tamea and C. Dalin, Water Debt Indicator Reveals Where Agricultural Water Use Exceeds Sustainable Levels, *Water Resour. Res.*, 2019, **55**(3), 2464–2477.
77 C. Sullivan, Calculating a Water Poverty Index, *World Dev.*, 2002, **30**(7), 1195–1210, available from: https://www.elsevier.com/locate/worlddev.
78 C. A. Sullivan, J. R. Meigh and A. M. Giacomello, The Water Poverty Index: Development and application at the community scale, *Nat. Resour. Forum*, 2003, **27**(3), 189–199.
79 D. W. Seckler, *World water demand and supply, 1990 to 2025: scenarios and issues*, International Water Management Institute, 1998, p. 40.
80 J. B. Bayart, S. Worbe, J. Grimaud and E. Aoustin, The Water Impact Index: A simplified single-indicator approach for water footprinting, *Int. J. Life Cycle Assess.*, 2014, **19**(6), 1336–1344.
81 Z. Zeng, J. Liu and H. H. G. Savenije, A simple approach to assess water scarcity integrating water quantity and quality, *Ecol. Indic.*, 2013, **34**, 441–449.
82 J. Liu, Q. Liu and H. Yang, Assessing water scarcity by simultaneously considering environmental flow requirements, water quantity, and water quality, *Ecol. Indic.*, 2016, **60**, 434–441.
83 W. Liu, X. Liu, H. Yang, P. Ciais and Y. Wada, Global Water Scarcity Assessment Incorporating Green Water in Crop Production, *Water Resour. Res.*, 2022, **58**(1), e2020WR028570.
84 Z. Hussain, Z. Wang, J. Wang, H. Yang, M. Arfan and D. Hassan, *et al.*, A comparative Appraisal of Classical and Holistic Water Scarcity Indicators, *Water Resour. Manag.*, 2022, **36**(3), 931–950.
85 D. Vanham, A. Y. Hoekstra and G. Bidoglio, Potential water saving through changes in European diets, *Environ. Int.*, 2013, **61**, 45–56.
86 Y. Ran, C. Cederberg, M. Jonell, K. Bergman, I. J. M. De Boer and R. Einarsson, *et al.*, Environmental assessment of diets: overview and guidance on indicator choice, *Lancet Planet. Health*, 2024, **8**(3), e172–e187.
87 J. F. Schyns, A. Y. Hoekstra, M. J. Booij, R. J. Hogeboom and M. M. Mekonnen, Limits to the world's green water resources for food, feed, fiber, timber, and bioenergy, *Proc. Natl. Acad. Sci. U. S. A.*, 2019, **116**(11), 4893–4898.
88 J. F. Schyns, A. Y. Hoekstra and M. J. Booij, Review and classification of indicators of green water availability and scarcity, *Hydrol. Earth Syst. Sci.*, 2015, **19**(11), 4581–4608.
89 Z. Hussain, Z. Wang, H. Yang, M. Arfan, W. Wang and M. Faisal, *et al.*, Evolution and Trends of Water Scarcity Indicators: Unveiling Gaps, Challenges, and Collaborative Opportunities, *Water Conserv. Sci. Eng.*, 2024, **9**(1), 8.
90 P. M. Pilane, H. Jordaan and Y. T. Bahta, A Systematic Review of Social Sustainability Indicators for Water Use along the Agricultural Value Chain, *Hydrology*, 2024, **11**(5), 72.
91 S. Pfister, S. Vionnet, T. Levova and S. Humbert, ETH Library Ecoinvent 3: assessing water use in LCA and facilitating water footprinting, *Int. J. Life Cycle Assess.*, 2016, 1349–1360.
92 A. Koehler, Water use in LCA: Managing the planet's freshwater resources, *Int. J. Life Cycle Assess.*, 2008, **13**(6), 451–455.
93 F V. UNEP/SETAC Life Cycle Initiative working group: assessment of water use and consumption within LCA, Veolia Environment, Paris, 2007.
94 A. M. Boulay, C. Bouchard, C. Bulle, L. Deschênes and M. Margni, Categorizing water for LCA inventory, *Int. J. Life Cycle Assess.*, 2011, **16**(7), 639–651.
95 Gabi, Product Sustainability Software and Data Suite| Sphera (GaBi), 2016, available from: https://sphera.com/product-sustainability-software/.
96 Ecoinvent, Ecoinvent Database, 2013, available from: https://ecoinvent.org/the-ecoinvent-database/.
97 Quantis, Quantis (2013) The Quantis water database, available at http://www.quantis-intl.com/waterdatabase.php, 30 July 2013, 2013.
98 FAOSTAT, FAO (2015) Food and Agricultural Organization of the United Nations. AQUASTAT, available at http://www.fao.org/nr/water/aquastat/main/index.stm, 3 Mar 2015, available from: https://www.fao.org/faostat/en/#home, 2015.
99 GEMI, GEMI (2013) Collecting the drops, Connecting the drops, The Local water tool, available at http://www.gemi.org/waterplanner/, Global Environmental Management Initiative, available from: https://gemi.org/solutions/, 2013.
100 S. Pfister, P. Bayer, A. Koehler and S. Hellweg, Projected water consumption in future global agriculture: Scenarios and related impacts, *Sci. Total Environ.*, 2011, **409**(20), 4206–4216.
101 S. Pfister, P. Bayer, A. Koehler and S. Hellweg, Environmental Impacts of Water Use in Global Crop Production: Hotspots and Trade-Offs with Land Use, *Environ. Sci. Technol.*, 2011, **45**(13), 5761–5768.
102 B. G. Ridoutt and S. Pfister, A new water footprint calculation method integrating consumptive and degradative water use into a single stand-alone weighted indicator, *Int. J. Life Cycle Assess.*, 2013, **18**(1), 204–207.
103 B. G. Ridoutt and S. Pfister, Reducing humanity's water footprint, *Environ. Sci. Technol.*, 2010, **44**(16), 6019–6021.
104 M. Z. Hauschild and H. Wenzel, *Environmental Assessment of Products*, 1998, vol. 2, Scientific Background, available from: https://orbit.dtu.dk/en/publications/environmental-assessment-of-products-volume-2-scientific-backgrou.
105 J. Dewulf, M. E. Bösch, B. D. Meester, G. V. D. Vorst, H. V. Langenhove and S. Hellweg, *et al.*, Cumulative exergy extraction from the natural environment (CEENE): A comprehensive life cycle impact assessment method for resource accounting, *Environ. Sci. Technol.*, 2007, **41**(24), 8477–8483.

Open Access Article. Published on 16 1403. Downloaded on 07/11/1404 10:48:58 ..
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

106 M. E. Bösch, S. Hellweg, M. A. J. Huijbregts and R. Frischknecht, Applying Cumulative Exergy Demand (CExD) indicators to the ecoinvent database, *Int. J. Life Cycle Assess.*, 2007, **12**(3), 181–190.
107 Foen, The Ecological Scarcity Method – Eco-Factors 2006, 2006.
108 E. Norbert, Hildesheimer Gabi Swiss Council for Sustainable Development, 2006, available from: **https://www.researchgate.net/publication/237790160**.
109 A. C. Brent, A life cycle impact assessment procedure with resource groups as areas of protection, *Int. J. Life Cycle Assess.*, 2004, **9**(3), 172–179.
110 PEF, Environmental Footprint methods - European Commission [Internet], available from: **https://green-business.ec.europa.eu/environmental-footprint-methods_en**.
111 M. Motoshita, N. Itsubo and A. Inaba, Development of impact factors on damage to health by infectious diseases caused by domestic water scarcity, *Int. J. Life Cycle Assess.*, 2011, **16**(1), 65–73.
112 M. Motoshita, N. Itsubo, K. Tahara and A. Inaba, Damage Assessment Model for Freshwater Consumption and a Case Study on PET Bottle Production Applied New Technology for Water Footprint Reduction, in *Towards Life Cycle Sustainability Management [Internet]*, ed. M. Finkbeiner, Springer Netherlands, Dordrecht, 2011, pp. 399–410, available from: **http://link.springer.com/10.1007/978-94-007-1899-9_39**.
113 WHO, Disability-adjusted life years (DALYs), 2020, available from: **https://www.who.int/data/gho/indicator-metadata-registry/imr-details/158**.
114 S. Humbert and R. Maendly, Characterization factors for damage to aquatic biodiversity caused by water use especially from dams used for hydropower 35 LCA forum Zurich Water in LCA, 2008.
115 K. Turgeon, G. Trottier, C. Turpin, C. Bulle and M. Margni, Empirical characterization factors to be used in LCA and assessing the effects of hydropower on fish richness, *Ecol. Indic.*, 2021, **121**, 107047.
116 M. Damiani, P. Roux, E. Loiseau, N. Lamouroux, H. Pella and M. Morel, *et al.*, A high-resolution life cycle impact assessment model for continental freshwater habitat change due to water consumption, *Sci. Total Environ.*, 2021, **782**, 146664.
117 F. Verones, K. Kuipers, M. Núñez, F. Rosa, L. Scherer and A. Marques, *et al.*, Global extinction probabilities of terrestrial, freshwater, and marine species groups for use in Life Cycle Assessment, *Ecol. Indic.*, 2022, **142**, 109204.
118 EPD, EPD International, 2018, available from: **https://www.environdec.com/home**.
119 A. M. Boulay, L. Lenoir and A. Manzardo, Bridging the data gap in the water scarcity footprint by using crop-specific AWARE factors, *Water*, 2019, **11**(12), 2634.
120 S. Pfister and P. Bayer, Monthly water stress: Spatially and temporally explicit consumptive water footprint of global crop production, *J. Cleaner Prod.*, 2014, **73**, 52–62.
121 M. J. Lathuillière, C. Bulle and M. S. Johnson, A contribution to harmonize water footprint assessments, *Global Environ. Change*, 2018, **53**, 252–264.
122 É. Pierrat, A. Laurent, M. Dorber, M. Rygaard, F. Verones and M. Hauschild, Advancing water footprint assessments: Combining the impacts of water pollution and scarcity, *Sci. Total Environ.*, 2023, **870**, 161910.
123 FAO, LEAP guidelines for water use assessment of livestock production systems and supply chains. Draft for public review, Livestock Environmental Assessment and Performance Partnership, FAO, Rome, Italy, 2019.
124 B. G. Ridoutt and S. Pfister, A revised approach to water footprinting to make transparent the impacts of consumption and production on global freshwater scarcity, *Global Environ. Change*, 2010, **20**(1), 113–120.
125 A. Boulay, P. Lesage, B. Amor and S. Pfister, Quantifying uncertainty for AWARE characterization factors, *J. Ind. Ecol.*, 2021, **25**(6), 1588–1601.
126 J. Sanchez-Matos, E. P. Andrade and I. Vázquez-Rowe, Revising regionalized water scarcity characterization factors for selected watersheds along the hyper-arid Peruvian coast using the AWARE method, *Int. J. Life Cycle Assess.*, 2023, **28**(11), 1447–1465.
127 R. N. Gejl, P. L. Bjerg, H. J. Henriksen, M. Z. Hauschild, J. Rasmussen and M. Rygaard, Integrating groundwater stress in life-cycle assessments – An evaluation of water abstraction, *J. Environ. Manage.*, 2018, **222**, 112–121.
128 F. Verones, D. Saner, S. Pfister, D. Baisero, C. Rondinini and S. Hellweg, Effects of Consumptive Water Use on Biodiversity in Wetlands of International Importance, *Environ. Sci. Technol.*, 2013, **47**(21), 12248–12257.
129 D. Gerten, H. Hoff, J. Rockström, J. Jägermeyr, M. Kummu and A. V. Pastor, Towards a revised planetary boundary for consumptive freshwater use: role of environmental flow requirements, *Curr. Opin. Environ. Sustain.*, 2013, **5**(6), 551–558.
130 R. Kaewmai, T. Grant, S. Eady, J. Mungkalasiri and C. Musikavong, Improving regional water scarcity footprint characterization factors of an available water remaining (AWARE)method, *Sci. Total Environ.*, 2019, **681**, 444–455.
131 P. A. Bontinck, T. Grant, R. Kaewmai and C. Musikavong, Recalculating Australian water scarcity characterisation factors using the AWARE method, *Int. J. Life Cycle Assess.*, 2021, **26**(8), 1687–1701.
132 E. P. Andrade, A. B. de Araújo Nunes, K. de Freitas Alves, C. M. L. Ugaya, M. da Costa Alencar and T. de Lima Santos, *et al.*, Water scarcity in Brazil: part 1—regionalization of the AWARE model characterization factors, *Int. J. Life Cycle Assess.*, 2020, **25**(12), 2342–2358.
133 K. De, F. Alves, E. P. Andrade, J. P. Savioli, A. Valerie and M. C. B. D. Figueirêdo, *et al.*, Implications of lca choices on interpretation of results and on decision support water scarcity in Brazil: part 2-uncertainty assessment in regionalized characterization factors, *Int. J. Life Cycle Assess.*, 2020, **25**, 2359–2379.

134 A. M. Boulay and L. Lenoir, Sub-national regionalisation of the AWARE indicator for water scarcity footprint calculations, *Ecol. Indic.*, 2020, **111**, 106017.

135 J. S. Lee, M. H. Lee, Y. Y. Chun and K. M. Lee, Uncertainty analysis of the water scarcity footprint based on the AWARE model considering temporal variations, *Water*, 2018, **10**(3), 341.

136 R. Kaewmai, T. Grant, J. Mungkalasiri and C. Musikavong, Assessing the water scarcity footprint of food crops by growing season available water remaining (AWARE) characterization factors in Thailand, *Sci. Total Environ.*, 2021, **763**, 143000.

137 P. Nilsalab, S. H. Gheewala and T. Silalertruksa, Methodology development for including environmental water requirement in the water stress index considering the case of Thailand, *J. Cleaner Prod.*, 2017, **167**, 1002–1008.

138 L. Ansorge and T. Beránková, LCA Water Footprint Aware Characterization Factor Based On Local Specific Conditions, *Eur. J. Sustain. Dev.*, 2017, **6**(4), 13–20.

139 J. Sieber, WEAP Water Evaluation and Planning System, 2015, available from: **https://scholarsarchive.byu.edu/iemssconference/2006/all/397**.

140 P. Quinteiro, S. Rafael, P. Villanueva-Rey, B. Ridoutt, M. Lopes and L. Arroja, *et al.*, A characterisation model to address the environmental impact of green water flows for water scarcity footprints, *Sci. Total Environ.*, 2018, **626**, 1210–1218.

141 L. García-Herrero, D. Gibin, M. Damiani, E. Sanyé-Mengual and S. Sala, What is the water footprint of EU food consumption? A comparison of water footprint assessment methods, *J. Cleaner Prod.*, 2023, **415**, 137807.

142 A. E. Calvillo-Arriola and P. X. Sotelo-Navarro, A step towards sustainability: life cycle assessment of coffee produced in the indigenous community of Ocotepec, Chiapas, Mexico, *Discov. Sustain.*, 2024, **5**(1), 17.

143 K. Usva, E. Virtanen, H. Hyvärinen, J. Nousiainen, T. Sinkko and S. Kurppa, Applying water scarcity footprint methodologies to milk production in Finland, *Int. J. Life Cycle Assess.*, 2019, **24**(2), 351–361.

144 P. Villanueva-Rey, P. Quinteiro, I. Vázquez-Rowe, S. Rafael, L. Arroja and M. T. Moreira, *et al.*, Assessing water footprint in a wine appellation: A case study for Ribeiro in Galicia, Spain, *J. Cleaner Prod.*, 2018, **172**, 2097–2107.

145 E. Borsato, E. Giubilato, A. Zabeo, L. Lamastra, P. Criscione and P. Tarolli, *et al.*, Comparison of Water-focused Life Cycle Assessment and Water Footprint Assessment: The case of an Italian wine, *Sci. Total Environ.*, 2019, **666**, 1220–1231.

146 S. Almunefi, R. Alessa and N. Alnajdi, Comparative Life Cycle Assessment On Fuel Types For A Formula 1 Mercedes Engine In Belgian Grand Prix [Internet], 2023, available from: **https://www.researchgate.net/publication/374472890**.

147 U. Lee, H. Xu, J. Daystar, A. Elgowainy and M. Wang, AWARE-US: Quantifying water stress impacts of energy systems in the United States, *Sci. Total Environ.*, 2019, **648**, 1313–1322.

148 A. Mas-Fons, R. Horta Arduin, P. Loubet, T. Pereira, A. M. Parvez and G. Sonnemann, Carbon and water footprint of battery-grade lithium from brine and spodumene: A simulation-based LCA, *J. Cleaner Prod.*, 2024, **452**, 142108.

149 P. Baustert, E. Igos, T. Schaubroeck, L. Chion, A. Mendoza Beltran and E. Stehfest, *et al.*, Integration of future water scarcity and electricity supply into prospective LCA: Application to the assessment of water desalination for the steel industry, *J. Ind. Ecol.*, 2022, **26**(4), 1182–1194.

150 J. S. Boeira, A. M. Boulay, M. Jacob, D. Dardor, P. Pedenaud and M. Margni, Use of the Life Cycle Approach for the Evaluation of Industrial Water Management Alternatives, in *SPE*, 2024.

Open Access Article. Published on 16 1403. Downloaded on 07/11/1404 10:48:58 ..
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.