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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.

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

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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.

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

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

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}

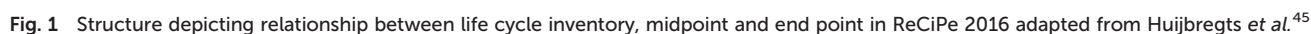
and LCA community were set up to address it. The WF and LCA communities have been engaged in an ongoing methodological discussion, primarily centered over the issue of considering the WF either as an impact-based or as a volumetric indicator. While the WF community favors volumetric indicator, they assert 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

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}

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



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, DTA_x, 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



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,

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

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 <i>per capita</i> 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 <i>per capita</i> 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 <i>per capita</i> 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 <i>per capita</i> per day) needed to produce 3000 kilocalories <i>per capita</i> 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 <i>vice versa</i>
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



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's⁷⁶ 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



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 water¹⁰ 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,



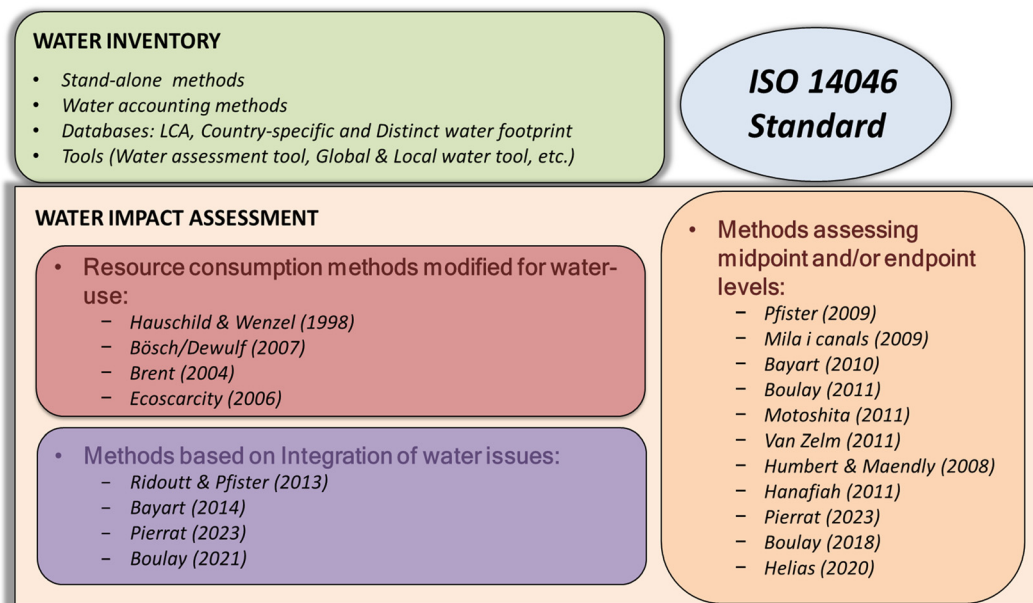


Fig. 3 Classification of water inventories and impact assessment methods obtained from the literature.

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

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 network⁴⁰). 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

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. Brent¹⁰⁹ 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 Pfister¹⁰³ in addressing and interpreting the water footprint. The revised method involved incorporating the stress CFs to calculate the stress-weighted water footprint expressed in H₂O 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 framework³⁷ 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

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

- *Damage to aquatic ecosystems due to damming.* The method developed by Humbert and Maendly¹¹⁴ 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

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 m³ 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 m³ year per m³.^{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-SETAC⁹³ 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:

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

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

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

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 AMD_i , understood as the surface-time equivalent needed to produce one cubic meter of unused water, STe_i , is given in eqn (4) below:

$$ST_{ei} = \frac{1}{AMD_i} \quad (4)$$

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

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

However, when the demand $\geq$ 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 $\text{m}^3_{\text{world eq.}} \cdot \text{m}^{-3}_{\text{i}}$. 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.

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

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 H₂O 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

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}

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.

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

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 Gabi⁹⁵ and Ecoinvent⁹⁶ 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, EDIP¹⁰⁴ 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 Brent¹⁰⁹ 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's²⁹ 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's²⁸ method addressed the issue of including human health considerations within Milà i Canals's²⁹ 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 Maendly¹¹⁴ 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

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 Hélias⁵⁶ 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 Australia¹³¹ 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 Beránková¹³⁸ 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

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 Pfister¹⁰² 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

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 <i>et al.</i> (2009) ²⁹	CF for FD: abiotic depletion potential	Midpoint	Resources
	CF for FEI: WSI by Smakhtin		Ecosystem
Bayart <i>et al.</i> (2010) ²⁸	CF: calculated using WTA, functionality, quality, and compensation ability factors	Midpoint	Human health
Boulay <i>et al.</i> (2011) ³¹	CF: water stress index	Midpoint	Human health, ecosystem and resources
	CF: fate, exposure and effect	Endpoint	Human health
Motoshita <i>et al.</i> (2011, 2018) ^{33,111}	Regression models to report damage in DALYs	Endpoint	Human health
Zelm <i>et al.</i> (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 <i>et al.</i> (2011) ⁴⁶	CF: based on water consumption, PDF, and volume of river basin	Endpoint	Ecosystem
Pierrat <i>et al.</i> (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 <i>et al.</i> (2014) ⁸⁰	Water scarcity index and water quality index	Midpoint	Ecosystem
Boulay <i>et al.</i> (2021) ⁵⁰	Water productivity and scarcity	—	—
Pierrat <i>et al.</i> (2023) ¹²²	WBF: CFs related to various parameters	Endpoint	Human health, ecosystem and resources
	WRF: pollution and scarcity deprivation potential and pollution weighting factor		

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.

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

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 Usua *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

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



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

Withdrawal to availability
(WTA)

midpoints into endpoints enhances the clarity and interpretability of LCIA results through various damage pathways but has a high uncertainty than midpoint

Rainwater stored in soil, used by plants, primarily in agriculture, impacting calculations of water use in food production

A method that examines the environmental impact of a product throughout its life cycle, from raw materials to disposal

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

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

Total freshwater used, directly and indirectly, in a product's life cycle, including consumption and pollution effects

A measure evaluating regional stress on water resources due to consumption, considering both availability and demand

A ratio that assesses the proportion of available water withdrawn, indicating regional water scarcity levels

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

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.

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