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Water footprint and AWARE LCA indicator: practices and recommendations

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- Les informations et les conclusions présentées dans le présent document ont été établies au vu des données scientifiques et techniques et d'un cadre réglementaire et normatif en vigueur à la date de l'édition des documents.

Pour la synthèse en anglais :

- SCORE LCA is an association that has been created to financially support collaborative research on LCA and related topics. It aims to promote and organize cooperation between companies, institutional and scientists in order to support the evolution of LCA methods and its practical implementation at European and international level.
- This work has been supported by ADEME (Agence de l'Environnement et de la Maîtrise de l'Energie) www.ademe.fr
- The views and recommendations expressed in this publication are those of the authors and do not necessarily reflect, unless otherwise stated, the views of all members of SCORE LCA.
- The information and conclusions presented in this document were established on the basis of scientific and technical data and regulatory and normative framework in force at the date of the publication of documents.

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1. Context and Objectives

1.1 Context

The "water" issue in Life Cycle Assessment (LCA) is a complex one. Water interacts with LCA systems in several ways:

- Its origin and nature, e.g. river water, groundwater/well water, rainwater, sea water etc., as a medium providing a resource, or providing services, and which can be impacted in different ways;
- The range of services it provides, as a source of "water" resources for humans (drinking, irrigation for agriculture, cooling for industry etc.) and ecosystems, as a means of transport (impacted by sargassum, plastics, scarcity, etc.), as a source of energy and food production, and for recreation;
- Its availability for intended uses varies over time, as there may be less water available for a specific use in summer compared to winter. For instance, withdrawing 1 m³/s net from a river with a flow of 2 m³/s is not equivalent to withdrawing the same amount from a river with a flow of 500 m³/s.
- Its quality before its use in the life cycle (perhaps requiring treatment to enable the desired use);
- Its depletion (quantitative and percentage-based) following its use (more or less efficient, see ISO 24528) considering what is returned versus what is withdrawn and where. For instance, discharging 1 m³/s back into a river after withdrawal is different from discharging 1 m³/s of evaporated water into the atmosphere after withdrawal from the same river;
- Its role as a transfer vector for substances affecting the water quality after use through the life cycle, both in terms of substance content (COD, BOD, N, P, SS, microplastics, persistent substances etc.) and temperature;
- The water excess (floods, tsunamis, etc.) or scarcity (drought) depends on climatic conditions and the effects of these extremes on the life cycle.

It is essential to be able to account for local considerations in LCA (as discussed in other SCORE LCA projects), such as the flow rate of the river where water is withdrawn or the temperature of river water before thermally polluted water is discharged. Such information is not typically collected in LCAs and goes beyond the collection of activity data for each industrial site and product-related data. Several existing environmental indicators (e.g. characterized in Product Environmental Footprint- PEF) will help the LCA practitioner wishing to analyze a product from the point of view of the "water" issue:

- Available Water Remaining (AWARE) method for water scarcity which is recommended at the international level and widely used by LCA practitioners;
- Eutrophication (freshwater and marine),
- Aquatic ecotoxicity,
- Water acidification, etc.

More generally, the ISO 14046 "Water footprint" (ISO, 2014) standard provides a comprehensive methodological framework based on the life cycle perspective for taking into account the various environmental impacts associated with water use~~.~~ It sets out requirements for transparency regarding what is being assessed and thus provides a dictionary of unambiguous definitions to be used in reporting.

Other practices such as those of the Water Footprint Network (WFN) also have a regional or even international recognition coupled with slightly different specific calculation methods. Those metrics and methods developed outside of LCA will be covered in Chapter 5.

1.2 Objectives

The objectives of the study are to:

- Identify how companies account for and assess water-related issues based on their practices (LCA and beyond), with a particular focus on water scarcity,
- Identify how LCA addresses water-related issues, as well as water-related issues that are not covered by LCA,
- Summarize how LCA guidelines and standards recommend assessing water-related issues,
- Analyze AWARE, as the prevalent water-scarcity LCA method, and compare it to non-LCA metrics and methods,
- Carry out case studies to identify issues of application and interpretation of methods and tools,
- Formulate practical recommendations in light of the state of the art and the results of the case studies.

As AWARE appears as the prevalent water scarcity method in LCA, a more detailed analysis is performed, highlighting its advantages and limitations. Some aspects analyzed are:

- The meaning and intended objective of the indicator,
- The quality and completeness of the data used to calculate the characterization factors,
- Geographical and temporal scales,
- Inventory data required to calculate results,
- The interpretation of results,
- The most suitable LCA software.

The expected benefits of this study are as follows:

- A better understanding of water-related indicators recommended and their link with the ISO 14046 standard,
- Identification of methodological and practical issues when calculating an LCA-based water footprint;
- Methodological and practical recommendations to consider water-related issues in LCA.

2. Impact assessment frameworks for water-related environmental issues and normative development

2.1 Definition of water-related environmental issues

Water-related environmental issues can be categorized into different types:

- water availability issues,
- water degradation issues and,
- issues caused by changes in habitats.

Water availability issues include problems related to situations where the demand for water of a certain quality exceeds the availability of that water in a given region. ISO 14046 (ISO, 2017) differentiates two types of water availability issues:

- **Water scarcity** is the "extent to which demand for water compares to the replenishment of water in an area, e.g. a *drainage basin*" (ISO, 2017). According to ISO, the demand and the availability of water considered in water scarcity do not take into account the water quality. Hence water scarcity would only be affected by the net physical consumption of water (i.e. water removed from the area after its use)[1].
- **Water availability** is defined as the "extent to which humans and ecosystems have sufficient water resources for their needs" (ISO, 2017). This includes the water physically removed from the area by other users (water scarcity) together with other elements that affect the amount of water available to respond to the needs of humans and ecosystems, namely 1) the loss of quality (e.g. an increase of pollutants in water affects the growing of aquatic species or the amount of drinking water available), and 2) the modification of ecosystems and habitats (e.g. the drainage of a wetland or the construction of a dam affect the available water in the area).

Both types of water availability issues strongly depend on the timing and the location, as human consumption and demand from the ecosystems vary depending on these two dimensions. They are also strongly influenced by the economic state of the region. Indeed, in wealthy regions, the loss of available water can be more easily compensated by economic and technological adaptation measures (desalinization, transfers of water from other regions).

Water degradation issues are caused by the emission of substances that affect "physical (e.g. thermal), chemical and biological characteristics of water concerning its suitability for an intended use by humans or ecosystems" (ISO, 2017). The modification of these characteristics can lead to direct impacts on humans (human toxicity, microbial diseases via drinking water…) and ecosystems (ecotoxicity, thermal pollution, eutrophication of water…) or indirect impacts, namely the decrease of water availability mentioned above.

Changes in habitats result in different environmental water-related issues both directly and indirectly. The flooding of an area due to the construction of a dam or the transformation of land into an agricultural field affects the availability of water resources both directly (increase of evapotranspiration, depletion of groundwater resources) and indirectly (runoff of pesticides, sedimentation, and alteration of natural water flow regimes).

As shown by the examples, these three types of water-related environmental issues are interconnected, and some impacts can be caused by a combination of these issues or one of these issues, and can result in an increase in other issues (e.g. increase in pollution can lead to a reduction of water availability of a certain quality).

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[1] The difference between water scarcity and water availability is not as clear as in ISO 14046 for all authors and sometimes both terms are used ambiguously.

As most basic human water-related needs are provided by freshwater (drinking and sanitation, agriculture), most of these issues, the metrics developed, and the measures proposed focus on this particular water resource.

Water-related environmental issues are caused by several factors:

- Water consumption and over-exploitation: The increasing demand for freshwater due to population growth and intensive use (mainly in agricultural and industrial activities) results in withdrawal rates over the renewability of the resource.
- Climate change: some of the effects of climate change are closely related to the water cycle: altered precipitation patterns, prolonged droughts, and glacial melt reduce the availability of freshwater. Additionally, sea level rise results in saltwater intrusion into freshwater aquifers, further limiting usable water supplies.
- Habitat change and urbanization: Outdated infrastructure and lack of water conservation practices result in significant water loss. Urban expansion increases impermeable surfaces, reducing groundwater recharge and exacerbating water shortages.
- Pollution from human activities: Industrial discharges, emissions from agricultural production (pesticides, fertilizers, and animal waste), and discharges from urban areas (sewage and wastes).
- Discharge of new substances: such as microplastics, drugs, and cosmetics, that arrive in water after their use and alter the quality of the water.

Main environmental consequences associated with water-related environmental issues can be grouped into:

- **Water deprivation for human needs**: the lack of water can affect the capacity to cover all needs (drinking, sanitation, etc.) for a population in a certain region. Also, the use of contaminated water sources when no alternative exists increases the prevalence of waterborne diseases such as cholera and dysentery.

- **Ecosystem Degradation and Biodiversity Loss:** Polluted waters impair the health of aquatic ecosystems, leading to reduced species diversity through different pathways (eutrophication, acidification, ecotoxicity). Activities such as wetland drainage, river damming, and deforestation degrade natural water filtration systems and disrupt aquatic habitats, further deteriorating water quality and altering the flow regimes. Those changes can result in loss of biodiversity and degradation of ecosystems.

The water-related environmental issues can also have impacts at economic and political levels:

- Economic impacts: water scarcity and low-quality water need to be compensated by water treatment processes (desalinization, wastewater treatments) and healthcare costs associated with treating waterborne diseases. Additionally, other industries such as fisheries and tourism can also be affected by the loss of quality and availability of water.

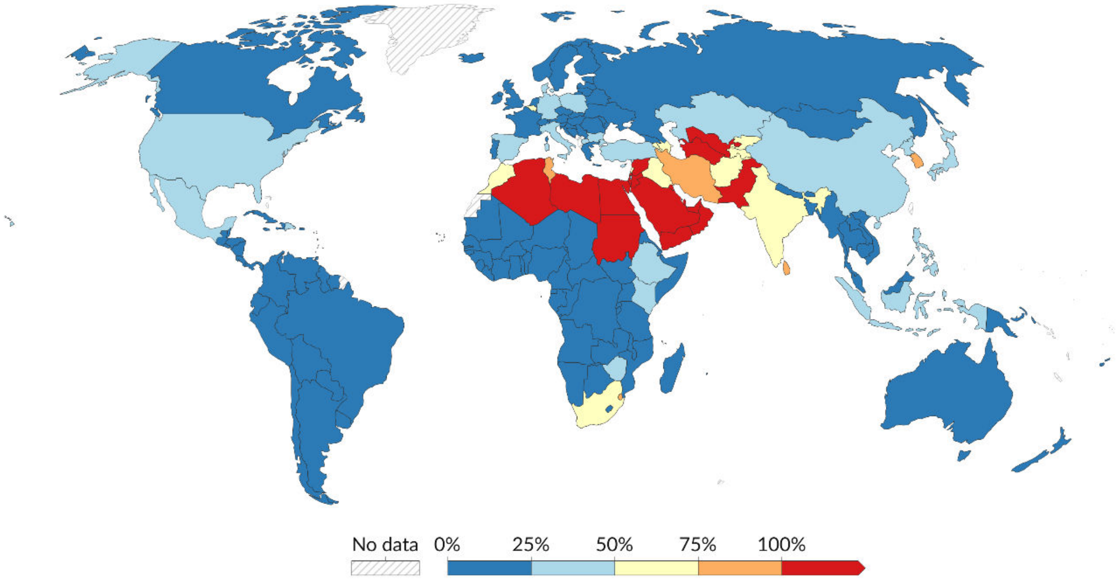
- Political conflicts: Competing demands for shared water resources can lead to regional tensions (although cooperation arises too from competing demands) (Kåresdotter et al., 2023).

The response to some of these impacts can produce an additional impact on the water resources. For example, water availability issues force the adoption of inefficient irrigation practices (illegal wells), leading to soil degradation and lower crop yields. Also, the lack of resources can lead to an overuse of groundwater that would result in lowered water tables, ground sinking, reduction of land usability and salinization of groundwater.

As mentioned, the unequal distribution of water resources on the globe combined with the different intensities of human activity (water consumption and human activities leading to water degradation) results in different intensities of the described impacts depending on the region. Figure 1 shows the variability over countries in freshwater withdrawals over the available freshwater in the World in 2021.

Freshwater withdrawals as a share of internal resources, 2021

Freshwater withdrawals refer to total water withdrawals from agriculture, industry and municipal/domestic uses. Withdrawals can exceed 100% of total renewable resources where extraction from non-renewable aquifers or desalination plants is considerable.



Data source: Food and Agriculture Organization of the United Nations OurWorldinData.org/water-use-stress | CC BY

Note: Five classes have been identified to signal different levels of stress on water sources: <25%: *no stress*, 25-50%: *low stress*, 50-75%: *medium stress*, 75-100%: *high stress* and >100%: *critical stress*.

Figure 1: Freshwater withdrawals as a share of internal resources in the World in 2021 (extracted from OurWorldinData.org).

Considering these environmental issues and the inequal distribution, the measure of the freshwater resources in the supply chain of companies has become an important issue in controlling different kinds of risk:

- Physical risks related to water scarcity or water degradation can affect the supply chain and result in lower productivity.
- Regulatory risks related to policies, laws, or governance structures can affect water use in supply chains.
- Reputational risks can affect the company's image and the public, investors and stakeholders' trust due to unsustainable or unethical water use practices.

2.2 Historical context for the assessment of water-related environmental issues

2.2.1 First non-LCA initiatives

The importance of the environmental issues related to water and the risks associated with them led to initiatives to assess and report the impact of human activities on water resources, mainly from the beginning of the 2000s.

- In 2002, Arjen Hoekstra introduced the concept of the water footprint for the first time (Hoekstra & Hung, 2002) (although similar concepts such as virtual water were already developed in the 90s), which quantifies the total volume of freshwater used in the supply chain to produce goods and services and emphasized the need to consider both direct and indirect water consumption of products and companies. Note that the definition of water footprint has evolved since then and varies depending on the framework (see sections 2.4.1 and 3.1).

- Also in 2002, The Global Environmental Management Initiative (GEMI) introduced the Water Sustainability (Global Environmental Management Initiative (GEMI), 2002) to help organizations understand and manage water resources and associated risks. A few years later, in 2006, the Global reporting initiative included in its Reporting Guidelines, specific performance indicators related to water (total water withdrawal, sources significantly affected by withdrawal, water recycled and reused).
- The CEO water mandate (2007), a UN Global Compact initiative, aimed to engage business leaders on water stewardship, sustainability, and the global water crisis, mainly by adopting comprehensive water strategies and reporting their progress.
- The Alliance for Water Stewardship (AWS) was established in 2008 as a global coalition of businesses, non-governmental organizations, and public sector entities dedicated to promoting responsible water use. The AWS's mission is to advance water stewardship worldwide by developing and implementing a universal framework for sustainable water management.
- The Carbon Disclosure Project (CDP) launched the Global Water Disclosure Project in 2009 to address the growing concerns of water scarcity and its implications for businesses and investors. This initiative provides a standardized platform for companies to disclose their water usage, management practices, and associated risks and opportunities.
- The Water Valuation Guidance Document, published in 2010 by the Canadian Council of Ministers of the Environment (CCME), provided a framework for establishing the value of water, including different values associated with water resources (economic, cultural, spiritual, traditional, and intrinsic values).
- The AWS published in 2014 the International Water Stewardship Standard, a framework for water stewardship, guiding organizations in understanding and managing their water use within the context of their catchment area.

2.2.2 Development of first tools

Following these initiatives and projects, different tools were developed to help assess water impacts and risks:

- The Global Water Tool (GWT), developed by the World Business Council for Sustainable Development (WBCSD), was first launched in 2007. It is a free, Excel-based resource designed to help companies and organizations map their water use and assess risks relative to their global operations and supply chains.
- Ceres Aqua Gauge, launched in 2011, is an Excel-based tool developed by Ceres to assist companies and investors in evaluating and enhancing corporate water management practices. It provides a structured framework to assess the comprehensiveness and effectiveness of a company's water stewardship effort.
- The Aqueduct Water Risk Atlas (2013), developed by the World Resources Institute (WRI), provides an online platform where global water risks can be identified and assessed. Several indicators are included in this tool.

2.2.3 Development within LCA

Within the life cycle assessment (LCA) community, the first accounting efforts of the water use impacts are the use of LCI results of the total water withdrawn in the life cycle as an additional impact category. This accounting was problematic since it was made at the inventory level and did not consider the Life Cycle Impact Assessment (LCIA) methods development principles. With this inventory level accounting, the impact of the consumption of 1 m^3 of water in an arid region such as Morocco, is equal to the consumption of the same amount in regions where freshwater resources are abundant.

LCIA methods rely on physical cause-effect chains to attribute a relative weight to different inventory flows based on their effect on the environment. In this case, the relative weight should consider key elements such as the temporality or the location of those withdrawals. Besides, the accounting was based on inventories calculated with databases where water flows were not complete nor balanced.

The first initiative to account for water issues in the LCA community appeared in 2007 when the UNEP/SETAC's Life Cycle Initiative launched the Water Use in LCA (WULCA) working group. This multi-stakeholder group had as its main objectives to:

- Develop a general assessment framework for water use including indicators that measure the environmental impacts on human health, ecosystems and freshwater resources(Bayart et al., 2010) detailed this framework. This framework tried to establish the environmental consequences of off-stream freshwater use (water extracted from the biosphere for human activities) and described the water types to be considered. Two types of impacts are covered by this framework, those based on water degradation and those associated with its use. The framework highlights the importance of considering the regional and temporal aspects of water scarcity.;
- establish adequate water inventory schemes and parameters;
- establish impact assessment methods for characterizing water use and related environmental impacts;
- derive recommended practice and guidance for LCA method developers and practitioners.

Alongside these initiatives, in 2009 ISO launched the works to develop an international standard for water footprint (ISO, 2014) (see sections 2.4.1 and 3.1 for further detail).

Following these initiatives, LCA-specific tools were developed also. In 2012, Quantis published the Quantis Water Database Framework (Vionnet et al., 2012). This framework provided the first structured approach to assess water-related impacts in LCA. This framework integrated water use data and regional scarcity factors to evaluate potential environmental impacts. The database and its approach were integrated into version 3 of ecoinvent in 2013. In the inventory phase, the Quantis Water Database Framework aimed to quantify water flows entering and leaving the system under study and to ensure that the water balance (inputs=outputs) was respected. Figure 2 shows the general LCI framework proposed. All inputs and output flows for the two main intensive water use categories of processes (industrial and agricultural). In both cases, the inputs from the biosphere, the water consumed (either incorporated in the product or evaporated) and the water returned to the biosphere are considered. Other flows such as seawater, water for turbine use or rain (naturally occurring) are included too.

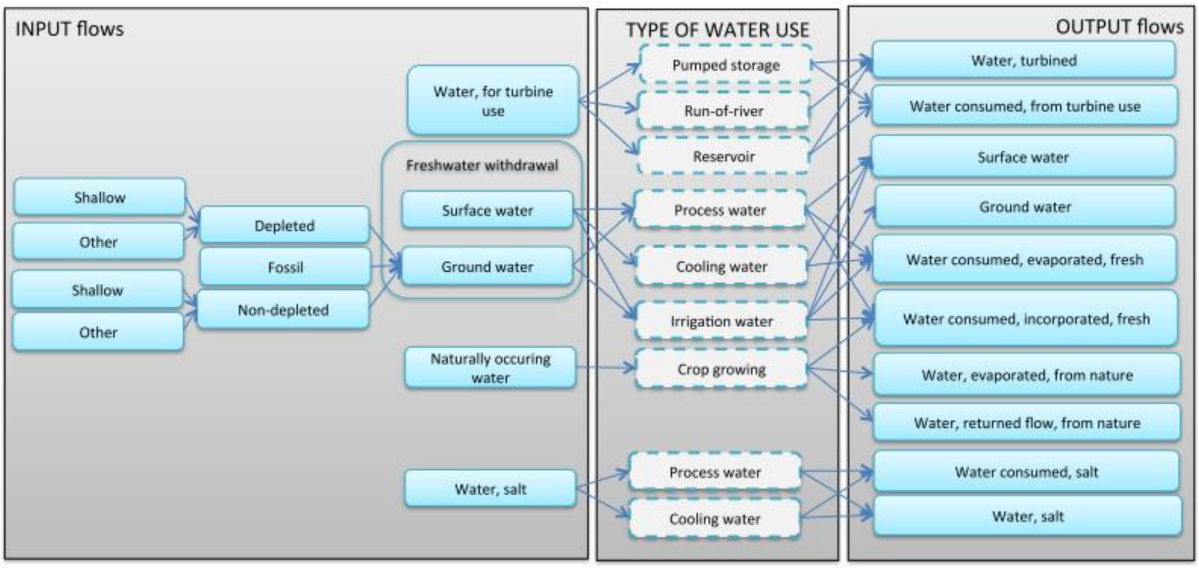


Figure 1: Life cycle inventory (LCI) framework of the Quantis Water Database

Figure 2: LCI framework from the Quantis Water Database Framework (extracted from Vionnet et al. 2012).

Several authors published LCIA methods to assess the potential impacts of water consumption at different levels, for instance:

- In 2009, Pfister published the Water Stress Index (WSI) (Pfister et al., 2009), which evaluates water scarcity by considering the ratio of water withdrawals to availability (WTA) in specific regions, adjusted for factors such as seasonal variability and flow regulation.
- (Boulay, Bulle, Deschênes, et al., 2011) developed a method to assess the impact on human health caused by water scarcity and water degradation.
- (Motoshita et al., 2011) developed a methodology to assess the human health impacts resulting from domestic water. This approach quantifies the potential health effects by linking water consumption to the prevalence of infectious diseases, particularly those arising from inadequate water access and considering socioeconomic variables to account for differences influencing the vulnerability of populations to water-related health issues.

In 2015, the AWARE method (Boulay et al., 2018). was developed under the work of WULCA group (see section 4 for further detail). This method was developed as a consensual method to harmonize practices. Several initiatives and guidelines have recommended AWARE since its publication:

- The UNEP/SETAC Life Cycle Initiative through the Pellston Workshop in 2016 and afterwards in their 2018 publication of the “Global Guidance on environmental life cycle impact assessment indicators” (Frischknecht & Jolliet, 2017), recommend this method to assess water-scarcity impacts in LCA.
- The European Commission also recommends this method in their LCIA method (European Commission, 2021).
- Multiple sectorial guidelines and Product Category Rules also recommend AWARE’s use for water-related impacts.

2.3 Main frameworks for assessing water-related environmental issues

Based on the historical development and the main aim of this report, we differentiated two approaches to assess water-related environmental issues:

- **LCA-based**, which adopts a life cycle perspective and follows standardized frameworks such as ISO 14040/44. This approach uses a systemic perspective, considering the whole life cycle, and translating inventory flows into potential environmental impacts. This approach produces

quantitative impact results used for comparative assessments (versus other products, a benchmark, etc.).
- **Non-LCA-based**, which adopts a variety of approaches to assess water-related environmental issues, such as risk assessment, assessment of quality, risks and availability. These methods vary in their perspective (only some consider the supply chain), the way of calculating the results (quantitative, qualitative) or the final use of the results.

This report primarily focuses on LCA-based approaches but some other widely used tools based on non-LCA-based approaches are also discussed in section 5.

2.4 Norms and guidelines for assessing water-related environmental issues using an LCA-based framework

2.4.1 ISO 14046 Water footprint

The development of ISO 14046 began in 2009 under the coordination of the Swiss Association for Standardization (SNV). The main objective was to establish a comprehensive framework to assess the environmental impacts of water use across the entire life cycle of products and services. The working process included about 100 experts from various countries, and it involved numerous working meetings and draft publications over the process. After five years of discussions and deliberations, the standard was published in August 2014 under the title *ISO 14046: Water footprint – Principles, requirements, and guidelines* (ISO, 2014). It is important to consider that the term “Water Footprint” does not originate from the LCA community. Instead, the term was originally used in the works of the “Water Footprint Network” (WFN, see section 5.1.4). The WFN approach is commonly referred to as a “volumetric” approach since it expresses the Water Footprint in volumes of water consumed and of water required to dilute pollutants below a certain concentration threshold. The LCA approach instead is referred to as “impact-oriented”.

ISO 14046 is strongly based on the ISO 14040/44 series. It introduces the concept of the water footprint, which quantifies the potential environmental impacts associated with water use in terms of both quantity and quality. While it is not clearly stated, the norm refers mainly to freshwater use. One of the main characteristics and big differences with ISO 14040/44 is the need to consider both the spatial and temporal dimensions when assessing the impacts of water use, such as water scarcity in different regions and sometimes the timing of water withdrawals and releases.

The standard provides a similar framework to ISO 10440/44 series, with the four phases of LCA: Goal and Scope definition (G&S), Inventory (LCI), LCIA and Interpretation. The four stages contain the same elements as those in ISO 14040/44 with some specificities linked to the unique character of water assessment. Section 3.1 provides further detail on certain aspects of the four phases in the context of their implementation with LCIA methods.

2.4.2 Other norms and guidelines

Following the publication of ISO 14046, the ISO/TR 14073 (ISO, 2017) was published. This technical report aimed to provide examples for applying the principles of ISO 14046 Water footprint. The document aims to guide users through the process of calculating and reporting water footprints by providing examples of different types of water footprint assessments for products, processes, and organizations, with a particular focus on the potential impact of water scarcity. Through the examples, the technical report highlights the importance of factors like location, seasonality, and the types of water used (freshwater vs. recycled) in the results of water footprint assessments. Also, the choice of appropriate impact assessment methods and the use of local data for more accurate results are covered in the examples.

As mentioned in section 2.2.3, international organisms such as the European Commission or the UNEP life cycle initiative include in its LCIA method a category to assess water use, including AWARE as the method to be used.

In the agri-food sector, the FAO has published several guidelines and documents over the years. The Sustainability Assessment of Food and Agriculture (SAFA) guidelines (FAO, 2014) provide a framework for evaluating the sustainability of agri-food supply chains. Multiple aspects of sustainability are covered by the guidelines (economic, environmental, social and governance). Water is one of the themes covered in the environmental aspects and it is evaluated by using the water withdrawal, with no specific LCA-based indicator mentioned. The LEAP (Livestock Environmental Assessment and Performance Partnership) guidelines (Boulay, Drastig, et al., 2021; FAO, 2019) provide specific information for conducting water use LCA of livestock production systems. These guidelines focus on water scarcity assessment and water productivity. For Water scarcity footprint (WSF) two different indicators are recommended: AWARE and the Blue Water Scarcity Index, based on WFN’s work. In the WBCSD Guidance on the assessment of freshwater use in LCA (WBCSD, 2021), AWARE is also mentioned as one of the indicators to measure changes in water availability.

Other sectorial guidelines including the assessment of water-related issues with an LCA perspective are:

- In the construction sector, EN 15804, specifically EN 15804:2012+A2:2019 (CEN, 2019), provides a comprehensive framework for assessing the environmental performance of construction products. Among the recommended indicators, AWARE is the one used for the water use category.
- In the chemical sector, the WBCSD published the Chemical Sector Life Cycle Metrics Guidance (WBCSD, 2014), including the WSI as the indicator to use for Water Scarcity assessment.

Among product category rules (PCR), the international Environmental Product Declaration (EPD) system includes AWARE as the indicator to use for the category of Water deprivation potential[2].

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[2] https://www.environdec.com/pcr/env-perf-indic/gpi4

3. Implementing the ISO Water Footprint using water-related LCA methods

As described in section 1.1, a multitude of environmental issues are related to or interact with the water compartment. Consequentially, many LCIA methods consider water somewhere along their impact pathway. The following sections first define the general framework of the ISO Water Footprint and water-related LCIA methods, before the implementation of Water Footprints using these methodologies is explored. The chapter closes with a summary of challenges occurring when implementing Water Footprints.

3.1 The general framework of the ISO Water Footprint

A **Water Footprint** (WF) helps to better understand the potential environmental impacts of human activities that are linked to water resources. The general framework of the WF is defined in the standard ISO14046 (ISO, 2014). Since ISO 14046 is based on the LCA framework defined in ISO 14044, the WF strongly resembles a typical LCA but focuses on water-related environmental impacts. It encompasses the four phases G&S, LCI, LCIA, and "Interpretation", which also form the basis of LCA according to ISO14040/44 (section 2.4).

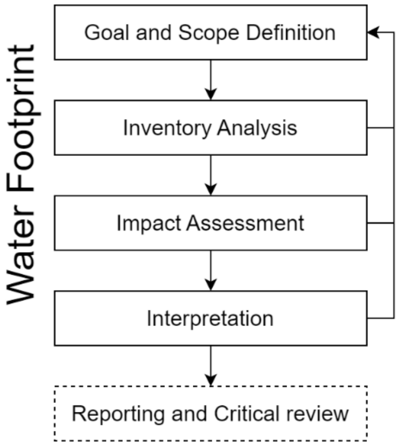

Figure 3. The four mandatory phases of a Water Footprint, and the optional steps of reporting and critical review as described in ISO14046. Note the iterative character: Findings in different phases can lead to an adjustment of the study for previous phases.

The **G&S phase** is required to define the goal of the WF (including the application intended and the targeted audience) and its scope. Several aspects can be relevant for the scope definition, most importantly the definition of the system under study and its boundaries, its functional unit and its spatiotemporal resolution and coverage. Indeed, when defining the system boundaries, the location of unit processes must be considered since water consumption issues depend on the local conditions of scarcity.

The G&S phase also defines the set of impact categories that will be used to assess the water-related impacts and whether they are weighted to obtain a single score. In a comprehensive WF, all relevant water-related impacts are assessed. If only a subset of impacts is assessed, e.g. water consumption impacts, this has to be specifically mentioned here. The selected impact categories determine whether the study can be called a (comprehensive) Water Footprint or whether a qualifier has to be used to further specify the scope, such as in "Water *Scarcity* Footprint".

In the **LCI phase**, relevant data is collected to conduct the WF. ISO 14046 lists data that might be required, for example, the types of water use (e.g. integration into product, evaporation, release in other watersheds, etc.), and the used quantities, their quality (e.g., physical and chemical parameters: temperature, BOD, COD, etc.) and type of resource (surface water, groundwater, etc.). It might be relevant to gather data on additional environmental perturbations that might affect water quality or quantity, such as land use changes. Note that the data requirements can depend on the environmental impacts to be assessed. For example, data on the emission of eutrophicating substances might not be required if the WF focuses on Water Scarcity impacts only. Additionally, attributes of the activities can be relevant, such as locations and timing of water use, or seasonal changes in the water bodies. The quality of the used data needs to be assessed and documented, including missing data points.

The inventory essentially constitutes a quantification of all activities relevant to the environmental impacts to fulfill the functional unit, and as such its creation might be an iterative process. The completion of the LCI phase results in the Water Footprint Inventory can be presented and interpreted at this phase, without the LCIA phase. However, "*the results of a water footprint inventory analysis may be reported, but shall not be reported as a water footprint*" (ISO, 2014).

In the LCI phase, sensitivity analyses should be conducted to refine the system boundaries according to which processes might additionally be relevant for the WF or which processes could be neglected based on their low relevance to the overall environmental impact. The sensitivity analysis commonly includes performing a preliminary impact assessment (see next paragraph) to evaluate the importance of specific parts of the inventory. At the end of the process, a collection of elementary flows is obtained. These elementary flows are the water-relevant flows exchanged between the Technosphere and Ecosphere. Consequentially, flows between human infrastructure (economic flows which are part of the Technosphere), such as wastewater flows from an industrial site towards a wastewater treatment plant, are not part of the inventory. The water released from a wastewater treatment plant into a river (an elementary flow between Technosphere and Ecosphere) however is part of the inventory.

In the **Impact Assessment phase**, potential environmental impacts of the inventory are evaluated. This phase presents the main differences with the reference norms. Depending on the impact categories included in the analysis, the definition of the WF differs. According to the norm, **all water-related categories should be included to calculate a comprehensive WF**. In this sense, the norm states that "*the term water footprint shall only be used to describe the result(s) of a comprehensive water footprint assessment. If water-related potential environmental impacts have not been comprehensively assessed, then the term water footprint shall only be used with a qualifier*" (ISO, 2014). "*A qualifier is one or several additional words used in conjunction with the term "water footprint" to describe the impact category/categories studied in the water footprint assessment, e.g. "water availability footprint", "water scarcity footprint", "water eutrophication footprint", "water ecotoxicity footprint", "water acidification footprint", "noncomprehensive water footprint*" (ISO, 2014).

LCA commonly defines Areas of Protection (AoPs), such as Natural Resources and Ecosystem Services, Human Health (HH), and Ecosystem Quality (EQ) (Bulle et al., 2019; Verones, Bare, et al., 2017). These AoP's represent the final receptors of environmental impacts. Besides assessing impacts on the AoP's (which is called "damage level" or "endpoint level" impact assessment), impacts can also be assessed on the environmental problem level (called the "midpoint level").

To evaluate the potential impacts, water-relevant impact categories (such as Freshwater Eutrophication, Freshwater Acidification, or Water Scarcity) are selected as planned in the G&S phase. Subsequently, the elementary flows relevant to these categories are classified – that is, assigned to these impact categories – and characterized according to their potential impacts. With LCIA methodology, the characterization to obtain the impact score for an impact category is a multiplication of the quantity of each elementary flow (e.g., 10 m^3 water per month extracted from groundwater) with their corresponding characterization factor (CF) that characterizes this flow according to its impact in the selected impact category. Performing this calculation for the entire inventory results in the "Water Footprint Profile", a collection of impact scores for the selected impact categories. **ISO14046 allows an aggregation of the Water Footprint Profile into a single indicator**. However, this aggregation must follow guidelines outlined in ISO14044 and is not allowed to be used for comparative statements disseminated to the public.

The norm highlights in this phase the importance of using LCIA methods that consider geographical and temporal issues, as water issues are highly dependent on them.

The **interpretation phase** completes the WF. It commonly includes a contribution analysis (which process, or flow contributes most to which impact category?) and sensitivity analyses (how would results change if certain assumptions were changed?). The conclusions of a WF study can be increased by performing an uncertainty assessment and checks of data consistency and completeness. Exploring spatiotemporal aspects can be especially relevant for a thorough interpretation. Furthermore, weighting individual impact categories to obtain one final standalone indicator is not required for a WF (but is possible).

In addition to the four phases described above, the ISO standard describes how the results of the WF shall be reported and, if required, critically reviewed. In the context of reporting, it is important to note that ISO 14046 does not allow offsetting, that is the reduction of impact assessment results by reducing environmental impacts somewhere else, not connected to the system under study. The entire WF result must originate from the system boundaries defined in the G&S phase and can not include compensations resulting from other activities.

Note that ISO 14046 explicitly defines the "**Water Footprint Inventory Study**" as a counterpart of the WF, skipping the Impact Assessment phase. While a Water Footprint Inventory Study informs on the exchanges (elementary flows) of a product system with the environment, it does not provide information on its potential environmental impacts and is thus of limited value for assessing the sustainability of water use. Thus, assessing the inventory without a subsequent impact assessment does not constitute a WF. This is an important aspect in the context of other inconsistencies in the use of the term "Water Footprint".

The literature also uses the term "Water Footprint" for analyses which differ substantially from the scope of this report. The most prominent examples are studies following the WFN approach (section 5.1.4). Except from these, Sturla et al. (2023) develop the "Social-Scarce Water Footprint" in the context of multi-regional input-output analysis which weights the CFs of the WSI (Pfister et al., 2009) by the Human Development Index. Schomberg et al. (2023) calculate "Water Quality Footprints" for the entire German bioeconomy (not an activity or process in the meaning of the Water Footprint ISO).

3.2 Which environmental issues should be covered by a Water Footprint?

According to ISO 14046, a "*water footprint considers all environmentally relevant attributes or aspects of the natural environment, human health and resources related to water (including water availability and water degradation*)" (ISO, 2014). In LCA, potential environmental impacts are assessed by applying LCIA methods to the inventory of elementary flows: These flows can represent emissions (e.g., the emission of a kg of NO_x to air, or the emission of $1m^3$ of water in air), or extractions (e.g., the extraction of 1 kg of iron ore, or the extraction of $1m^3$ of water from surface water). A multitude of LCIA methods are related to water and could therefore be part of a WF. The identification and selection of these methods require a definition of "water-related".

In this report, "water-related" LCIA methods are methods where water is involved as a contaminant exposure media (i.e. Human Toxicity, Acidification, Eutrophication, Thermal Pollution) or a used resource and habitat (Water Depletion and Scarcity, River Fragmentation). ISO 14046 states that in specific cases water types other than freshwater can be relevant to a WF and that the modeller needs to evaluate whether including them is appropriate (ISO, 2014). However, later in this report, we focus on *freshwater*-related impacts. Since a core part of this report is guidance on the use of the AWARE method, an important focus of the report will be on Water Scarcity Footprints. Impact categories concerning marine impacts are out of the scope of the report. We furthermore do not consider methods characterizing green water use, such as (Núñez et al., 2013; Quinteiro et al., 2018).

3.2.1 Identifying water-related LCIA methods

There are three groups of water-related LCIA methods, defined by their impact pathway (Figure 4):

- **"Quantitative" changes of the water compartment**: These impacts regard the hydrological characteristics of a freshwater body. Examples are the human consumption of freshwater and subsequent reduction in water availability, or the change of a river flow regime (and thus water availability and its temporal characteristics) due to the operation of hydropower dams (Dorber et al., 2024).

- **“Qualitative” change of the water compartment** (in the following called “water degradation”): Water degradation commonly results from water polluting activities, which means that the water body’s chemical or physical properties are changed. One example is the emission of heavy metals into water bodies, which changes the chemical composition of the water and might have toxic effects on aquatic species (Douziech et al., 2024).
- **Changes in the aquatic (freshwater) habitat**: There currently is only a handful of LCIA methods dealing with this impact pathway. One example is the estimation of changes in wetland areas due to water consumption (Verones & Pfister, 2013).

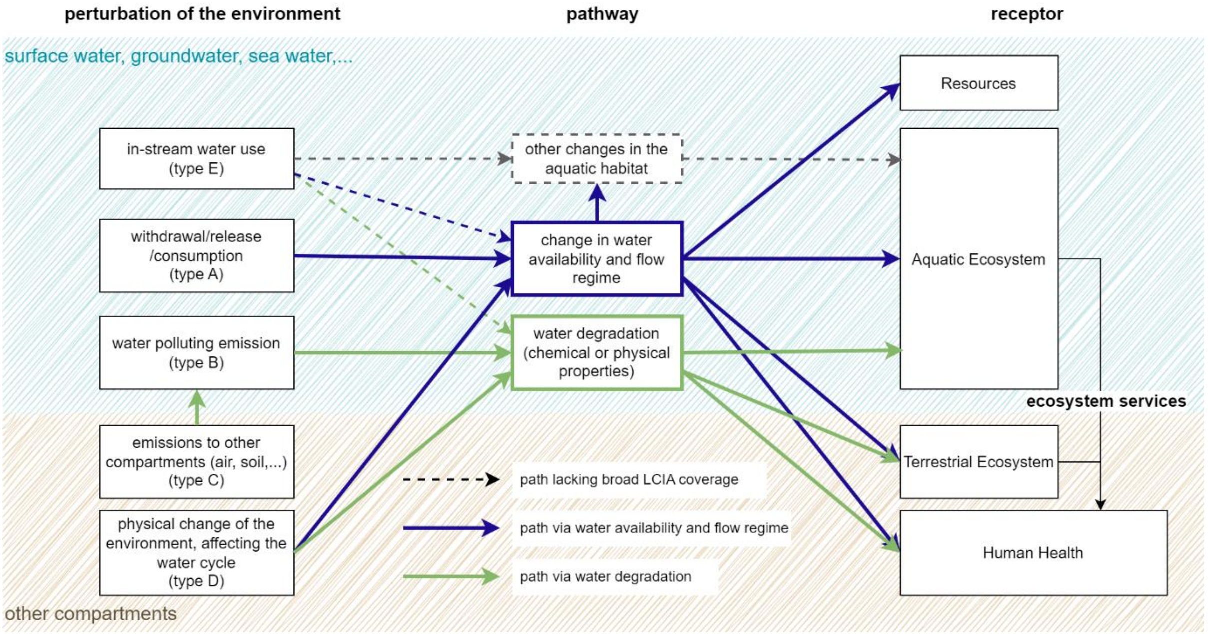

Figure 4. A general overview of potential and already covered water-related pathways in LCIA. Human Health can be impacted directly via changes in the quality or availability of drinking water, but impacts can also arise from the link of the aquatic and terrestrial ecosystems to human health via other ecosystem services, such as the provision of food.

Different human activities can lead to water-related impacts via different kinds of perturbation of the environment, as displayed in Figure 4. Some activities do not directly interact with water but have indirect water-related effects. This applies to land use impacts or climate change impacts, where multiple pathways lead to impacts on humans and the ecosystem, with changes in the water cycle being just one of several. Since these impact pathways do not primarily focus on the water compartment, they are not considered in the remainder of this study.

Furthermore, there is a group of water-related activities not well represented in LCIA methodology yet – in-stream water use. It either affects water availability or quality or leads to a direct physical change in the aquatic habitat (Gracey & Verones, 2016). One example is river fragmentation due to dam construction, which lacks an LCIA method (Dorber et al., 2024). Note that impacts of fishing (Stanford-Clark et al., 2024) are not water-related in the scope of this report, since they are independent of water as an exposure medium or resource.

3.2.2 Requirements for implementing an ISO Water Footprint

According to the ISO/TR 14073 (ISO, 2017), a comprehensive WF could include the impact categories shown in Table 1. For most of these impact categories, LCIA methods are currently available. While the example accounts for marine impacts (which is in line with ISO 14046), this is rather uncommon in WF practice. Comprehensive WFs in literature often focus on freshwater-related impacts. Furthermore, to the author's knowledge, no methods specifically addressing ionizing radiation impacts on marine EQ currently exist. However, ISO/TR 14073 recommends including the current state-of-the-art in a WF. This means that with increasing coverage of environmental issues with new LCIA methods, an increased set of impact categories might be relevant for a comprehensive WF.

*Table 1: Set of impact categories recommended by ISO/TR 14073 for a comprehensive WF. Note that this example uses the term "Water Consumption Impacts" for the impact category that is used for calculating a Water Scarcity Footprint, even though water consumption impacts are not limited to water scarcity issues. * no LCIA method available yet*

Impact Category	**Type of perturbation**	**Possible Area of Protection**
Water Consumption Impacts	Type A	EQ, HH, Resources
Freshwater Ecotoxicity	Type B & C	EQ
Marine Ecotoxicity	Type B & C	EQ
Freshwater Acidification	Type B & C	EQ
Marine Acidification	Type B & C	EQ
Freshwater Eutrophication	Type B & C	EQ
Marine Eutrophication	Type B & C	EQ
Ionizing Radiation (impacts on freshwater EQ)	Type B & C	EQ
Ionizing Radiation (impacts on the marine EQ) *	Type B & C	EQ
Thermally Polluted Water	Type B & C	EQ
Human Toxicity, Carcinogens	Type B & C	HH
Human Toxicity, Non-Carcinogens	Type B & C	HH
Ionizing Radiation (impact on HH)	Type B & C	HH

As explained in section 3.2.1, LCIA methods can address an environmental issue at the midpoint or endpoint level. Since the ISO WF is built on the LCA framework, this distinction can be made as well for the WF, but the standard does not make any of them mandatory.

Furthermore, the standard offers the option to focus on specific subcategories of water-related issues. In place of a comprehensive WF, so-called "**non-comprehensive Water Footprints**" can express these impacts. Non-comprehensive WF should always be referred to with a qualifier, indicating which type of impact is assessed. For example, if a WF focuses on Water Scarcity impacts, it should be called a "**Water Scarcity Footprint**". If it is limited to Water Degradation impacts, it should be called "**Water Degradation Footprint**". Further limiting of the scope is possible (e.g., a Water Eutrophication Footprint), but should be done with a reasonable explanation. It is important to note that the use of a non-comprehensive WF might be relevant when important inventory data for a comprehensive WF is missing. Furthermore, the type of inventory data required might be affected by the choice of the LCIA method.

The following sections establish a collection of LCIA methods relevant to the WF. Like in the above example from ISO/TR 14073, type D methods (Figure 4) are not considered. The contrary would open a vast field of impact categories for which pathways via the water cycle often are only a small part of the overall impacts (e.g., Climate Change) or for which the coverage of the water-related pathways differs strongly between approaches (e.g., Land Use). In WF practice, these pathways most of the time are not considered. Nevertheless, if via one of these pathways, significant impacts are to be expected on water resources, it should be considered since the ISO standard mandates a coverage of all relevant environmental impacts related to water.

3.2.3 Available impact categories in LCIA methodologies

The following section summarizes the implementation of water-related methods in the LCIA methodologies IMPACT World+ (Agez et al., 2024; Bulle et al., 2019), ReCiPe2016 (Huijbregts et al., 2017), EF3.0 (Fazio et al., 2018), LC-IMPACT (Verones et al., 2020). While there is an additional LCIA methodology currently being finalized, GLAM (Life Cycle Initiative, 2023), it is not included in this analysis, since its documentation at the time of writing the report is not mature enough for a final assessment. The selection of impact categories is derived from the WF definition, but not strictly prescribed by ISO 14046. The appendix provides a detailed list of the individual methods with their sources (section 10.1).

Table 2 provides an overview of the impacts covered at the midpoint level, which shows that ReCiPe2016 lacks an indicator for Freshwater Acidification impacts and uses the volumetric amount of water consumed as an indicator for Water Consumption impacts. Thus, ReCiPe2016 does not characterize Water Scarcity impacts at the midpoint level, only at the endpoint level. LC-IMPACT does not account for impacts at midpoint. IMPACT World+ and EF3.0 have the broadest coverage of water-related issues at the midpoint level. Furthermore, IMPACT World+ defines a subset of impact categories relevant to the Area of Concern water, facilitating the calculation of a WF (Bulle et al., 2019).

*Table 2: Coverage of water-related impact categories in LCIA methodologies at the midpoint level. * ReCiPe2016 uses the volumetric water consumption inventory as an indicator of Water Consumption impacts.*

	Water Scarcity	Freshwater Acidification	Freshwater Eutrophication	Freshwater Ecotoxicity	Ionizing Radiation	Human Toxicity
IMPACT World+ v2.0.1	X	X	X	X	X	X
IMPACT World+ v2.1	X	X	X	X	X	X
ReCiPe2016	-*	-	X	X	X	X
EF3.0	X	X	X	X	X	X
LC-IMPACT	-	-	-	-	-	-

Except for the EF3.0, all methodologies assessed here provide CFs for LCIA at the endpoint (Table 3). IMPACT World+ provides the largest set of water-related endpoint CFs, assessing the impact category of Thermal Pollution as well as the category of Freshwater Acidification. ReCiPe2016 does not assess Ionizing Radiation impacts on ecosystem quality at the endpoint level.

Table 3: Coverage of water-related impact categories in LCIA methodologies at the endpoint level.

	Water Availability, HH	Water Availability, freshwater EQ	Water Availability, terrestrial EQ	Thermally Polluted Water	Freshwater Acidification	Freshwater Eutrophication	Freshwater Ecotoxicity	Human Toxicity	Ionizing Radiation, EQ	Ionizing Radiation, HH
IMPACT World+ v2.0.1	X	X	X	X	X	X	X	X	X	X
IMPACT World+ v2.1	X	X	X	X	X	X	X	X	X	X
ReCiPe 2016	X	X	X	-	-	X	X	X	-	X
EF3.0	-	-	-	-	-	-	-	-	-	-
LC-IMPACT	X	X	X	-	-	X	X	X	X	X

Note that IMPACT World+ in its version 2.1 includes the impact categories of “Fisheries Impact” and “Plastics Physical Effects on Biota” (Agez et al., 2024). However, these are not featured in this report since “Fisheries Impact” does not follow the pathways defined in Figure 4 (Stanford-Clark et al., 2024), and “Plastics Physical Effects on Biota” only considers marine effects for now (Corella-Puertas et al., 2023). Although this report focuses on freshwater-related impacts, it is nevertheless possible to include Plastics' Physical Effects on Biota in a comprehensive WF if relevant.

3.2.4 Impact methods assessing changes in water availability and flow regime

LCIA methods for the assessment of impacts on water availability and flow regime can cover different water-related compartments (such as surface water, and groundwater) or types of water, such as blue water or green water[3]. This report focuses on methods assessing changes in blue water availability and this section therefore describes LCIA methods of type A (impacts due to water consumption) and E (impacts due to in-stream water use, see Figure 4). The framework of impact pathways for freshwater use, refined to the scope of this report, is shown in Figure 5, loosely based on a review paper by (Quinteiro et al., 2018). Note that Figure 5 shows an impact of water consumption that is not represented by water scarcity: It is a change in soil or groundwater salinity due to a lowering groundwater table. **This shows that water consumption impacts are not limited to the impact category of Water Scarcity, even though appropriate LCIA methods to reflect these other impacts are not yet available.**

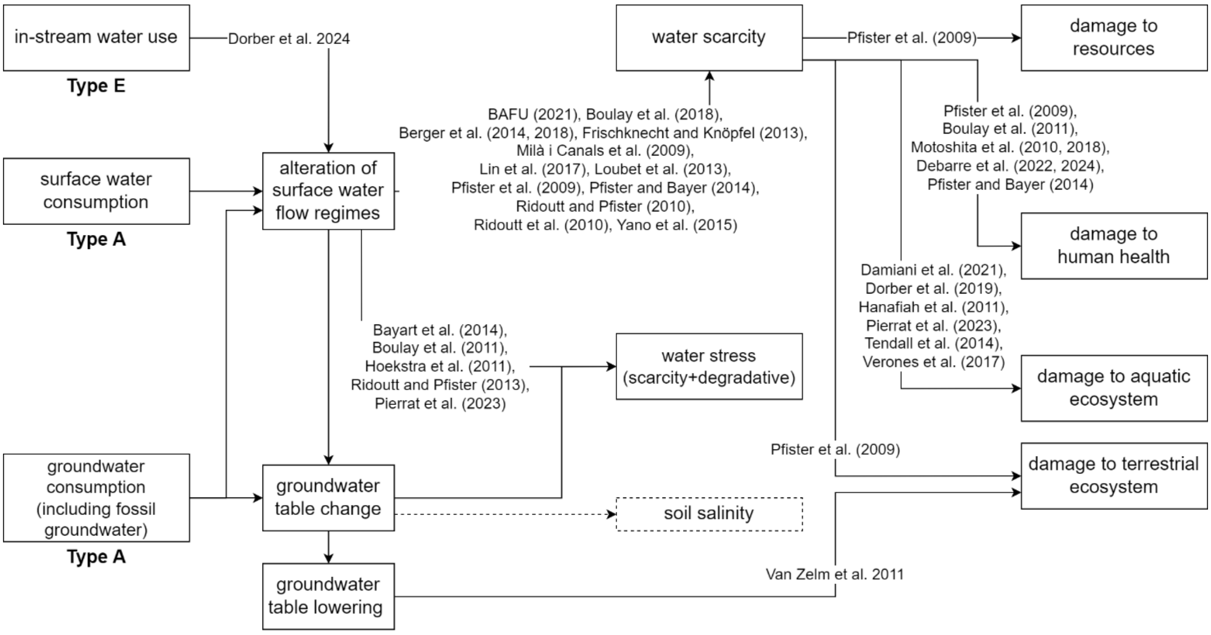

Figure 5. A framework of impact pathways identifying existing impact methods for the assessment of changes in water availability and flow regime due to freshwater use in LCA updated version based on (Quinteiro et al., 2018).

3.2.4.1 Methods for the assessment of water consumption impacts (type A)

The LCIA literature provides a wide range of impact methods for water consumption impact assessment at midpoint. They can be differentiated by the core equations used to classify watersheds according to the potential impacts of water withdrawal or consumption on their water scarcity and can thus be used for WSFs. The first methods were based on either the ratio of water withdrawal to water availability (**Withdrawal-To-Availability, WTA, Figure 7)** or on the ratio of **water consumption to water availability (Consumption-To-Availability, CTA,** Figure 8**)**. In both cases, only water withdrawal or consumption by humans is considered. With the introduction of the term “water demand”, both human water consumption and environmental water requirements are considered in the ratio of **water demand to water availability (Demand-To-Availability, DTA)**, which never led to an actual method but was part of the development process for AWARE**.** Finally, approaches based on the difference between

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[3] Blue, green and grey water are terms introduced by the WFN methodology. See section 5.1.4 for further definition.

water availability and water demand are available (**Availability-Minus-Demand, AMD,** Figure 10). For the definition of the respective variables see Figure 6 and its caption.

Individual examples of WTA, CTA, DTA, and AMD-based methods are presented in the following subsections. Section 4.1 will discuss the drawbacks of the first three approaches which made the AMD the consensus followed in the AWARE method.

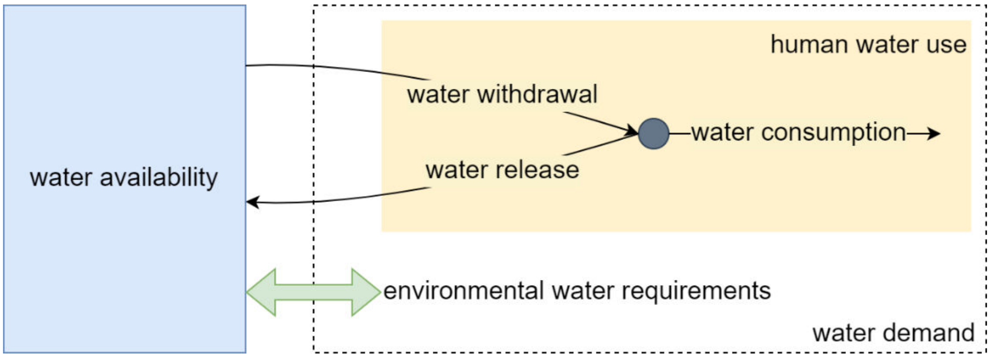


Figure 6. Water Availability and its relationship with water withdrawal, water consumption, and environmental water requirements. While water withdrawal refers to all water that is withdrawn from the environment, water consumption is limited to the amount of water that is not released to the watershed again. Environmental water requirements comprise both the requirements of terrestrial and aquatic ecosystems. Due to the complexity of combining water requirements of the terrestrial ecosystem with common approaches for water scarcity assessment, methods respecting environmental water requirements usually only consider the aquatic ecosystem.

3.2.4.1.1 WTA-based methods

WTA-based methods use the ratio between human water withdrawals and water availability as a starting point for classifying watersheds regarding the potential impacts of water consumption (Figure 7). One of the first methods for water scarcity impact assessment is the Water Stress Index (WSI) (Pfister et al., 2009). It is based on a WTA that is adjusted for the variability of precipitation to account for extreme events that might lead to increased water stress. The resulting “WTA*” is transformed using an S-curve function that maps it to values between 0 and 1, which are then used as CF. Different authors have added to the concept of the WSI: Ridoutt and Pfister (2010) use the WSI characterization factors not only for water consumption inventory but also for water degradation, employing the concept of grey water (the amount of water that is required for a sufficient dilution of water pollutants). Pfister and Bayer (2014) increase the temporal resolution of the WSI by providing monthly instead of annual characterization factors. Further WTA-based CFs were calculated by (Milà I Canals et al., 2009) and (Lin et al., 2017). (Frischknecht & Büsser Knöpfel, 2013) loosely base their method on the WTA.

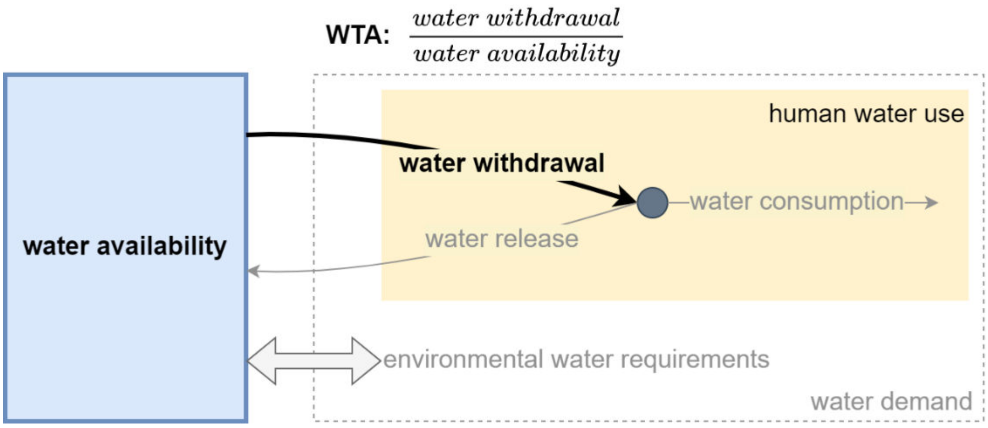


Figure 7. Core variables used in WTA-based methods. Greyed-out variables are not considered.

3.2.4.1.2 CTA-based methods

Consumption-to-Availability methods base the assessment of potential water scarcity impacts on the ratio between water consumption in a region and the amount of available water (Figure 8). Loubet et al. (2013) studied a variation of the approach that acknowledges the impacts of upstream water consumption on downstream water users. WAVE+ (Berger et al., 2018) is the successor of WAVE, the "Water Accounting and Vulnerability Evaluation" method (Berger et al., 2014). WAVE CFs are CTA-based, where availability includes available water in surface water stocks and groundwater. The CTA is transformed into the Water Deprivation Index (WDI) for Relative Water Scarcity using an S-curve function. In WAVE+, the WDI additionally accounts for Absolute Water Shortage. WAVE and WAVE+ set themselves apart from other methods with an additional calculation step: The WDI is adjusted for basin internal evaporation recycling because a part of the evaporated water of an LCA inventory might soon precipitate in the same watershed and therefore is not lost for the environment.

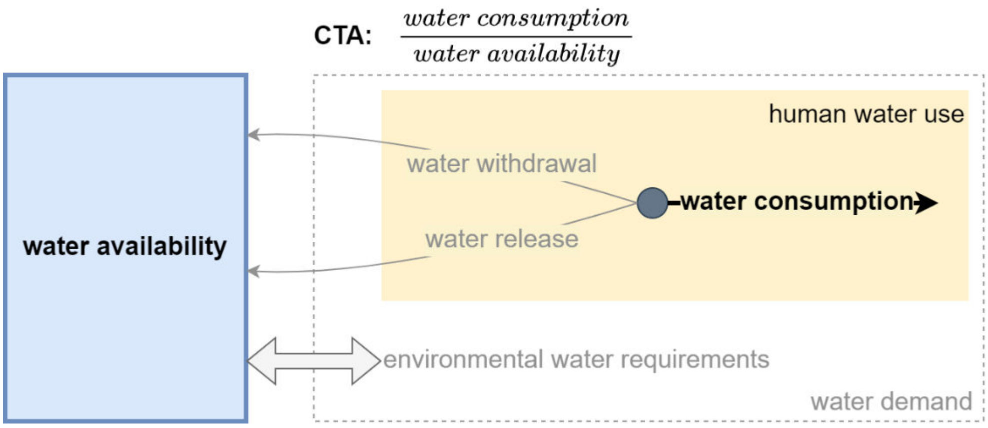


Figure 8. Core variables used in CTA-based methods. Greyed-out variables are not considered.

3.2.4.1.3 DTA-based methods

DTA-based methods combine human water consumption and environmental water requirements to the overall water demand and divide it by the local water availability (Figure 9). To date, there is no consensus on how to calculate environmental water requirements that include both the aquatic and the terrestrial environment. Therefore, different definitions of the environmental water requirement are used in the literature. Several candidates of DTA-based LCIA approaches are discussed in Boulay et al. (2018). However, they were not finally recommended as a consensus and should hence rather be seen as milestones towards the AMD-based method AWARE.

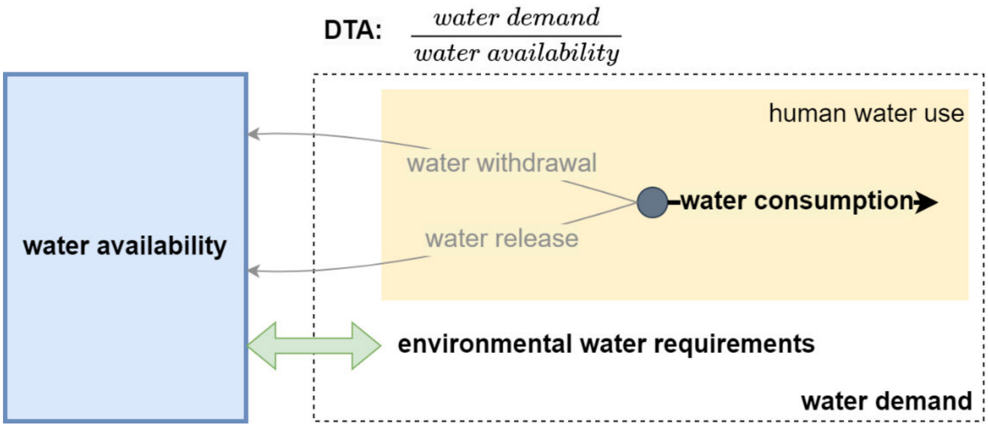


Figure 9. Core variables used in DTA-based methods. Greyed-out variables are not explicitly considered. The water demand comprises both human water consumption and environmental water requirements.

3.2.4.1.4 AMD-based method: The AWARE method

AMD-based methods subtract the human water consumption and environmental water requirement from the available water to calculate the available water remaining after both human and environmental water demands are satisfied (Figure 10). The AMD is calculated per m² watershed area to enhance the comparability of differently sized watersheds. The AWARE method (Boulay et al., 2018) compares the local watershed value with the global average to obtain a characterization factor. The calculation of the CFs is described in detail in section 4.2.1. Multiplication of a product's water consumption inventory with AWARE CFs provides the Water Deprivation Potential (WDP), also named the AWARE (impact) score. The current version of the Swiss Ecoscarcity methodology uses AWARE as a starting point for the assessment of freshwater consumption impacts (BAFU, 2021), but additional steps are taken for the creation of the CFs, notably implementing a reference to the Swiss conditions as a "baseline".

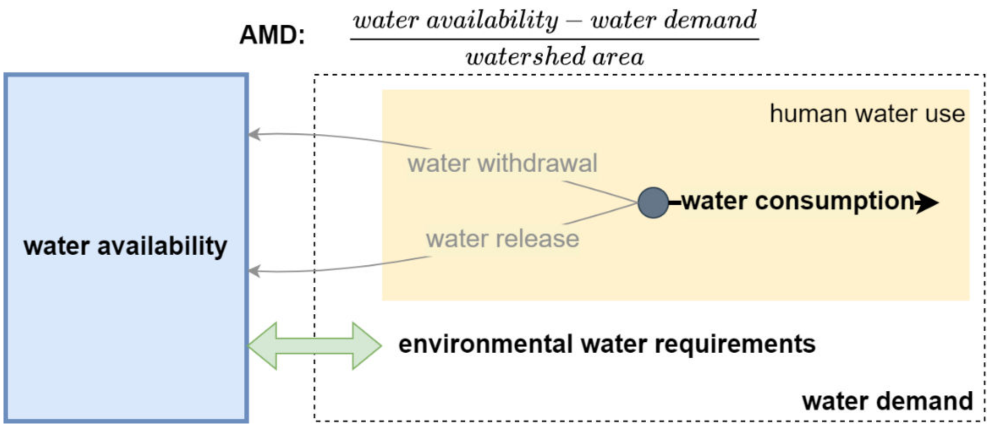


Figure 10. Core variables used in AMD-based methods. Greyed-out variables are not explicitly considered. The water demand comprises both human water consumption and environmental water requirements.

3.2.4.1.5 Other methods

(Yano et al., 2015) present a method based on the area that is required to regenerate a m^3 of water in the time of one year and differentiate the elementary flows precipitation, surface water and groundwater. (Motoshita et al., 2018) calculated CFs representing water consumption impacts on food production in agriculture, considering the vulnerability of the agricultural sector and society. Hélias (2020) suggested an approach based on "Demand-to-Remaining", where the ecosystem water requirements are divided by the water available remaining after human water consumption.

3.2.4.1.6 Endpoint methods

Often, endpoint methods can also be classified according to their core variables. However, there is a higher variability in the approaches that can be expressed via WTA/CTA/DTA/AMD and several additional modelling choices are affecting the resulting CF, such as for modelling exposure and vulnerability of the AoP. Therefore, such classification is not performed here.

Human Health

Impacts on human health at endpoint are commonly expressed in Disability Adjusted Life Years (DALY) per m^3 water consumed. (Pfister et al., 2009) provide endpoint CFs for water consumption impacts on human health based on malnutrition. (Boulay, Bulle, Bayart, et al., 2011) calculated CFs for human health impacts of water consumption, differentiating water quality types and covering both malnutrition impacts as well as impacts on the occurrence of water-borne diseases. (Debarre et al., 2022, 2024) build on this framework, providing CFs for the impact of water consumption on the occurrence of diarrheal diseases. (Motoshita et al., 2011, 2018) provide CFs for the impact of water consumption on water availability for agriculture. The endpoint factors express the resulting damage due to malnutrition.

Aquatic Ecosystem Quality

Impacts on aquatic and terrestrial ecosystem quality are commonly expressed in the Potentially Disappeared Fraction (PDF) of species per m³ water consumed. (Hanafiah et al., 2011) provide a framework and the resulting CFs for the impacts on freshwater species richness incurred by both water consumption and greenhouse gas emissions. (Tendall et al., 2014) extend this framework, albeit without providing CFs for watersheds worldwide, accounting for the variation in intra-watershed biodiversity by subdividing watersheds into longitudinal river zones. Using data about wetland species (flora and fauna) (Verones, Pfister, et al., 2017) employ the approach for water consumption impacts on wetland area change (Verones & Pfister, 2013) to provide endpoint CFs for impacts on ecosystem quality. Both (Damiani et al., 2021) and (Dorber et al., 2019) provide frameworks for impacts on aquatic ecosystem quality but do not provide CFs on a global scale. (Pierrat, Barbarossa, et al., 2023) provide new CFs on a global scale, using the most comprehensive input datasets.

Terrestrial Ecosystem Quality

(Pfister et al., 2009) developed endpoint CFs for the impact of water consumption on terrestrial ecosystem quality, using the vulnerability of net primary production as a proxy for the vulnerability of biodiversity. (Verones, Pfister, et al., 2017) use the approach of (Pfister et al., 2009) for the calculation of new CFs for impacts on terrestrial ecosystem quality. (van Zelm et al., 2011) provide CFs for water consumption impacts of groundwater extraction for the Netherlands. In IMPACT World+ v2.1, these are extrapolated to other regions using data on groundwater depth variation (Agez et al., 2024; Jasechko & Perrone, 2021).

Resources

Water consumption impacts are rarely assessed at the Resources endpoint. However, Pfister et al. (2009) calculated CFs for this purpose, and a new framework for the assessment was developed (Pradinaud et al., 2019) which suggests separating short-term (via scarcity) and long-term (via resource depletion) impacts of water consumption.

3.2.4.2 Methods for in-stream water use impacts (type E)

Dorber et al. (2024) developed a first midpoint method for the impact assessment of hydropower turbine water use. The method assumes that hydropower affects the river flow regime, depending on the size of the corresponding reservoirs. As such, the CFs characterize watersheds regarding the presence of hydropower dams and their potential impacts on the flow regime, without further modeling these impacts themselves. Dorber et al. (2024) find that due to potential differences in results, it is relevant to assess this impact category separately from Water Scarcity impacts. Turgeon et al. (2021) provide endpoint CFs for biodiversity impacts of hydropower reservoir operations.

3.2.4.3 Methods combining consumptive and degradative impacts

Besides the LCIA methodologies presented above, researchers also created dedicated WF methods combining both water consumption and water degradation impacts (Mikosch et al., 2021). (Pierrat et al., 2023) aim to combine both water consumption and water degradation impacts in a harmonized approach. They propose two harmonized indicators, the water biodiversity footprint and the water resource footprint, putting aside the common classification of a WF profile as either at the midpoint or the endpoint level. While the biodiversity footprint is expressed at the endpoint level for impacts on freshwater ecosystem quality, the water resource footprint is expressed at a midpoint of m³ freshwater unavailable per year to a certain water use sector (agricultural, industrial, domestic). Importantly, the water resource footprint considers water quality changes and freshwater scarcity in one value. (Ridoutt & Pfister, 2013) aim to combine consumptive and degradative water use in a single WF indicator expressed in H_2Oe, where “e” represents “equivalents”. Similar work is performed in (Bayart et al., 2014). (Boulay et al., 2011) integrate water quality considerations in the calculation of the water consumption availability impacts.

3.2.5 Methods assessing water degradation

Since this report focuses on water scarcity impacts, LCIA methods for water degradation are only briefly touched on here. The LCIA methodologies presented in section 3.2.3 typically include water degradation-related LCIA methods for:

- Freshwater Eutrophication (Azevedo, Henderson, et al., 2013; Azevedo, van Zelm, et al., 2013; Helmes et al., 2012; Scherer & Pfister, 2015; Struijs et al., 2013; Tirado-Seco, 2005; Zhou et al., 2023, 2024)
- Freshwater Ecotoxicity (Dong et al., 2014; Douziech et al., 2024; Gandhi et al., 2010; Oginah et al., 2023; Owsianiak et al., 2023; Rosenbaum et al., 2008; van Zelm et al., 2009)
- Human Toxicity (Fantke & Jolliet, 2016; Rosenbaum et al., 2008, 2015).

Since the USETox model (Rosenbaum et al., 2008) is based on a consensus model, it is widely used for toxicity impact assessment. However, different LCIA methods might use different versions of the method. Other less commonly provided impact categories are

- (Freshwater) Acidification (Posch et al., 2008; Roy et al., 2012, 2014; Seppälä et al., 2006)
- Ionizing Radiation (Frischknecht et al., 2000; Garnier-Laplace et al., 2009; Paulillo et al., 2020, 2023)
- Thermally Polluted Water (Pfister & Suh, 2015; Verones et al., 2010).

3.3 Challenges in the implementation of the Water Footprint using LCIA methods

The following section summarizes challenges that might occur in the implementation of WFs, especially in the industrial context.

3.3.1 Data availability and accuracy

Collecting comprehensive and accurate data on water use across the entire supply chain can be difficult. Often, companies may not have detailed water usage data or may lack the tools to accurately measure water consumption at different stages of production. Sometimes, data may need to be sourced from secondary sources, studies, or databases, which can reduce the accuracy of the data.

A further aspect to raise is the spatiotemporal validity of the data and the corresponding impact assessment method. Water-related impacts are highly variable depending on the location or timing of the water use, which should be respected in the assessment. While impact assessment methods often are regionalized, the potential of this regionalization is not always leveraged by using adequate spatially resolved inventory data.

3.3.2 Lack of consensus on impact coverage and impact methods to use

For now, no consensus exists on which LCIA methods to use for a comprehensive WF according to ISO 14046. To cover all relevant impacts as mandated by the standard, first, suitable impact assessment methods must be available. However, the set of impact assessment indicators is still evolving, which means that some impacts can not be covered yet, while other indicators exist but without a general endorsement by the scientific community. The only available consensus method in the field of the WF by now are USEtox (for toxic impacts) and AWARE (for Water Scarcity impacts). The lack of a consensus on the indicators to use might challenge a large-scale industrial application of WF, for example, due to reduced comparability between individual studies.

3.3.3 Incompatibility of some LCIA methods’ scope with Water Footprint scope

Existing water-related LCIA methods often cover a multitude of impact pathways. For example, impact methods for Human Toxicity in USEtox by default include different exposure pathways, which are not all water-related. The use of these methods in the context of a WF might therefore overestimate the actual Human Toxicity impacts related to water. The LCIA methodology IMPACT World+ defines the “Area of Concern” water and thus aims to provide a set of CFs specific to water-related impacts for enabling WFs. However, this approach is not yet available to the public.

3.3.4 Inconsistency in the use of the term “Water Footprint”

As described in section 3.1, the term WF is sometimes used with meanings differing from the definition in the WF ISO standard. This can create confusion about the correct interpretation of results and the comparability between studies.

4. Diving into the AWARE method

The AWARE method is the only existing consensus-based method in the realm of assessing the impacts of water consumption on water scarcity in LCA. As such, it is widely used by LCA and WF practitioners. Therefore, this report focuses on AWARE and in the following sections provides a detailed description of its emergence and the methodological concept, best practices in using AWARE, and its advantages and drawbacks. First, the emergence of AWARE as a consensus method is explained in the historical context. Subsequently, the concept of AWARE is explained, describing the input data used and available CFs. The chapter further covers best practices in the application of AWARE and additional methodological aspects. Finally, a step-by-step guide for the implementation of AWARE is provided and the chapter is closed with a critical analysis of the method.

4.1 Historical context for choosing the relevant methodological approach

In the early 2000s, several methods for water scarcity assessment on a global scale were developed (see section 2). While impacts due to eutrophication, acidification or toxicity had been addressed in LCA from early on, the development of methods for water scarcity impact assessment came comparatively late and led to a wide variety of methods in a short time. This variety and the resulting comparability issues in the “Water Scarcity” impact category prompted the UNEP SETAC Life Cycle Initiative to mandate a method harmonization process. This harmonization process was started in 2013 by WULCA.

As a starting point, WULCA identified the question the consensus indicator would have to answer as “***What is the potential to deprive another freshwater user (human or ecosystem) by consuming freshwater in this region?”*** (Boulay et al., 2018). Several methodological approaches were discussed, which can be summarized by the core equations that were used for the calculation of the proposed CFs (see section 3.2.4 for the definition of the four approaches).

- **Withdrawal-to-Availability (WTA)**: This approach was not further investigated in the harmonization process, because using water withdrawals as a proxy of pressure on water resources neglects the high proportion of water that is withdrawn and immediately released in the same watershed, hence not leading to a decrease in water availability. As an example, thermal power plants often use water for cooling and are therefore situated close to a river. However, only a small part of the water extracted is finally consumed. The remaining water is released back into the river. Consequentially, the water availability in the watershed is not reduced by the amount of water withdrawn, but by the amount consumed. The released water can be withdrawn and released multiple times without leading to a decrease in overall water availability and thus without direct impacts on other freshwater users. Therefore, the WTA was rejected by the WULCA working group.

- **Consumption-To-Availability (CTA):** While the CTA is more refined than the WTA in that it does not consider withdrawals that are returned to the ecosystem as exerting pressure on the environment, it lacks the inclusion of the ecosystem water demand. Disregarding ecosystem water demands leads to a human-centred view of water scarcity, while the WULCA working group aimed to assess potential environmental impacts on both humans and the ecosystem. The CTA might support the statement for a specific region that there is sufficient water remaining for humans but hide that the human water consumption already led to a decline in river flow or groundwater table, detrimental to the ecosystem. Consequentially, CTA-based methods could not answer the question defined by the WULCA working group, targeting potential impacts on all freshwater users.

- **Demand-To-Availability (DTA):** The DTA represents pressures on the ecosystem and humans at the same time. However, as DTA is a ratio (as well as WTA and CTA), two regions can have extremely different water availability but the same DTA, which might not be intuitive. As an example, a rainforest region might have a DTA of 0.5, indicating that half of the available water is required to satisfy human and ecosystem water demand. The same ratio of 0.5 might occur in an arid region that is only sparsely populated and where the ecosystem requires little water since then both water availability and water demand are low. In Water Scarcity LCIA, the potential environmental impacts of water consumption are assessed. While consuming one additional m³ of water in the rainforest region might have negligible impacts, additional water consumption in the arid region might be much more impactful. Therefore, the DTA, like the WTA and the CTA, could lead to a misinterpretation of the potential impacts of water consumption.

- **Availability-Minus-Demand (AMD)**: For the AMD, the difference between available water and the water demands of humans and ecosystems is calculated. The result is divided by the watershed area. Dividing by watershed area allows us to compare the amount of water remaining after satisfying human and ecosystem water demand between differently sized watersheds: Otherwise, larger watersheds might appear to have a high water availability simply because they are large and thus collect more water than a small watershed. Using the AMD instead of the DTA considers human and environmental water requirements while acknowledging the amount of water available per surface area and thus provides a more intuitive result: Regions where human and environmental water demands are low, but water availability is low as well, are still considered water scarce.

Since Availability-Minus-Demand describes the amount of water that remains available after satisfying the current water demand of humans and ecosystems, the method developed based on this value was named Available Water Remaining (AWARE). Being the outcome of the WULCA consensus process, it is recommended in several LCA frameworks, such as the Global Guidance on Environmental Life Cycle Impact Assessment Indicators (Jolliet et al., 2018), the LCIA method IMPACT World+ (Bulle et al., 2019), the Product Environmental Footprint (European Commission, 2017), and the guideline on LCA in livestock production systems and supply chains by the Food and Agriculture Organization (FAO, 2019).

4.2 Concept and resulting CFs

The AWARE method aims to quantify the potential impact, via deprivation, of consuming one cubic meter of water on other freshwater users, including humans and ecosystems. This potential impact is assumed to be 1) sensitive to the time of year and the location in which the water consumption occurs and 2) limited to the local watershed. It is expressed as the “Water Deprivation Potential” based on the hypothesis that *“the potential to deprive another user of water […] is […] inversely proportional to the available water remaining”* after human and ecosystem demands have already been satisfied (Boulay et al., 2018).

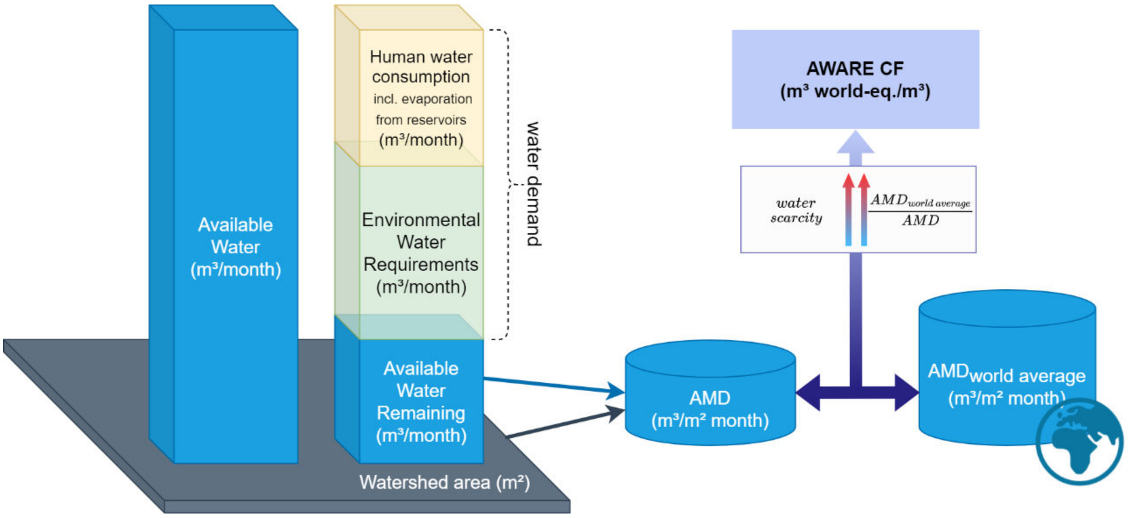


Figure 11. The AWARE concept: The available water remaining per area of a watershed after human water consumption and satisfaction of environmental water requirements, the AMD, is set in relation to the global average AMD where water is consumed. This comparison results in the AWARE CF.

AWARE is designed as a generic midpoint LCIA method, which means that it is based on a limited set of input variables and does not trace the impacts from water consumption to potentially affected organisms. Instead, it aims to enable a combined assessment of potential impacts on both humans and ecosystems at the same time. This sets it apart from WTA- or CTA-based methods, which focus on potential impacts on human water users.

4.2.1 Calculation and meaning of the AWARE CFs

The calculation of the AWARE CFs is divided into four steps:

- Calculation of the available water remaining per area in a watershed and month, the AMD,
- Calculation of the global reference value, the $\mathrm{AMD}_{\mathrm{world\_avg}}$,
- Calculation of the CF by dividing the $\mathrm{AMD}_{\mathrm{world\_avg}}$ by the watershed-specific AMD at the monthly scale,
- Application of an upper and a lower cut-off to the CFs

These steps are described in the following sections.

4.2.1.1 Calculation of the AMD

As presented in section 4.1, the core of AWARE is the Availability Minus Demand (AMD, in m^3/m^2month), which expresses the available water remaining after human and ecosystem water demand has been satisfied (Equation 1).

Equation 1

$$AMD_{ij} = \frac{(Availability - HWC - EWR)_{ij}}{Area_i} \left[\frac{m^3}{m^2 month}\right]$$

The AMD is calculated for every watershed *i* and month *j* from *Availability* (m^3/month), human water consumption (*HWC*, m^3/month), environmental water requirement (*EWR*, m^3/month), and the watershed area ($Area_i$, m^2). *Availability* represents the water availability in the watershed and the month before any human impacts such as water consumption. *HWC* represents all human water consumption. This covers water consumed for domestic uses, as well as for other sectors such as industry or agriculture. The *EWR* represents environmental water requirements and ideally would encompass water requirements for aquatic ecosystems as well as for terrestrial ecosystems. However, as will be explained in section 4.2.2, AWARE for now only considers the water requirements of aquatic ecosystems. These mainly result from the aquatic ecosystem's need for water as a habitat. AMD_{ij} represents the water per m^2 that is potentially remaining in a watershed for a certain month. The higher the AMD_{ij}, the more available water is remaining per area.

4.2.1.2 Calculation of the $\mathrm{AMD}_{\mathrm{world\_avg}}$

The AMD_{ij} is not directly used as the characterization factor of AWARE. This would not work since high AMD_{ij} does not indicate high potential impacts. Instead, the impact is inversely proportional to the AMD_{ij}. Furthermore, the AMD_{ij} lacks a way for a quick interpretation: Is an AMD_{ij} of 0.003 m^3/m^2month rather high or rather low? To increase the interpretational value of the AMD_{ij}, AWARE relates it to the world average conditions as a reference. Thus, two steps are performed to arrive at the AWARE CF:

First, the global consumption-weighted average of all AMDs, AMD_{world_avg}, is calculated. This becomes the reference value, representing the world average conditions (Equation 2).

Equation 2

$$AMD_{world\ avg} = \frac{\sum_{i,j} AMD_{ij} \cdot HWC_{2010,ij}}{\sum_{i,j} HWC_{2010,ij}} \left[\frac{m^3}{m^2 month}\right]$$

AMD_{world_avg} represents the world average of water remaining per m² where water is consumed. It is calculated as a weighted average of all AMD_{ij} worldwide and therefore has the same unit as the AMD_{ij}, m³/m².month. As a weight, for every watershed and month, its total human water consumption of 2010 is used, $HWC_{2010,ij}$. This means that the AMDs of watersheds and months with higher water consumption have a higher weight in the global average, while basins or months with low water consumption have a low weight.

Consequentially, the AMD_{world_avg} is not a simple average of all AMDs but instead represents the AMD value we would find if a random m³ of water consumed in 2010 was selected from the world map, regardless of whether it was consumed for agricultural, domestic, or other water uses. Naturally, if we would like to know the AMD that belongs to a randomly picked water consumption in 2010, our best guess would consider where and when there was high water consumption in 2010. This is represented by the consumption-weighted average.

4.2.1.3 Calculation of the AWARE CFs

The final AWARE CF for watershed *i* and month *j* is obtained by dividing the AMD_{world_avg} by the AMD_{ij} (Equation 3):

Equation 3

$$AWARE\ CF_{ij} = \frac{AMD_{world\ avg}}{AMD_{ij}} \left[\frac{m^3 world - eq.}{m^3}\right]$$

The AWARE CFs are expressed in m³ world-equivalent per m³ consumed (m³ world-eq./m³). If the CF for a watershed and month is larger than 1 m³ world-eq./m³, this means that the watershed has less available water remaining per area in this month than the global average. For example, a CF of 10 m³ world-eq./m³ indicates that the available water remaining in the watershed and month analyzed is one-tenth of the available water remaining for random water consumption worldwide (in 2010).

4.2.1.4 Meaning of CF units: m³ world-equivalents

The meaning of the CF unit results from the calculation as a comparison between the global reference value (the AMD_{world_avg}) and the AMD. The "m³ world-equivalent" represents the idea that the CF shows the equivalent water consumption in a world average location and month that would be required to have the same potential impact as the water consumption in the local watershed and month. The CF essentially is a coefficient that "scales" the impact of the local water consumption to how global average water consumption would be required to obtain the equivalent impact. This is a similar idea as when calculating Global Warming Potential (GWP) with CFs in kg CO_2-eq./kg. The impact of an emission, e.g. methane, is scaled to the equivalent emission in kg CO_2 (Table 4).

Table 4: Analogy between AWARE and the GWP

AWARE	Analogous elements in the GWP	function
$AMD_{world\ avg}$	impact of emitting 1 kg CO_2	reference condition
AMD	impact of emitting 1 kg of greenhouse gas of interest	condition specific to elementary flow
m^3 world-eq./m^3	kg CO_2-eq./kg	unit of the CF
m^3 world-eq.	kg CO_2-eq.	unit of impact score

4.2.1.5 Application of cut-offs

The AWARE CFs are subject to cut-offs: Values below 0.1 m³ world-eq./m³ and values exceeding 100 m³ world-eq./m³ are set to these limits (Figure 12). The range of 0.1 to 100 was deemed an appropriate balance between allowing to differentiate of as many basins as possible and not distorting results due to a few very high CFs. In some basins and months, AMDs can become negative because the EWR exceeds the water availability remaining after human water consumption. In these cases, the CFs are set to the upper cut-off value of 100 m³ world-eq./m³.

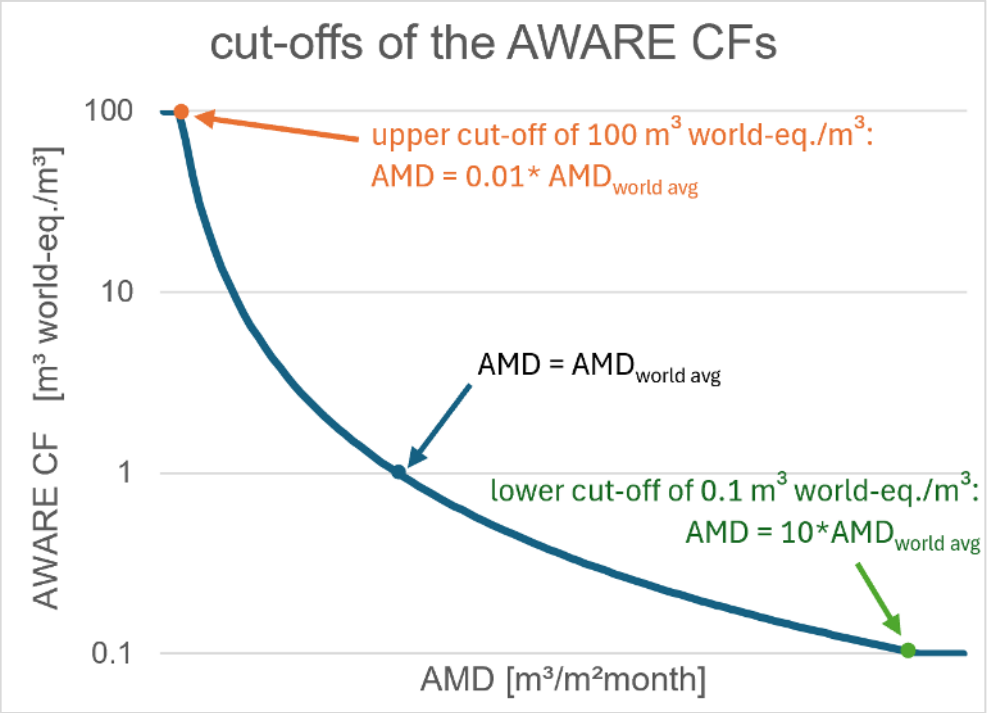


Figure 12. AWARE CFs are cut off at 100 m³ world-eq. and 0.1 m³ world eq./m³. (figure according to (Boulay et al., 2018))

Maps with the final AWARE CFs for every month are presented in Figure 50.

4.2.2 Input data for the calculation of the AWARE CFs

AWARE is based on the output of global hydrological models. River flow in m³/month at the outflow of a watershed is used to estimate the equation term (*Availability – HWC)*, aiming at representing the water remaining available after all human water consumption in the watershed has occurred. Human water consumption in this case covers direct consumption such as via evaporation from irrigation, as well as indirect anthropogenic water consumption, such as the additional evaporation from hydropower reservoirs compared to a natural river.

The *HWC* used for weighting *AMDs* in the calculation of the AMD_{world_avg} represents the year 2010 and was calculated by Flörke et al. (2013). Note that it is not the same value as the *HWC* in the *AMDij* calculation, since for the calculation of the term (*Availability-HWC)*, *HWC* is only implicitly considered in the discharge at the watershed outflow. Furthermore, the discharge is a monthly average value over 51 years, while *HWC* for weighting is for 2010 only.

The river flow data used for AWARE originates from WaterGAP2 (also the HWC calculated by Flörke et al. (2013) was created in the context of working on WaterGAP). WaterGAP2 is a global hydrological model operating with a 0.5° x 0.5° grid, which roughly equals 55 x 55 km at the equator(Figure 13). This resolution is reflected in the watershed delineations in AWARE: The smallest AWARE watersheds consist of one grid cell only. WaterGAP2 operates in daily timesteps. It consists of two components, the WaterGAP Global Hydrology Model (WGHM), and the GroundWater Surface Water USE (GWSWUSE) module. GWSWUSE calculates human water abstractions and releases for five sectors on grid cell resolution. WGHM uses the output of GWSWUSE and other data such as air temperature and precipitation data to simulate hydrological variables. WaterGAP2 is calibrated so that it approximately (±1%) meets the observed long-term river discharge for different gauging stations in the world. This leads to a good performance for river discharge in comparison to other global hydrological models. However, since the calibration requires observational data, performance can be worse in regions where no such data exists. Especially water-scarce regions have a low data availability for river flow measurements. Consequently, model performance is difficult to measure and maintain for these regions and the uncertainty is therefore higher than in many water-abundant regions. (Müller Schmied et al., 2014)

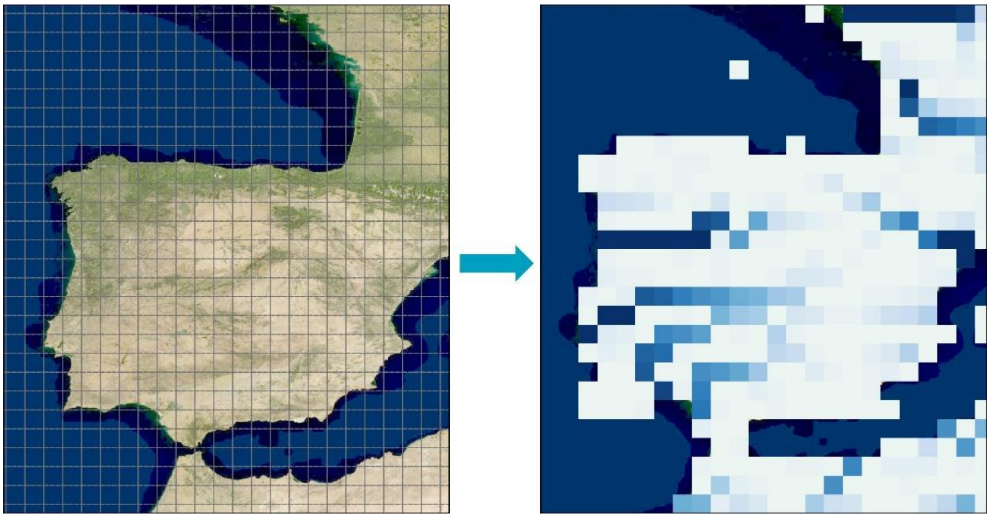


Figure 13. Resolution of a 0.5°x0.5° grid over Spain & Portugal and the final grid used in WaterGAP2.2e, showing grid cells of larger rivers in dark blue. The image uses a more recent version of WaterGAP2 since this type of data was not available for the version used in AWARE. (satellite imagery: NASA Earth Observatory).

While WaterGAP2 covers 5 different water consumption sectors (domestic, industrial, livestock, manufacturing, and agriculture), not all water consumption is explicitly included. For example, water consumption for mining is lacking. WaterGAP2 considers some water management practices, such as reservoir operation, and calibrates a set of variables so that the long-term average discharge meets observed values. Nevertheless, some aspects are not modelled explicitly in the model version used for AWARE, such as long-range water transfers, desalination or evaporation from rivers (evaporation from lakes is considered). Like the *HWC* used for calculating the AMD_{world_avg}, the water consumption used in WaterGAP2 is based on the methodology by Flörke et al. (2013). **Water use for irrigation** is modelled on a daily time step, distinguishing two crop types: paddy rice and non-rice. Based on cropping patterns and further input data, net irrigation requirements per grid cell are determined and translated into gross irrigation requirements. **Livestock water consumption** is based on the number of animals per grid cell, distinguishing 10 livestock types, and their water requirement per capita. **Thermal power plant water use** is based on electricity generation data, and water consumption intensity for 14 combinations of combustion and cooling technologies. **Domestic and manufacturing water use** are based on national statistics, downscaled to grid cells. Power plant, domestic, and manufacturing water use are furthermore subject to technological and structural changes over time, which are also estimated by GWSWUSE. (Müller Schmied et al., 2014)

The EWR used in AWARE ideally would represent the water requirements of the aquatic as well as terrestrial and groundwater ecosystems and could encompass water requirements for consumption (e.g., for trees reaching the groundwater table), but habitat as well (e.g. for freshwater fish). However, little scientific knowledge was available at the time of the AWARE development about links between freshwater availability and groundwater or terrestrial ecosystems on a global scale. Consequentially, the EWR was calculated according to a method for estimating aquatic ecosystem water requirements, the so-called environmental flows. The concept of environmental flows is well established in hydrology and water management:

“Environmental flows describe the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems.” (10th International River Symposium, 2007)

A simplified methodology to calculate environmental flows from data from global hydrological models was used for the EWR calculation in AWARE. The environmental flows were calculated according to the Variable Monthly Flow (VMF) method (Pastor et al., 2014) as a fraction of the naturally available water. Pastor et al. (2014) obtained this fraction as a percentage value referring to a fraction of the naturally available water modelled with the global model LPJmL (Table 5). This fraction of natural river flow represents the flow that is required to sustain the aquatic ecosystem in a “fair” state. Targeting a fair state acknowledges that a fully pristine environmental state for most rivers is impossible to achieve if they already are degraded to some degree (Boulay et al., 2018).

For AWARE, the watershed average of the fractions calculated by Pastor et al. (a value between 30% and 60%) was subsequently multiplied with the naturally occurring river flow at the outflow of the watershed, from WaterGAP2. The natural river flow is calculated with a different mode of WaterGAP2 than the river flow used to estimate *(Availability-HWC).* In this different mode, human activities such as water consumption and reservoir operation are disabled. Therefore, the naturally occurring river flow represents the flow that would occur if there was no human impact on water resources.

Table 5: Allocation of naturally available water for the EWR, using fractions specific to the hydrological season of the month. The hydrological season is determined from the flow intensity x (ratio of monthly to mean annual flow). (Pastor et al., 2014)

Flow intensity x	Hydrological season	Fraction of natural availability allocated for EWR
x ≤ 0.4	Low flow	60%
0.4 < x ≤ 0.8	Intermediate flow	45%
x > 0.8	High flow	30%

4.2.3 Online availability and updates of AWARE

The AWARE CFs are provided in different formats on the website of the WULCA working group (https://wulca-waterlca.org/aware/download-aware-factors/, last accessed 2024-09-20). Individual watersheds can be identified using the available *GoogleEarth* file, whereas the most current versions of the CF datasets are available as Microsoft Excel workbooks. The most current Excel file for country-level CFs is from 2019, while the most recent Excel file on watershed level is from 2024, where a bug was corrected that had affected some watersheds with especially low water availability.

Furthermore, different spatiotemporal aggregations are available for AWARE (including a global default CF), discussed in section 4.2.4 of this report.

The AWARE CFs are representing the average water availability remaining between 1960 – 2010. However, due to climate change and socioeconomic dynamics (e.g., population growth), this temporal period might not be representative of available water remaining now. Regular updates of AWARE would be required to maintain the spatiotemporal representativity of the CFs. Furthermore, these updates could address the limits of the AWARE method as presented in section 4.7. Therefore, an update of AWARE, AWARE2.0 was created recently (Seitfudem et al., 2025). AWARE2.0 uses more up-to-date water availability data and improves some calculation aspects of AWARE. AWARE2.0’s CFs are published here: https://doi.org/10.5281/zenodo.14205922 (Seitfudem et al., 2024)

4.2.4 Spatiotemporal resolutions and aggregation in AWARE

AWARE CFs are calculated on basin resolution for every month of the year, with large watersheds divided into sub-watersheds.

In LCA, however, practitioners often do not know the exact month of the water consumption and require annual CFs which can be used with their annual water consumption inventory. Calculating annual CFs as an arithmetic average of all months is not recommended, since it can be misleading for seasonal water use, especially for irrigation. Since most irrigation occurs in warm and dry months with high CFs, an arithmetic average of all months would underestimate the potential impact of water consumption. Instead, the annual average should reflect the seasonal pattern of water consumption of the assessed activity. This is, like in the calculation of the AMDworld avg, achieved by weighting the months according to their water consumption. To better represent the seasonal patterns of water consumption for specific water use sectors, three types of annual CFs differentiated by the type of water use are provided for AWARE:

- **Annual average CF for unknown water use**, weighted by the entire monthly human water consumption, encompassing irrigation, households, industry, livestock farming, and electricity production (Figure 14, the “default” CF).
- **Annual average CF for agricultural use**, weighted by the monthly irrigation water consumption inventory (see Figure 15 for a comparison with the “default CF”).
- **Annual average CF for non-agricultural use**, weighted by non-agricultural water consumption. Since non-agricultural water consumption is assumed to be constant throughout the year, this equals an arithmetic average of the monthly CFs. Note that this is the way water consumption is modelled in WaterGAP2 (Müller Schmied et al., 2014).

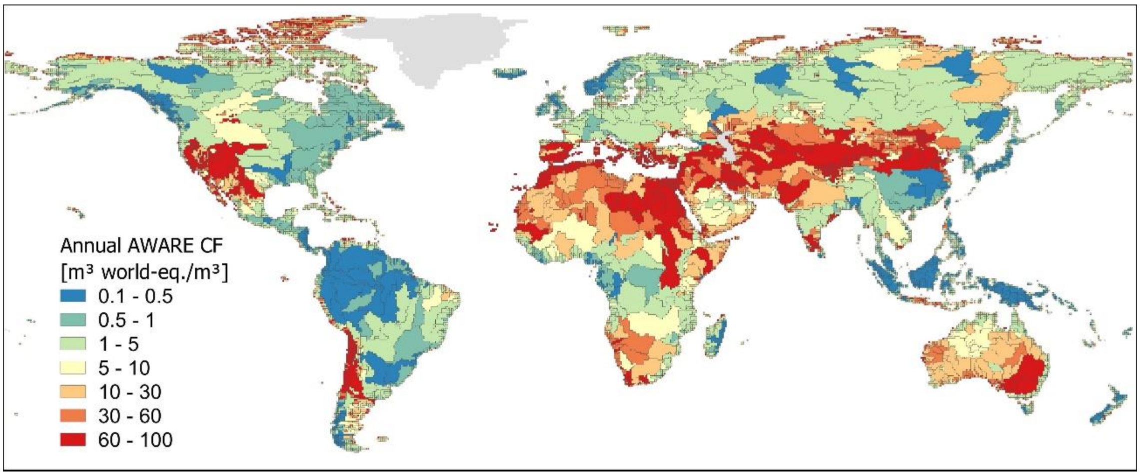


Figure 14. Map of the annual AWARE CFs for unspecified water uses inventory on a watershed scale.

In addition, LCA practitioners often do not know the exact location of the water consumption and require CFs at a lower spatial resolution, e.g. country level. Therefore, AWARE CFs are also provided on the country level and even higher aggregations, such as continents. Since water consumption is not evenly distributed throughout a country, a simple arithmetic or area-weighted average of all watershed CFs would misrepresent the Water Deprivation Potential. Therefore, the same approach as for the annual CF aggregations is used: A weighting of basins by human water consumption in each basin. This means that the monthly CFs on the country level represent the spatial pattern of water consumption, while the annual CFs on the country level represent both spatial and temporal patterns in water consumption over the country’s territory and the entire year. Note that the same distinction of water use sectors as in the annual watershed CFs (unknown water use, agricultural water use and non-agricultural water use) applies to the country CFs.

Two different aggregation levels from watershed to lower resolution are available online:

- **Country-scale CFs**, provided as Excel Files on https://wulca-waterlca.org/aware/download-aware-factors/ (last accessed 2024-09-20).

- **CFs aggregated to subnational administrative regions**, available here: https://wulca-waterlca.org/aware/sub-national-aware/ (last accessed 2024-09-20, documented in (Boulay & Lenoir, 2020)).

Furthermore, **global default CFs** were provided for the case where there is no information available to the LCA practitioner about the location of the water use. The global default CF is calculated the same way as the country aggregations, by consumption weighting distinguishing the three previously introduced water use types. Therefore, three different default values are available, the agricultural water use CF of 45.74 m^3 world-eq./m^3, the non-agricultural water use CF of 20.30 m^3 world-eq./m^3 and the unknown water use CF of 42.95 m^3 world-eq./m^3. However, when global CFs are applied in LCA databases, often the distinction between water use sectors is not made, and the value of 42.95 m^3 world-eq./m^3 is applied to all processes without respecting their water use sector. The global value for unknown water use is strongly influenced by the seasonality of agricultural irrigation in arid regions, hence the rather high value, and therefore might lead to overestimations of the WDP for non-agricultural processes, such as industrial water use.

It is important to note that **the global default CF for unknown water consumption is not 1 m^3 world-eq./m^3**, even though this might be unintuitive given the definition of the CFs as relative to the world average water consumption using the $AMD_{world\ average}$. However, this results from the calculation of the CFs with the AMD in the denominator and the subsequent nonlinear relation between AMDs and CFs. Table 6 shows this with a simple mathematical example:

- From weighting the five AMDs by their water consumption, this example follows a "AMDworld avg" of 5.9 m^3/m^2month (Equation 2).
- Applying Equation 3 using the five AMDs and the AMDworld avg results in the watershed CFs in the respective column.

Neither the weighted global average nor a simple arithmetic average of the five CFs results in the value of 1 m^3 world-eq./m^3. This is because of the calculation of the CFs where the AMDs are the denominator of the division – it is not due to the consumption weighting!

Table 6: Simple example showing that the mathematical formulation of the CFs does not lead to a global average of 1 m^3 world-eq./m^3. The temporal resolution is neglected for easier representation.

	AMDs (m^3/m^2month)	**water consumption (m^3/month)**	**$AMD_{world\ avg}$ (m^3/m^2month)**	**CFs (m^3 world-eq./m^3)**	**global CF (m^3 world-eq./m^3)**
watershed 1	1	7	-	5.90	-
watershed 2	4	2	-	1.48	-
watershed 3	9	9	-	0.66	-
watershed 4	8	7	-	0.74	-
watershed 5	5	5	-	1.18	-
global level (always consumption-weighted)			5.90	-	2.04

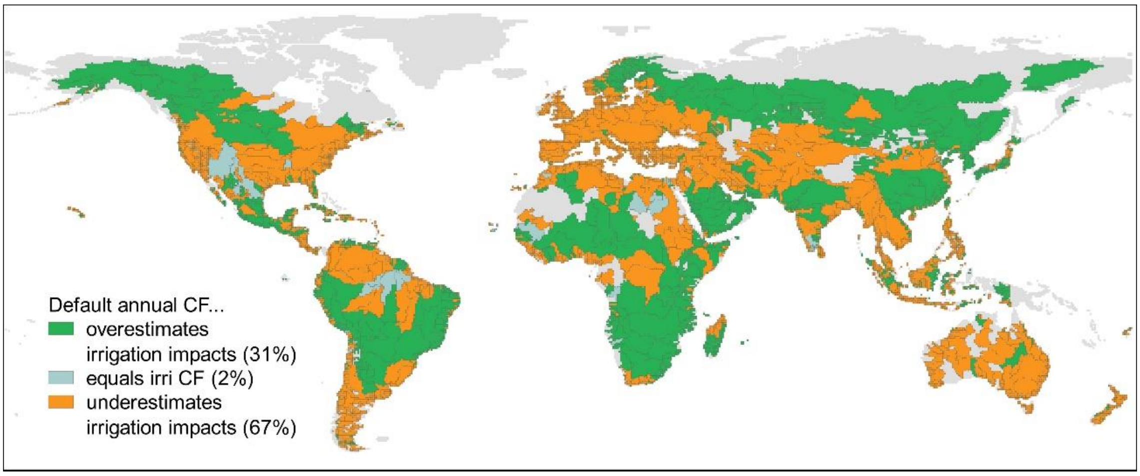


Figure 15. Comparison of AWARE CFs for unspecified water use with CFs for irrigation water use. In many basins, the use of default CFs would underestimate irrigation impacts. Some watersheds show no irrigation water consumption; therefore, the irrigation CF is not defined everywhere (in the CF dataset, the arithmetic average is provided as a workaround).

4.2.5 Additional aggregated CFs available for specific water use sectors

In addition to the country CFs provided with AWARE, different research groups created additional aggregations to the country scale.

(Northey et al., 2018) developed **globally aggregated CFs for the mining sector** based on production quantities, noting the lack of a global dataset on mining water use.

(Boulay et al., 2019) developed **crop-specific aggregated CFs**, which offer better accuracy than CFs for the entire agricultural sector. Similar work was done by (Kaewmai et al., 2021) for crops in Thailand.

(Karimpour et al., 2021) calculated **aggregated CFs for the electricity production sector in the United States**.

4.3 Calculation of the AWARE score

4.3.1 Calculating the AWARE score of a water consumption

The AWARE CFs are LCIA indicators for the calculation of the Water Deprivation Potential (WDP) of water consumption, also called the AWARE score. The CFs signify the WDP *per m³ of water consumption* in watershed *i* and month *j*. To obtain the WDP_{ij} of freshwater consumption in watershed *i* and month *j*, the AWARE CF must be multiplied by the net volume of freshwater consumed in m³ ($netC_{ij}$ in Equation 4). Section 4.6.1.1 explains the calculation of $netC_{ij}$.

Equation 4
$$Water\ Deprivation\ Potential\ (WDP)_{ij} = AWARE\ CF_{ij} \cdot netC_{ij} \quad [m^3 world - eq.]$$

This multiplication results in the WDP_{ij} of the assessed water consumption in the respective watershed and month, expressed in m³ world-equivalents.

This example is for the general application of AWARE to one water-consuming process. For a WSF according to ISO14046, all water-consuming processes of the assessed product system need to be assessed, and their WDP_{ij}'s need to be summed up (see section 4.6.3).

4.3.2 Which types of water use can be evaluated with AWARE?

In the previous section, the calculation of the WDP of water consumption was explained as a multiplication of the net renewable freshwater consumption, *netC* [m³], with the respective AWARE CF. It is important to respect the types of water use that contribute to a water consumption characterizable with AWARE.

AWARE is used to characterize net (renewable) freshwater consumption. Freshwater is defined by ISO 14046 as “water having a low concentration of dissolved solids […] generally accepted as suitable for withdrawal and conventional treatment to produce potable water”. Different sources can provide freshwater, most notably surface water and groundwater bodies, including fossil groundwater. However, **AWARE only applies to renewable freshwater**. This excludes fossil groundwater sources since these do not renew on human timescales. “Net consumption” refers to the water consumption as defined in Figure 6. The prefix “net” is added here to stress the difference between water withdrawal and water release. To summarize, following the definition of net renewable freshwater consumption, **the consumption of marine or fossil water is out of the scope of AWARE**. However, as long as no method is used to explicitly assess the long-term impacts of fossil groundwater consumption, AWARE could be used as a precautionary measure. The section on edge cases discusses fossil groundwater use in more detail (section 4.6.5).

Note that **AWARE does not distinguish different renewable freshwater bodies such as rivers, lakes, or groundwater** – all are characterized by the same monthly, watershed-specific CF. Furthermore, **water quality is not in the scope of AWARE** – pollutant emissions to freshwater are not considered by the method.

In LCA and WSF terminology, “elementary flows” are the flows between the assessed processes or activities and the ecosphere (the natural environment), e.g. emissions of CO_2 to air, abstraction of water from a river, or deposit of heavy minerals into soil. **The net freshwater consumption of a process can be calculated from a balance of water-related elementary flows**, but not all water-related elementary flows are required. LCA databases provide several different elementary flows related to water, such as “water from river”, “water to air”, “water to lake”. Since the scope of AWARE is limited to renewable freshwater consumption, AWARE CFs should only be applied to a subset of these elementary flows. Section 4.6.1.1 explains which of them are relevant.

4.3.3 Interpreting the AWARE score

For the interpretation, it is important to keep in mind that AWARE is a generic indicator. That is, it does not quantify an actual impact on the ecosystem or humans but rather assesses the relative potential of deprivation via the amount of water remaining compared to an average location where water is consumed. The classification of watersheds and months with a corresponding CF is used as an indicator of the potential to deprive other freshwater users when consuming water there.

From Equation *3* follows: **The CF shows how much more (if > 1) or less (if < 1) water remains available per area for consumption in a location and month representing global average consumption, compared to water consumption under local conditions.**

In AWARE, the hypothesis is made that the CF can be interpreted as a relative potential to deprive another freshwater user of water: **The CF represents the potential to deprive another freshwater user by consuming freshwater under local conditions, expressed relative to the deprivation potential in the world average location where water is consumed.**

The meaning of the final AWARE score (the WDP) follows from the latter interpretation of the CF: **The WDP represents the potential of the water consumption linked to an activity of interest to deprive another user of freshwater, compared to the global average consumption of 1 m^3 of freshwater.**

Below is an example:

When consuming 2 m^3 of freshwater with a CF of 10 m^3 world-eq./m^3, the WDP equals 20 m^3 world-equivalents. This means that the deprivation potential of this consumption is 20 times as high as for the global average consumption of 1 m^3.

In a comparison of two WDPs, the reference to the world average consumption is not necessary for interpretation: If the WDP of water consumption 1 is 300 m^3 world-eq., and WDP of water consumption 2 is 1,100 m^3 world-eq., this indicates that the potential to deprive another freshwater user is more than three times as high for water consumption 2 than for water consumption 1

Note that the WDPs are additive: If one water consumption happens in January, with a WDP of 46 m^3 world-eq., and the other one in February with 11 m^3 world-eq., they can be added together to obtain the overall WDP of the activities. The result would be interpreted as such: The potential to deprive another freshwater user by the activities is 57 times as high as the deprivation potential of consuming 1 m^3 of water on a world average. This additivity is required for the WSF, since the WSF represents an overall impact score for an entire product system, potentially including a multitude of processes.

It is noteworthy that the global average impact of consuming 1 m³ of water does not equal 1 m³ world-eq. (see section 4.2.4 for details on the global average). Furthermore, a WDP > 1 m³ world-eq. does not indicate a “bad” Water Scarcity Footprint, as well as there is no basis for stating that a WDP < 1 m³ world-eq. is “good”. Furthermore, AWARE does not provide absolute information about impacts or their relation to “hard limits” like the planetary boundaries.

4.4 Best practices for harnessing spatiotemporal features of AWARE

4.4.1 Temporalization and sector-specific CFs

To represent the seasonal changes in water availability in the watersheds, AWARE CFs are calculated in monthly resolution. Consequently, **LCA with AWARE ideally uses water consumption inventory in monthly resolution**. To obtain the LCIA result, the water consumption inventory of month A in m^3 is multiplied by the AWARE CF of month A and the results for all months are summed up. This way, seasonal hotspots in water use can be identified. Since the CFs can vary by two orders of magnitude in the same watershed throughout the year, using temporally resolved inventory can have a strong influence on the final LCIA result.

In practice, temporally resolved water consumption inventory is not always available. The sector-specific annual CF aggregations mentioned in sections 4.2.4 and 4.2.5 can offer a compromise between seasonal variation in water availability and the reality of low-resolution inventory data. In that case, **LCA with AWARE should at least use water consumption inventory differentiated water use for agricultural purposes or non-agricultural purposes** and use the corresponding CFs accordingly**.**

4.4.2 Spatialization

AWARE CFs are firstly provided on the watershed level – AWARE is a regionalized LCIA method. Since the AWARE input data is resolved on a 0.5°x0.5° spatial grid, watersheds smaller than this size are not possible to be resolved in AWARE. The geographic extent of watersheds in AWARE is therefore only an approximation of reality.

While regionalization is often used as an umbrella term for increasing the spatial detail in LCA, there are different ways of increasing spatial detail, as described in the ScoreLCA report on regionalization (ScoreLCA, 2024):

1. **Regionalizing the inventory**: ensuring that the inventory flows represent well the local technological conditions (e.g. not using the global average irrigation water consumption for corn production to model corn production in Quebéc, Canada)
2. **Spatializing the inventory**: Attributing a location to the inventory flows, so regionalized impact assessment methods can be used (e.g., assign the location “Quebéc” to an elementary flow, which allows for selecting the corresponding Quebéc CF).
3. **Regionalizing an impact assessment method**: Instead of calculating one characterization factor that is valid globally, calculate characterization factors for specific geographical regions.
4. **Spatializing an impact assessment method**: Attributing a location to the impacts modelled in the LCIA method (e.g., the CFs for greenhouse gas emissions are the same regardless of the emission location, but since different regions are impacted differently by climate change, a spatialization of impacts might be interesting). This spatial aspect of LCA and WF is not discussed in this report since it is poorly studied in literature and not readily available for analysis in most LCA software tools. **For AWARE, it is assumed that all Water Scarcity impacts occur in the watershed of the water consumption.**

For an optimal implementation of the method, LCA practitioners need to spatialize their inventory on the watershed level. In the first step, practitioners need to identify the watershed the water consumption is located in. To this end, Geographic Information System (GIS) files are provided with AWARE. These allow the identification of the correct watershed ID based on the inventory's geographic location.

Instead of a manual process, it is possible to use geographic coordinates assigned to the inventory for an automated identification of the matching watersheds. However, in combination with the grid-based spatial resolution of AWARE, this approach can introduce inaccuracies in the LCIA result, as shown in Figure 16. Therefore, automated retrieval of AWARE CFs based on coordinates should always be critically supervised by the practitioner. The error rate of using coordinates could be reduced by allowing "buffer zones" around the coordinate (Mutel et al., 2012; Patouillard et al., 2015), but this workaround originally addresses a different issue and would not completely avoid the problem.

In some cases, identification of the correct watershed is not possible for the LCA practitioner. For this situation, country CFs are available. However, country CFs can hide the spatial variability of water availability in a region. Especially for large countries such as the United States, Russia, or China, CFs can vary significantly between watersheds. This variability leads to uncertainty in the results and should be avoided. Therefore, when the identification of the correct watershed is not possible, **the recommendation is to use CFs on a lower administrative level (sub-country CFs), when possible**.

Both temporalization and spatialization of the inventory are relevant for ensuring a good quality of the LCIA results with AWARE. When resources are limited, prioritization might be required. The Excel file with country-level CFs at https://wulca-waterlca.org/aware/download-aware-factors/ shows which of the two is more relevant for each country and can help to decide whether improving spatial resolution (watershed instead of country) or temporal resolution (monthly instead of annual CFs) should be the main focus (see also section 7.2.4.8).

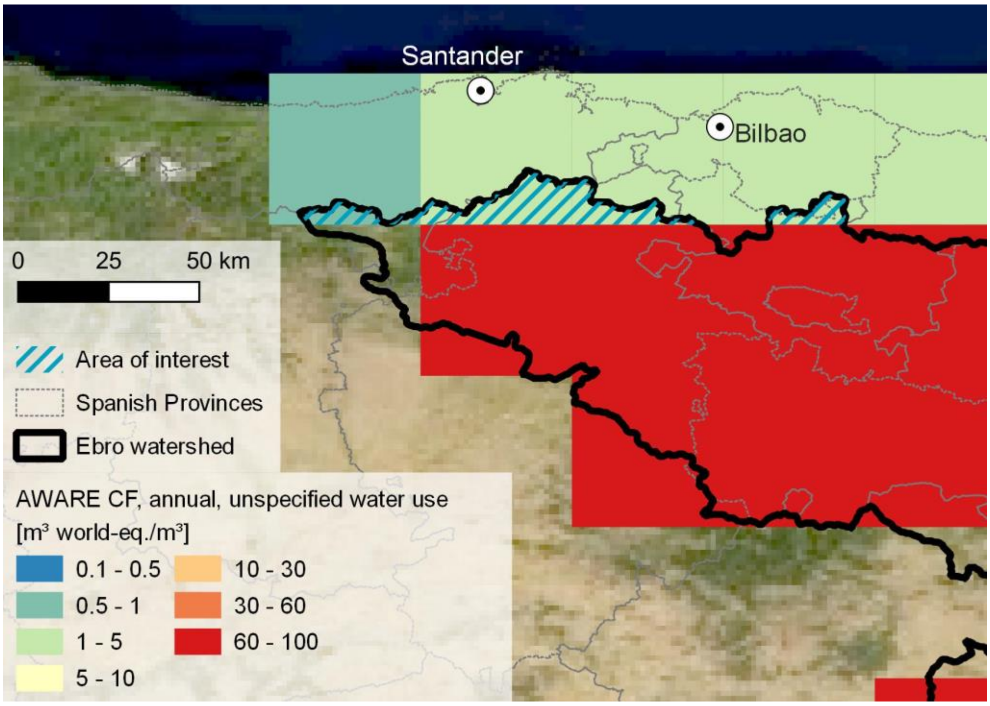


Figure 16. In the northern part of the Spanish Ebro watershed, grid cells and watershed do not align, but the neighbouring AWARE CFs strongly differ. In the "Area of interest", using coordinates to obtain the AWARE CF would lead to large underestimations of the water deprivation potential. (satellite imagery: NASA Earth Observatory)

4.5 Other important aspects of the interpretation of AWARE

The following sections detail three additional aspects important for the interpretation of AWARE. Section 4.5.1 discusses its applicability for water consumption inventories of different sizes, section 4.5.2 provides information on the uncertainty linked to AWARE, and section 4.5.3 presents approaches for prospective LCA with AWARE.

4.5.1 Marginal versus non-marginal impacts

In general, LCIA methods either assess an "average" or a "marginal" impact. AWARE is a method for marginal water consumption impacts. The LCA product system is treated as the "last" water user. In other words, impacts by the LCA product system are assumed to be a very small, negligible addition to the already occurring total water consumption in the watershed, the "background situation".

As AWARE is based on the available water remaining after ecosystem water requirements and human water consumption have been satisfied, its CF would have to change if the overall water consumption in a watershed changes significantly. Large additions to the total water consumption theoretically could reduce the available water remaining (the *AMD*). Therefore, a large additional water consumption evaluated in a WF study would require a CF specifically tailored to this addition. However, for a water consumption inventory that is very small compared to the entire water consumption in a watershed, the available water remaining stays approximately constant and the "static" CFs provided by WULCA are applicable.

Therefore, **the AWARE CFs are only valid for water consumption inventories that are relatively small compared to *HWC*.** Boulay et al. (2020) recommend only applying the CFs to inventory that is smaller than 5% of *HWC.* The annual values of *HWC* are available online in the same file as the AWARE CFs and can be used to assess whether the characterized LCI surpasses this threshold.

To bridge the gap between large water consumption inventories and AWARE, Boulay et al. (2020) **developed non-marginal AWARE CFs in country resolution** (watershed resolution CFs are available at https://wulca-waterlca.org/aware/non-marginal-aware/, last accessed March 2025). These do not treat the LCA inventory as minor additional water consumption but distribute the impact of all water users equally. Consequently, these non-marginal CFs are also called "average CFs" – note that this is unrelated to averaging CFs over different months or regions. Multiplying the average CF with the entire water consumption of country A provides the total "Water Deprivation Potential" of all of the country A's human water consumption. Furthermore, the non-marginal CFs are useful for large water consumption LCI where it is safe to assume that it is already included in the *HWC* used to calculate the CFs.

Since they represent an average instead of an additional impact, the non-marginal CFs by Boulay et al. (2020) by definition are equal or smaller than the marginal CFs. While the absolute value of the CFs might be lower by one order of magnitude, the ranking between different watersheds does not change significantly and therefore would probably not lead to large differences in comparative WFs. However, changes are most relevant for watersheds with high marginal CFs where human water consumption is the main source of water scarcity. For these watersheds, the distinction between marginal and average CFs is the most important.

The approach in Boulay et al. (2020) does not solve the issue of large additional water consumption LCI, since this LCI and the resulting additional impacts are LCA project specific. Boulay et al. (2020) suggest the implementation of integration-based LCIA (i-LCIA) to overcome this issue. Forin et al. (2020) agree and propose the use of this approach even for inventory that is included in the current total water consumption, depending on the goal and scope of the study. Since the i-LCIA approach requires a link between inventory and CF calculation, it is more complex to implement than conventional CFs and therefore not available in LCA software.

4.5.2 Uncertainty of AWARE CFs

Using the AWARE method, such as any other method in the impact category "Water Scarcity", bears uncertainty. For a robust assessment, these uncertainties need to be considered. Three types of uncertainty closely linked to AWARE can be distinguished:

- Uncertainty of the AWARE input parameters,
- Uncertainty of the modelling assumptions in AWARE,
- In the case of using spatiotemporal aggregations (annual CFs, country CFs): Uncertainty of correctly representing the location or temporal pattern of the studied process.

The uncertainty of the AWARE input parameters and their influence on the CFs was studied by Boulay et al. (2021), differentiating four main sources:

- Uncertainty of precipitation datasets,
- Uncertainty of the Global Hydrological Model,
- Uncertainty due to water consumption estimates (HWC),
- Uncertainty of the EWR.

The AWARE CFs are most sensitive to the precipitation datasets and global hydrological model influence. Especially for water-scarce regions, the absolute uncertainty of the AWARE CFs can be large.

For half of all watersheds, the dispersion of possible values of the annual CF due to the input data uncertainty is larger than 1.3 times the static value (e.g., for an annual CF of 10, there is a probability of 95% that the CF's "real value" is between 3.5 and 16.5). The relevance of this dispersion however depends on the LCA study and its geographical scope. Boulay et al. (2021) find that in most cases the uncertainty for the final impact of water consumption is more influenced by using temporally aggregated (annual instead of monthly) or spatially aggregated (country instead of watershed) CFs than by the input data uncertainty of AWARE. For country CFs, this is because the watershed CFs inside a country might span several orders of magnitude. This spatial variability tends to be larger than the uncertainty of individual watershed CFs and is hidden when using country CFs without uncertainty assessment. Therefore, **Boulay et al.** (2021) **recommend practitioners desiring to decrease the uncertainty of their assessments prioritize spatialization and temporalization of their water consumption inventory** (see as well section 4.3). The country-level CF Excel file at https://wulca-waterlca.org/aware/download-aware-factors/ shows which of the two (temporalization or spatialization) is more relevant for each country.

The uncertainty of AWARE is as well influenced by the assumptions and hypotheses made for its calculation, first and foremost the hypothesis of available water remaining to be a proxy of "Water Deprivation Potential". It is therefore recommended to increase the robustness of the LCIA step by comparing AWARE results to results obtained with other LCIA methods for water consumption impacts, most notably endpoint methods for impacts on HH and EQ.

Boulay et al. (2021) provide the parameters of the uncertainty distribution of the AWARE CFs on watershed and country level as supplementary material to their article, which makes it possible to integrate it in LCA studies using LCA software such as *openLCA* or *brightway2*.

4.5.3 Prospective AWARE CFs

With the ongoing research in prospective LCA, efforts were made to create future projected AWARE CFs. This is necessary because anthropogenic and climatic influences can change water availability over time and the CFs are sensitive to these changes (Seitfudem et al., 2025). Baustert et al. (2022) future projected AWARE CFs in their study on desalination in the future steel industry and showed that by 2050 they could by change more than 20% in several countries of the European Union. The resulting CFs on country and regional levels are provided in their supplementary material. However, prospective LCIA is not yet implemented in conventional LCA software. Therefore, the use of prospective AWARE CFs still requires significant manual effort, such as the remapping of CFs to their respective elementary flows.

4.6 Performing a water scarcity footprint using AWARE

The calculation of a water scarcity footprint (WSF) using AWARE can be split into 4 different steps. These are explained in the following using the simplified example of a tomato produced under irrigation.

Note that for using AWARE in a Water Footprint, **the G&S phase of the Water Footprint should explain why AWARE is used and what requirements the study has because of that, e.g. in terms of input data**. The following sections detail these requirements. WSFs are usually calculated with LCA software, but in theory, their calculation is also possible to do manually. Since the final version of this report will contain examples of how to calculate a WSF with LCA software, this chapter focuses on the theory, which will help to better understand how AWARE works.

Please note that there is no official guideline for the application AWARE, so most aspects of this chapter are based on the authors' experience and personal communication with other WF practitioners.

4.6.1 Inventory data collection

As described in section 4.3.2, AWARE is intended to characterize freshwater consumption. **In AWARE, the net freshwater consumption of a process is defined as the net removal of water from the freshwater bodies in a watershed.**

4.6.1.1 Identifying the relevant flows and calculating the net freshwater consumption of a process

A studied process can consume freshwater in different ways. Examples of water consumption are the evaporation of water, the incorporation of water into a product, or the release of freshwater into the sea. In all three cases, the freshwater is not available to the watershed anymore. Figure 17 shows possible inputs and outputs of a water-using process.

Freshwater can enter the process in two different ways: First, as direct extraction from freshwater bodies (lakes, rivers, groundwater,…) and second, as water content in a product that is used by the process. One example of the latter is the use of tap water: It is a product from the Technosphere and contains 100% freshwater. A process can have different types of water output: First, water could be forwarded to another process in the Technosphere. The respective elementary flow could be wastewater that is forwarded to a wastewater plant, or water in a product to be consumed, such as in a beverage. Second, process outputs to the Ecosphere could target different environmental compartments, such as the air (via evaporation), other freshwater bodies (rivers, lakes,…), or the ocean.

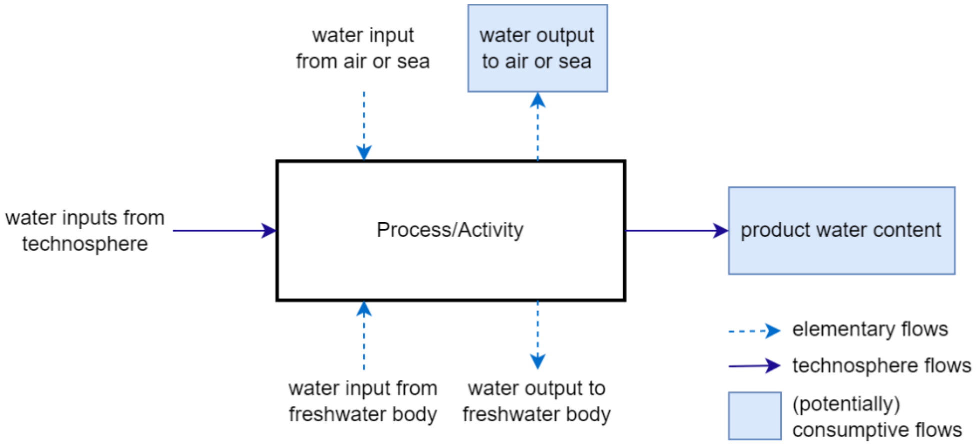


Figure 17. Water consumption in a simple LCA process.

All water flows entering and leaving a process can be summarized in the following equation (Equation 5), closing the water mass balance to 0:

Equation 5

$$0 = IN_{freshwater\ bodies} - OUT_{freshwater\ bodies} + IN_{technosphere} - OUT_{technosphere} + IN_{air,ocean} - OUT_{air,ocean}\ [m^3]$$

With $IN_{freshwater\ bodies}$ and $OUT_{freshwater\ bodies}$ as the elementary flows from and to freshwater bodies of the watershed in m^3, $IN_{technosphere}$ and $OUT_{technosphere}$ as the elementary flows from and to the technosphere in m^3, and $IN_{air,\ ocean}$ and $OUT_{air,\ ocean}$ as the elementary flows from and to the air and ocean compartments in m^3. Note that there are additional environmental compartments that might be covered by $IN_{air,\ ocean}$ and $OUT_{air,\ ocean}$, such as bodies of brackish or saline water in inland sinks. However, these are often not specified in LCA databases. For better readability, we neglect the temporal dimension in the notation. Ideally, Equation 5 is applied in monthly resolution. Therefore, the flows would represent a respective month's total in m^3.

It is important to note that there are two considerably different approaches for creating an inventory for AWARE, which depend mostly on whether the Water Scarcity Footprint is performed manually or with LCA software. In the first case, the WF practitioner might calculate the net freshwater consumption for every process individually and subsequently apply the AWARE CFs. In the second case, all relevant elementary flows are collected and used to create a product system model in LCA software. Subsequently, the LCA software calculates the overall Water Scarcity footprint of the product system, by first applying the AWARE CFs to individual elementary flows (not net consumption!) and subsequently calculating their overall balance (which can later be disaggregated into the results for individual processes).

In the following, two approaches for the first ("manual") process of assembling the inventory are described. Equation 5 can be sorted to reflect the local net freshwater consumption *netC* in m³ in a watershed, by balancing $IN_{freshwater\ bodies}$ and $OUT_{freshwater\ bodies}$ as (Equation 6):

Equation 6

$$netC = IN_{freshwater\ bodies} - OUT_{freshwater\ bodies} = OUT_{technosphere} - IN_{technosphere} + OUT_{air,ocean} - IN_{air,ocean}\ [m^3]$$

Therefore, two approaches can be taken to calculate the net freshwater consumption *netC* of a process:

- **The "watershed differential" approach: Balancing $IN_{freshwater\ bodies}$ and $OUT_{freshwater\ bodies}$.** Freshwater bodies here are surface water (lakes, rivers,…) and groundwater (section 4.3.2). The watershed differential represents the difference between the water "taken from" and "released to" the freshwater bodies in a watershed by the studied process. This does not mean that for a calculation of the *netC* a WSF modeler needs to know which exact watershed the *netC* is linked to. Assuming that water withdrawal and release of most technological processes occur in the same region, the knowledge of how much water is withdrawn or released for a certain process in most cases is sufficient for calculating the *netC* with the watershed differential approach.
- **The "consumptive flows" approach: Balancing $IN_{technosphere}$, $OUT_{technosphere}$, $IN_{air,\ ocean}$, and $OUT_{air,\ ocean}$.** This approach only considers water flows which are not directly linked to the watershed's freshwater bodies. These represent the reasons why the process consumes water or releases water back to the watershed: Because it is incorporated into technosphere flows the process uses or produces (e.g., a can of tomato soup), because it is captured from rain or air moisture, evaporated, or because it is taken from or released to the ocean. Note that water inflows from precipitation are an edge case to be treated carefully (see section 4.6.5.3).

Note that these equations can result in a negative *netC*, indicating that the process increases water availability in the watershed. These replenishments are seen as a credit and reduce the overall water consumption impacts. Wastewater treatment plants are an example of negative *netC* since they release freshwater into the environment.

To summarize: **There are two ways a practitioner can calculate the net freshwater consumption of a process, *netC*) – either by applying the watershed differential approach, or the consumptive flows approach**. In a well-balanced system, both approaches should lead to the same result. Therefore, to calculate a Water Scarcity Footprint with AWARE manually, it is not necessary to record all water flows around a process. Nevertheless, if the WSF is calculated in LCA software, both the flows relevant for the watershed differential approach and the consumptive flows approach are required to set up a consistent product system model. Specifically, while the technosphere flows are required to link the individual processes of the product system in the LCA software, it finally only uses the elementary flows belonging to the "watershed differential" to calculate the AWARE score (see also the section on current practices, section 6.2.2).

4.6.1.2 Collecting the net freshwater consumption data from relevant flows

In the inventory data collection for AWARE, the practitioner collects water consumption data and required attributes as defined in the WSF's goal and scope. Figure 18 shows examples of water flows entering and leaving a process. All of these flows should be recorded for a consistent product system model with AWARE, using LCA software. However, not all finally contribute to *netC*. Therefore, if the WSF is calculated manually, only a subset of flows is required, depending on which approach is chosen for *netC* (see previous section). Precipitation inputs are an edge case that should be handled with care (section 4.6.5).

To collect the relevant flows, a balance around the process should be established and all water inputs and outputs identified. It is important to ensure a closed balance by verifying that the difference between the mass of water inputs and outputs equals zero. Even though for the mass balance an expression of the flows in kg water is required, the elementary flows in the final inventory should be expressed in m^3, since the AWARE CFs require this unit for multiplication (see Equation *4*). The mass balance also helps to detect water leakage from a system, which is sometimes overlooked and can contribute to the overall water consumption where the leaked water does not reach the watershed again (Ansorge & Stejskalová, 2025).

There is no further distinction required between compartments beyond the distinction of freshwater bodies and non-freshwater compartments, even though these elementary flows are further distinguished in LCA databases (as "from or to river", "from or to groundwater", etc., see section 4.3.2).

Since AWARE does not consider water pollution, polluted water returned to the environment is treated the same as the return of clean freshwater. However, it is recommended to assess the pollution with complementary LCIA methods, e.g. for Freshwater Acidification.

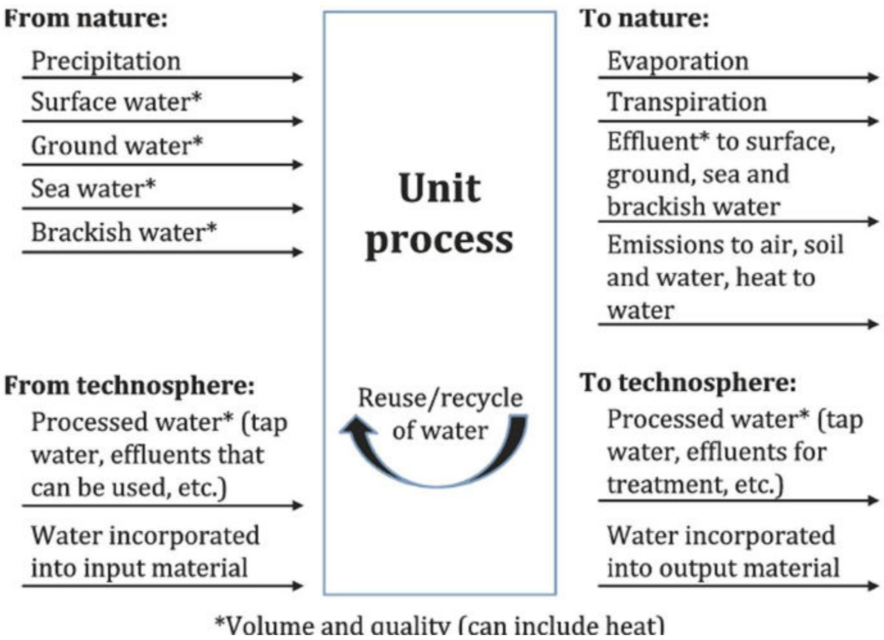


Figure 18. Potentially relevant flows for an LCA inventory for AWARE (from (ISO, 2017)).

After mass balance is ensured, the final inventory of *netC* is created from the elementary flows required for the "watershed differential" or the "consumptive flows approach". For the watershed differential approach, only elementary flows from and to freshwater bodies ($IN_{freshwater\ bodies}$ and $OUT_{freshwater\ bodies}$) are considered and balanced according to Equation 6. For the consumptive flows approach, $IN_{technosphere}$, $OUT_{technosphere}$, $IN_{air,\ ocean}$, and $OUT_{air,\ ocean}$ are considered. The final inventory is a list of *netC* as shown in Table 7. The required spatial and temporal resolution are discussed in the following sections.

Table 7: Exemplary final freshwater consumption inventory for use in AWARE.

process	*netC* [m³]	month	location
process 1	5	January	48°51'30.29"N, 2°17'40.77"E
	4	February	
	5	March	
	9	April	
	0	May	
	0	June	
	0	July	
	0	August	
	4	September	
	5	October	
	3	November	
	4	December	
process 2	-10	January	Paris, France
	-9	February	
	…	…	
…	…	…	…
process n	…	…	
	4	December	35°39'31.14"N, 139°44'43.68"E

4.6.1.3 Required levels of spatiotemporal detail for inventory data

To be able to apply the AWARE CFs in their most detailed version, the water consumption inventory should be created in monthly resolution and location-specific. To obtain the appropriate temporal resolution of the elementary flows, different strategies can be applied. In the ideal case, water flows are already measured in a time-resolved manner, e.g. in m^3/s with several data points per day. Then, this data can be used to calculate monthly totals in m^3.

If the water flows are only available on annual resolution, assumptions can be made for their distribution to monthly resolution. For industrial processes, the water flows might be constant throughout the year, justifying an equal distribution over 12 months. For other processes, e.g. irrigation water use, information about the growing seasons of the crops could help to distribute the water consumption, or monthly data on the energy use of water pumps. It is important to note that while water might be consumed in month Y, it might be consumed from a pond that was filled in a different month. For the most accurate results, the water consumption should be allocated to that month.

When choosing the appropriate AWARE CFs later in the analysis, the watershed of water extractions or release needs to be known. Since the watershed resolution of the AWARE method is relatively coarse, the best way to prepare the inventory is to register the approximate location so that it later can be matched with an AWARE watershed on the map. Types of location can be the exact coordinates of withdrawal or release or an approximate location such as a city. This information later helps to identify the correct watershed. Note that the extraction of freshwater for tap water supply can sometimes be in a different watershed than the use of tap water. Therefore, it might be relevant to explicitly determine the location of the freshwater sources of the tap water supplier.

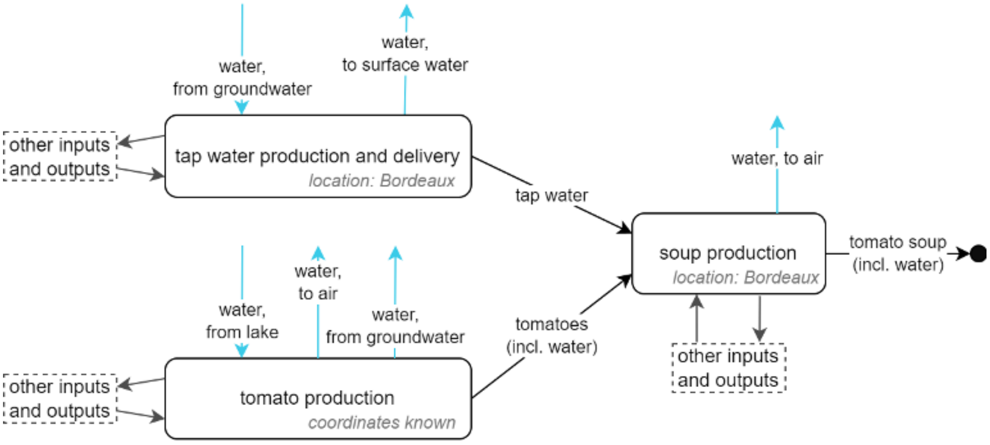
In theory, if the watershed of water consumption or release is known, this information could directly be used in the later process of matching the AWARE CFs. However, because of the coarse resolution of AWARE, this only works for large watersheds. Since the smallest watersheds in AWARE have a size of 0.5°x0.5° (55x55km at the equator, but less towards the poles), an accuracy of a few kilometres is usually sufficient for the location.

4.6.1.4 Elementary flows with low spatiotemporal detail

In some cases, the location or timing of a flow is not known to the WSF practitioner in the detail that would be required to apply a watershed-scale assessment in monthly resolution. If the information about the location does not suffice for identification of a watershed-level CF, nevertheless the region might be known, e.g. by administrative boundary or country. This information is then used as the location. If the flow can’t be attributed to specific months, it suffices to use the annual total flow in m^3. In both cases, it is important to classify the flow regarding its water use sector, e.g. agricultural, non-agricultural, or unknown. This is required to match the appropriate aggregated CF to the flow.

Example box: Cradle-to-gate WSF of tomato soup – Inventory collection

A cradle-to-gate WSF of a can of tomato soup is conducted. The flow chart shows the simplified process of tomato soup production with 3 main water consuming processes – tap water production, irrigation of the tomato plants, and the production of the tomato soup.



In the tap water production and delivery, tap water is generated from groundwater, with wastewater cleaned on-site and returned to the environment (water, to surface water). The tomato production uses water from a lake for irrigation, of which a part evapotranspirates (water to air), a part recharges the groundwater (water to groundwater), and a part is included in the harvested tomatoes. In the soup production, water is evaporated (water to air), and a part of water remains in the tomato soup product. The final inventory of elementary flows for the watershed differential approach consists of the following flows:

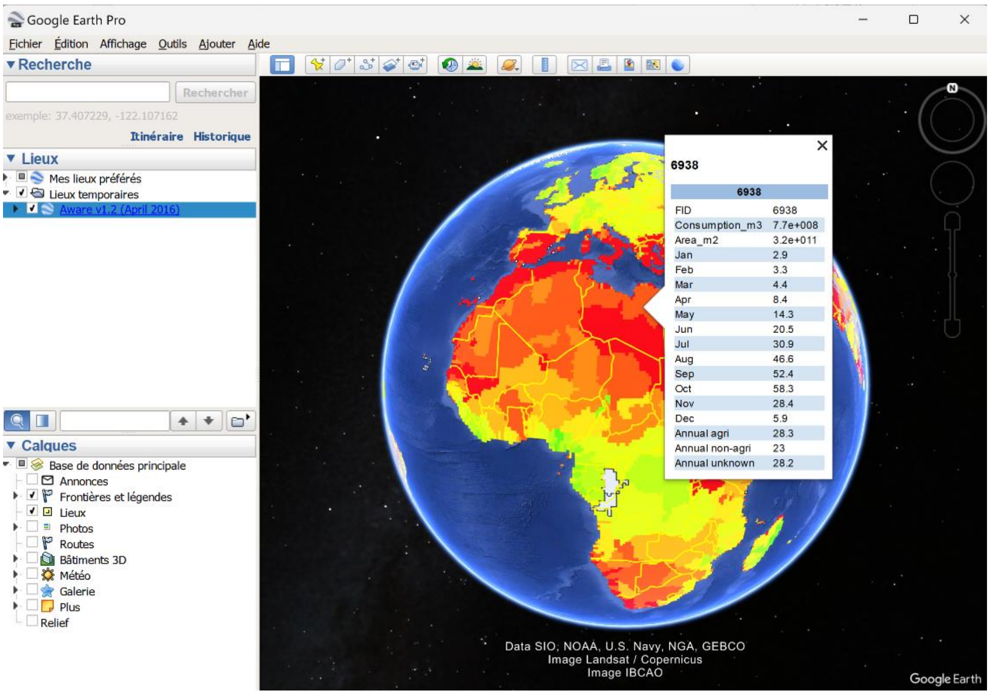
tap water production	**water content**	**Spatiotemporal resolution**	***netC***
water, from groundwater	0.5 kg	City, same month as soup production	
water, to surface water	0.1 kg	City, same month as soup production	0.0004 m³
tomato production			
water, from lake	10 kg	Coordinates & irrigation months	
water, to groundwater	1.1 kg	Coordinates & irrigation months	0.0089 m³
soup production			
No relevant elementary flows			0 m³

Above table represents the elementary flows that would be required in LCA software to calculate the AWARE scores (using the “watershed differential”). However, the *netC* could also be calculated with the “consumptive flows approach”. Following flows would be relevant:

tap water production	**water content**	**Spatiotemporal resolution**	***netC***
Output: tap water	0.4 kg	City, same month as soup production	0.0004 m³
tomato production			
Output: 1 kg tomatoes	0.9 kg	Coordinates & irrigation months	
Output: water, to air	8 kg	Coordinates & irrigation months	0.0089 m³
soup production			
Input: 1 kg tomatoes	0.9 kg	City, same month as soup production	
Input: tap water	0.4 kg	City, same month as soup production	
Output: water, to air	0.5 kg	City, same month as soup production	
Output: 1.1kg can of soup	0.8 kg	City, same month as soup production	0 m³

4.6.2 Choice of AWARE CFs

For the identification of the appropriate CFs, the practitioner can use the .kml file provided at https://wulca-waterlca.org/aware/download-aware-factors/. It is possible to open this file in Google Earth (https://earth.google.com/web/) and other GIS software, which allows to identify the correct watersheds by the attribute "FID" (feature identifier, a consecutive number assigned to the watersheds). As explained in section **Erreur ! Source du renvoi introuvable.**, it is important to ensure that the correct watershed is selected, since using an automated retrieval by coordinates might lead to misleading results. Note that the dataset does not contain a mapping between river names and FIDs.



6938

6938	
FID	6938
Consumption_m3	7.7e+008
Area_m2	3.2e+011
Jan	2.9
Feb	3.3
Mar	4.4
Apr	8.4
May	14.3
Jun	20.5
Jul	30.9
Aug	46.6
Sep	52.4
Oct	58.3
Nov	28.4
Dec	5.9
Annual agri	28.3
Annual non-agri	23
Annual unknown	28.2

Figure 19. Screenshot of Google Earth, displaying the AWARE CF map. By clicking on a watershed, the corresponding AWARE CFs and the watershed ID (FID) are displayed.

If the watershed FID is known, the corresponding CFs can be retrieved from the AWARE Excel file, which is available in a more recent version than the GIS file. At the time of preparing this report, the most current version of the Excel file is version 1.2 of June 3rd, 2024.

Using the provided total annual water consumption in m³, the marginality assumption (section 4.5.1) can be tested. If the total water consumption inventory in a watershed X exceeds 0.1% of the total annual water consumption provided for X in the AWARE file, it should be investigated whether the marginality assumption of AWARE is justified by evaluating the monthly water consumption data provided on the WULCA website and considering the discussion in 4.5.1.

If the spatiotemporal attributes of a *netC* are not known in the required resolution, aggregated CFs must be used, always preferring the highest resolution possible. Thus, if the location of a flow is known in terms of an administrative subnational unit, the appropriate subnational resolution CF should be used. If the only spatial information available is the country of the process, a country CF should be used. These CFs are not available with the main AWARE CFs of Boulay et al. (2018) but can be downloaded separately (see section 4.2.4). The use of global CFs is not recommended.

For annual inventory that can not be subdivided into months, annual CF aggregations must be used. These are available on watershed, subnational and country level. Consequently, in the final WSF calculations, some processes might use watershed-level monthly CFs, while others use subnational or country CFs on annual resolution. To not systematically over- or underestimate the AWARE score, the water use sector of the process should be used to identify the appropriate aggregation type. Three choices are possible, either agricultural, non-agricultural or unknown water use. See section 4.2.4 about the potential to misrepresent impacts by using the “unknown water use” CFs.

Example box: Cradle-to-gate WSF of tomato soup – Matching CFs to inventory

It is assumed that the tomatoes are irrigated throughout the growing season **from May to August**, with August requiring double the amount of water than the other months. The soup production happens in the **harvesting month August**. Therefore, the tap water for the soup production is assumed to be produced and supplied in August. For the tomato production, the watershed with the FID 6293 was identified by using coordinates. For the soup production, which is situated in Bordeaux, the tap water supplier is a communal water supply agency, and the water is assumed to be from the local watershed with the FID 5360. The CFs of the relevant months are highlighted in below table.

FID	Consum.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
6293	4.4E+09	2.99	3.31	5.57	7.96	**14.7**	**51.0**	**100**	**64.3**	10.5	5.98	2.98	2.39
5360	2.2E+09	0.37	0.45	0.47	0.52	0.64	1.60	7.94	**14.7**	3.18	0.97	0.53	0.40

Since the total water consumption in the two watersheds equals more than 1 billon m³ per year, whereas the product system inventory in each watershed is in the order of magnitude of less than

4.6.3 Calculation of impact scores

For the calculation of the impact score (also: Water Scarcity Footprint, Water Deprivation Potential), the freshwater consumption inventory of the respective month for each watershed is multiplied by the respective CFs (Equation 7) and added up.

Equation 7
$$S = \sum_{i,j,k,p} CF_{ijk} \cdot I_{ijkp} \quad [m^3 world - eq.]$$

Where S is the impact score, CF_{ijk} is the CF of watershed i, month j and elementary flow k in m^3 world-eq./m^3. I_{ijkp} is the flow amount in m^3 for watershed i, month j, elementary flow k and process p.

For applying Equation 7, two different approaches are possible: The first one is the manual approach as detailed in the previous sections, where the *netC* has already been calculated for every process. Then I_{ijkp} represents $netC_{ijp}$ for every process p. Thus, there is only one I_{ijkp} per process p, and k is redundant.

The second approach represents the classical way of calculating LCA results and is the way the calculations are implemented in LCA software (see section 6.2.3). In this case, there are multiple elementary flows I_{ijkp} per process p, which must be indexed by k. For example, a process might have a freshwater inflow from groundwater, and outputs to a lake and a river. Then, k represents each of these elementary flows individually. Following Equation 6, I_{ijkp} flows have specific signs: If using the watershed differential approach, process inputs are included in the calculation with a positive sign, while process outputs are assigned a negative sign. For the consumptive flows approach in turn, inputs are negative, and outputs are positive.

Whether the manual approach with *netC* is selected or the classical LCA way: It does not matter whether the watershed differential or the consumptive flows approach is used (see section 4.6.1). However, it is of paramount importance to not mix both approaches. Finally, most current LCA software tools do not provide a straightforward approach for temporalized impact calculations, which limits a full application of Equation 7. Instead of a monthly resolution, the annual resolution is used in this case. The index *i* of the equation consequently becomes obsolete. See section 7.2.4.7 for an example of how to still consider monthly resolution in LCA software.

Example box: Cradle-to-gate WSF of tomato soup – Calculation of impact score

The AWARE score is calculated by multiplying *netC* and CF.

AWARE impact score of the tap water production:
0.0004 m^3 x 14.7 m^3 world-eq./m^3 = 0.006 m^3 world-eq.

AWARE impact score of the tomato production:
The relevant CFs are 14.7, 51.0, 100, and 64.3 m^3 world-eq./m^3. Three fifths of the irrigation water consumption occur in May, June, and July, while two fifths happen in August. This leads to the LCA result for the four months:

May: 0.00178 m^3 x 14.7 m^3 world-eq./m^3 = 0.026 m^3 world-eq.

June: 0.00178 m^3 x 51.0 m^3 world-eq./m^3 = 0.091 m^3 world-eq.

July: 0.00178 m^3 x 100 m^3 world-eq./m^3 = 0.178 m^3 world-eq.

August: 0.00356 m^3 x 64.3 m^3 world-eq./m^3 = 0.229 m^3 world-eq.

In total, the WSF of the tap water production therefore equals 0.006 m^3 world-eq., while the WSF of the tomato production equals 0.524 m^3 world-eq.

Note that for these results it is irrelevant whether the watershed differential or the consumptive flows approach was used for calculating *netC* (see Equation 6), or if, as in LCA software, the CFs are directly applied to the elementary flows instead of to *netC*.

4.6.4 Interpretation of results

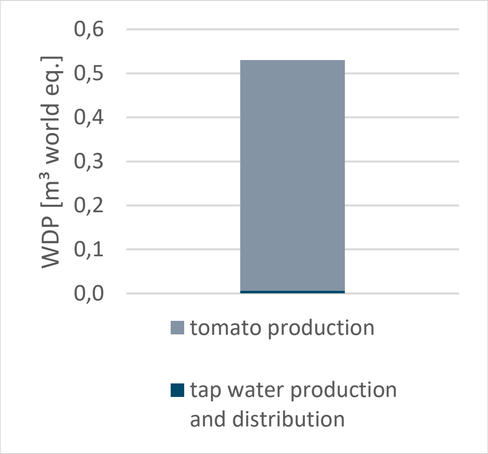
The impact score obtained by using AWARE represents the **WDP** of the product system. It provides an estimation of the **potential of the product system to deprive another freshwater user (human or ecosystem)**. Since it is a generic midpoint indicator, AWARE aims to approximate impacts on human health and ecosystem quality but does not model the overall cause-effect chain up to these receptors (section 4.2.1).

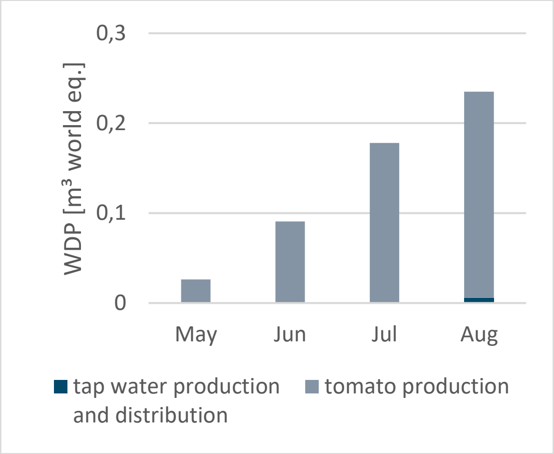
The unit of the WDP is m^3 world equivalents. As such, the result is expressed relative to the potential impacts of the average global consumption of 1 m^3 of water. As an example: **If the WDP of product A equals 0.5 m^3 world-eq., this suggests that the product's potential to deprive humans or the ecosystem of water is half as large as the global average consumption of 1 m^3 of freshwater.** For a detailed interpretation of the WDP see section 4.3.3.

The analysis and interpretation can have different aims, such as hot-spot analysis, or the comparison of several product systems. For the interpretation, bar charts can be useful. Note that there can be processes with negative AWARE scores. Differentiating these in the visualizations might improve the overall interpretability.

However, the practitioner needs to be cautious in the interpretation of the results. First, the AWARE CFs are subject to uncertainty (section 4.5.2). While they are quite robust in their order of magnitude, limited confidence should be placed in differences in results due to differences in CFs, if they are small. Furthermore, the resulting uncertainty is a combination of the uncertainty of the CFs and the inventory. Therefore, a difference in WDP of just a few percent is not necessarily meaningful enough to judge one product as being superior to another. In this case, to clarify whether the products are that close, it can help to refine the spatialization/temporalization of the main contributing processes and improve their inventory data quality. However, if the differences still are small, no conclusion can be made. Second, it is important to note that the results have a limited scalability. While the water consumption of product A might be marginal and the AWARE CFs justified, the water consumption of the entire production year, encompassing 1 million units of A, might be non-marginal. Therefore, deducing the impacts of the annual production from the WDP of one product unit might be misleading.

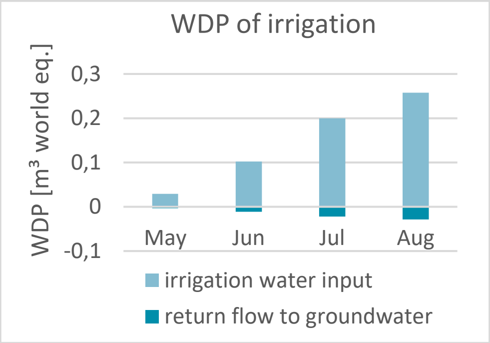
Example box: Cradle-to-gate WSF of tomato soup – Interpretation of the impact score





The total WDP of the tomato soup equals 0.53 m³ world-eq., which means that the cradle-to-gate impact of the soup is half as large as the global average consumption of 1 m³ of water.

Hotspot analysis:
The largest part of the WDP is attributed to the tomato production, that is, the irrigation water consumption. The largest impact of water consumption occurs in August. Therefore, one of the recommendations to the tomato soup producers could be to reduce the irrigation water consumption, especially in the dry months of July and August, e.g. by increasing the irrigation efficiency. This could reduce the excess evapotranspiration (e.g. from earth or leaf surfaces) and thus lead to lower requirements of irrigation water.



The WDP could as well be reduced by decreasing the evaporation in favour of more return flow to groundwater, for example by protecting the soil around the tomato plants. This would increase the amount of return flow in the calculations and lead to a lower net WDP of the irrigation.

4.6.4.1 Spatial contribution analysis of results

The overall impact score shows the potential impacts but does not allow for a further interpretation regarding the spatiotemporal aspects of the impacts. However, especially when two product systems are compared, further insight might be gained with a spatial analysis of impacts. For example, it could be that the regional hotspots of the WSF differ between two products: One might have its largest impacts in the watershed or country A, while the largest impacts of the other product might be in the watershed or country B. Therefore, disaggregating the total impact score in space can be important for the interpretation of the differences between both products.

4.6.4.2 Negative impact scores

For some processes or even an entire product system, the AWARE impact score might become negative. This happens either when more freshwater is released than withdrawn, e.g. for wastewater plant operations, or when the water is released with a different CF than when withdrawn. While it is technically possible to move water from one watershed to another, the latter case can also point toward an inconsistency in the characterization of the elementary flows. For example, a process could contain water inputs subject to a global CF and water outputs with a watershed-level CF and thus lead to flawed results.

In general, negative AWARE impact scores indicate that the product system reduces freshwater scarcity. Sea water desalinization is used to increase water availability for human users and can eventually lead to higher water availability in a watershed. Wastewater plants (WWTPs) are another example of processes with negative impact scores.

A negative AWARE score should however be interpreted carefully: Regardless of a WWTP's existence, the wastewater to be treated would in most cases have been released back to the watershed. The plant should also be seen in a broader context: Water that is released was previously extracted from the watershed. Therefore, the negative AWARE score does not mean that the water released by the WWTP is available in addition to the naturally available water. Finally, the aspect that the treated wastewater poses reduced harm to humans and the ecosystem should be assessed with water degradation LCIA methods.

4.6.4.3 Aggregation to a single indicator for a comprehensive WF

While ISO14046 allows the aggregation of a Water Footprint Profile into a single indicator, there is no recommendation on how to accomplish such aggregation with AWARE. If a standalone indicator is required, e.g. separated into the total impact on humans and total impact on the ecosystem, endpoint indicators should be used instead of AWARE.

4.6.4.4 Alternative ways of conveying AWARE results

In the dissemination of AWARE results to non-expert audiences, WF practitioners might want to facilitate the interpretation by comparisons to reference values. While the volume of water consumption in m^3 can be compared to illustrative references such as "the size of an Olympic swimming pool" (2.500 m^3), such an assertion is only partly transferable to AWARE.

A WDP of 25.000 m^3 world-eq. represents a potential impact of consuming water worth ten Olympic pools in the global average location where water is consumed, but only with the assumption that this impact is marginal in the world average location. Moreover, this does not mean that water worth ten Olympic pools is missing in the environment and there is no link to be made between the value in m^3 world-eq. and potentially deprived water users. This is similar to the Global Warming Potential (GWP) where no assertion is possible about how many humans will be affected by the emission of a greenhouse gas.

The analogy with the GWP opens another option to convey the AWARE results: Using a reference impact that was already calculated. For example, the GWP of a greenhouse gas emission might be 2400 kg CO_2-eq. This might be reported as "twice the impact of taking a plane from Paris to New York". Analogous, the AWARE score of 25.000 m^3 world-eq. could be represented as "four times the impact of producing a ton of green coconuts in Brazil" (Sampaio et al., 2021). The appropriateness and relevance of the reference value might depend on the field of study.

4.6.5 Edge cases of using AWARE

There are several edge cases in which the application of AWARE CFs might be less clear than in a standard industrial process. Six of them are presented in the following sections, along with a recommendation on how to handle them. These examples are all relevant to AWARE but not all unique to this method only, meaning that they would apply to any water scarcity footprint assessment.

4.6.5.1 Dams and reservoirs

Dams and reservoirs influence the water availability in a watershed. Reservoirs that are created to ensure water supply, commonly retain water in dry seasons to make it available for humans and agriculture in the wet season. However, they also influence the river flow and thus water availability for water users downstream. On an annual average, they might lead to increased evaporation and thus a seemingly adverse impact on water availability (Coelho et al., 2017; Herath et al., 2011). However, to assess their impacts, it is important to consider the seasonality of reservoir operations. ISO/TR 14073 provides an example of how a WSF of reservoir operation can be calculated. A balance between reservoir inflow and outflow is calculated for every month. This balance represents the change in water availability downstream due to the reservoir operation and is then interpreted as the water consumption of the reservoir. The example in ISO/TR 14073 shows that the positive effects of reservoir operation for dry months can outweigh the potential water scarcity impacts of reducing flows in wet months or increasing total annual evaporation from the reservoir. Pfister et al. (2020) compare the WSFs of reservoirs obtained by using different Water Scarcity LCIA methods, respecting the non-marginal character of reservoir operation. Section 7.2 of this report presents a case study on the assessment of reservoir operations in the context of AWARE.

4.6.5.2 Fossil groundwater

Fossil groundwater is a non-renewable water source. As such, AWARE does not apply to it, since AWARE focuses on renewable freshwater. It does not consider fossil groundwater stocks. Fossil water consumption is critical from a Resource AoP perspective, like other non-renewable resources, e.g. mineral oil. However, fossil groundwater is often used in water-scarce areas and excessive use increases the overall freshwater scarcity, while no LCIA method addresses the interplay between renewable and non-renewable water scarcity. Therefore, it is often considered in Water Scarcity Footprints and its use is treated the same as the use of renewable freshwater resources. If possible, fossil groundwater should however be treated in the “Resource” AoP.

4.6.5.3 Rainwater harvesting

Rainwater harvesting refers to the collection and storage of rainwater in ponds or similar for later use. This storage might reduce water availability for other water users in the watershed, e.g. by reducing runoff. For the assessment of rainwater harvesting impacts on Water Scarcity, it is important to consider that not all rainwater would have contributed to runoff. Instead, it might have evaporated and not contributed to freshwater availability in the watershed. Depending on the continent and leaving aside Antarctica, between 50% and 70% of annual precipitation evaporates and is thus not available for runoff generation (Miralles et al., 2011). In the case of rainwater harvesting, only the part of the collected rainwater that would have contributed to runoff should be interpreted as missing from the watershed. This amount of retained water represents the actual consumptive impact.

4.6.5.4 Brine and wastewater

Freshwater is first defined by its quality, which sometimes leads to confusion about whether a specific elementary flow should be characterized with AWARE. However, it is important to consider where the brine and wastewater flows originate from and to which environmental compartment or further use they are forwarded. This can be illustrated for an arbitrary industrial process that might use brine or wastewater:

1. If further up the supply chain the water was extracted from a freshwater source and later polluted, it should be appropriately characterized in that process as freshwater extraction with a corresponding AWARE CF.
2. If further up the supply chain it was extracted from a non-freshwater source (e.g., a saline lake), it should not be characterized with AWARE.

Since the extraction happens upstream, the water quality at the time when the water enters the industrial process is not relevant for the water consumption. A similar classification of options applies to wastewater that is forwarded to downstream processes, including purification or not.

1. If further downstream the water is released into a freshwater body, it should be treated as increasing water availability and characterized with AWARE.
2. If it is released into a non-freshwater body, e.g. the ocean, it should not be characterized with AWARE as it is considered consumed.

It is important to consider that the release of polluted water does not by definition increase freshwater scarcity. This is because it might be sufficiently diluted by the freshwater body it is released to. However, water quality aspects of a release of polluted water should always be simultaneously assessed with appropriate LCIA methods. To appropriately depict the impacts, the system boundaries should be set in a way that allows for consideration of the relevant upstream and downstream processes in the supply chain.

4.6.5.5 Freshwater consumption close to the sea

It might be argued that freshwater consumption close to the sea has a negligible impact on other water users since the consumed freshwater would anyways have only benefitted a small additional population of humans and aquatic or terrestrial species before running into the ocean. However, this neglects that estuarine ecosystems might be specifically sensitive to river discharge at a river mouth and that water consumption close to the sea might lead to reduced groundwater tables, affecting other water users and potentially leading to saltwater intrusion. While the latter environmental impact is not explicitly accounted for in the design of AWARE, these examples show that the assumption of a “burden-free” freshwater consumption close to the sea is not true and rather points to a spatial resolution issue in CFs. Following the precautionary principle, it is recommended to still characterize these impacts with AWARE.

4.6.5.6 Agricultural ponds filled with groundwater

Calculating an AWARE score for the storage of groundwater in open ponds for the agricultural industry – discussed as “mega-basins” in France – is similar to other water-consuming activities. Since in AWARE the water consumed from (non-fossil) groundwater is attributed to the month of consumption, the same can be done for the water extraction from groundwater for agricultural ponds. If an agricultural water user withdraws water to fill the pond in winter months, the AWARE CFs must be selected accordingly for the monthly withdrawals.

Regarding the pond alone and assuming no seepage through its sealing layer, the entire AWARE score is described by the AWARE score of the groundwater extraction. However, when considering the pond in combination with its water use in irrigation, e.g. when calculating a WSF of an agricultural product, the AWARE score might change. This is because part of the water used in irrigation might return to the watershed. These return flows will happen in rather dry months with potentially high CFs and might lead to a credit in the AWARE score. Consequentially, similar to the edge case of reservoirs, the temporalization of the WSF is key for a robust assessment of agricultural ponds.

4.7 Critical analysis of AWARE

AWARE is the outcome of a two-year consensus process with various stakeholders and as such subject to compromises. In some places, the method might misrepresent the potential to deprive other humans or the ecosystem of freshwater, either due to input data flaws or weaknesses in the methodology. These are collected in the following paragraphs, based on referenced literature and personal communication.

4.7.1 Limitations of input data used in the AWARE modelling

- The input data of AWARE is uncertain, especially in water-scarce regions. This is because WaterGAP2 might not adequately represent hydrological processes in these regions, but as well because in these regions there is less data to measure model performance. (Müller Schmied et al., 2014)

- WaterGAP2 does not implement long-range water transfers. However, these are used to alleviate water scarcity in several world regions and the misrepresentation of the transfers in the modelling might lead to flaws in the model output. (Simmons et al., 2022)

- Dams and reservoirs are considered to exist during the entire time of the model runs, neglecting their construction year. This could lead to over- or underestimations of the multi-year average water availability.

- Other aspects not explicitly represented in the WaterGAP version used for AWARE:

    - Desalination
    - Glacier melting
    - Bifurcation (splitting up) of rivers in river deltas

- AWARE has a rather low spatial resolution, resulting from its input data resolution. The watershed boundaries and size are based on a 0.5x0.5 degree grid, one grid cell representing more than 3000 km^2 at the equator, approximately 2000 km^2 in Central Europe, and down to less than 1000 km^2 in the highest latitudes covered by AWARE. This rather coarse grid might lead to inconsistencies with actual watershed boundaries.

- Moreover, the watershed resolution neglects that groundwater aquifers might connect different watersheds (Gejl et al., 2018). Water consumption could therefore impact more than one watershed.

- The area values used to calculate the AWARE CFs are not the land area, but the grid cell area. This leads to overestimated CFs in small coastal watersheds, where the land area is smaller than the area of the square grid cell (Baustert et al., 2022; Seitfudem, 2022).

4.7.2 Limitations of the AWARE methodology – Availability

- AWARE does not directly consider water stocks such as reservoirs or dams. Using the outflow of a watershed as a proxy for available water remaining might misrepresent the amount of water that is still available to humans via these man-made storages. (Simmons et al., 2022)

- Long-range water transfers are not considered in the AWARE methodology. However, in some places, the water that is consumed does not originate from the local watershed. Potential impacts in the source watershed by this consumption are therefore not included in AWARE.

- Groundwater sources are not considered explicitly in AWARE even though they can be a source of freshwater. The river discharge representing renewable freshwater availability in AWARE is subject to inflows of groundwater, but it does not provide information on how much groundwater remains available (Gejl et al., 2018). In addition, AWARE does not treat fossil groundwater use differently from renewable groundwater. Fossil groundwater can be considered a non-replenishable stock (see point 1).

- AWARE does not consider the fact that the evaporation of water does not indefinitely remove the water from the water cycle. In some regions, the water that is consumed might precipitate in the same watershed a few days later (Berger et al., 2018).

- AWARE does not assess how technologies such as atmospheric water harvesting could affect water availability for other freshwater users.

4.7.3 Limitations of the AWARE methodology – EWR

- The EWRs used in AWARE are subject to uncertainty since they follow a simplistic approach and do not differentiate ecosystem types. Furthermore, they only consider aquatic ecosystems, while freshwater availability is also important for terrestrial ecosystems (Boulay et al., 2018; Boulay, Lesage, et al., 2021).

- Calculating the EWR from natural water availability in some places disregards the impacts of flow regulation. For example, a river might have an annual flooding season that humans aim to prevent with dams. Calculating the EWR based on the natural cycle including a flooding season that is deliberately mitigated with a dam might lead to unrealistically high allocation of water to the ecosystem.

- The EWR is calculated from the output data of two different models: Natural Availability is taken from WaterGAP2, while the flow percentage required for sustaining the ecosystem is calculated with LPJmL, a different model. This might lead to inconsistencies in the EWR, e.g., where LPJmL assumes a month with low flow, requiring 60% of the natural flow, while WaterGAP2 assumes a high flow month, leading to an overestimation of water required for the ecosystem in AWARE.

4.7.4 Limitations of the AWARE methodology – General limits

- The cut-offs at both ends of the CF range do not allow to differentiate regions with very high or very low water scarcity. While for highly water-scarce regions this might make sense considering the increased uncertainty of input data for these regions (Müller Schmied et al., 2014), it nevertheless can be interpreted as a limit of the methodology (Hélias, 2020).

- Upstream-downstream interactions are not considered when subdividing large watersheds. Subbasins are treated in isolation from each other, sometimes resulting in low CFs for upstream subbasins even though water consumption might impact a subbasin with high CF downstream.

- The AWARE method does not provide guidelines on how to use the CFs in combination with an inventory that is not directly linked to monthly freshwater availability. As an example, farmers might have ponds on-site which they use for irrigation. It is unclear from which month CFs should be taken if a pond is filled during a rainy season, but the water is consumed in a dry month.

- The simple approach of AWARE neglects aspects that can be crucial for the impacts of water consumption on humans, e.g. the quality of the water supply infrastructure and adequate water management (Simmons et al., 2022). Furthermore, water quality is not considered, which might lead to unintuitive results where water is heavily polluted but regarded as “available water”.

- The marginal approach of AWARE (and other WSF approaches) disregards that water users might be prioritized, and some water consumption is essential to HH or EQ. For instance, calculating a WSF that focuses on life-essential water-consuming activities, like operating a hospital, might not be compatible with the assumption that the activity leads to additional freshwater deprivation, seen from a societal water use prioritization perspective.

- The use of area in the calculation of the AMDs in some cases makes the CFs sensitive to the way the watershed boundaries are set. This is relevant for rivers such as the Nile, where discharge does not increase proportionally to the additional catchment area when moving downstream.

4.7.5 Advantages of AWARE

While AWARE is not “the perfect method”, there are several advantages of using it:

- The meaning of AWARE is straightforward: How high is the potential to deprive other water users of freshwater, compared to the global average potential of consuming 1 m³ of freshwater?
- The method estimates impacts on both humans and the ecosystem
- AWARE considers spatiotemporal dynamics in water availability, allowing high-detail
- The CFs are both influenced by the ratio of demand to availability and the absolute freshwater availability, which leads to more intuitive behaviour of the CFs than using ratios such as CTA or DTA (section 4.1)
- The method is based on a consensus process between experts and thus is more likely to be accepted by stakeholders from industry, academia and governance
- The method is rather simple, and results can easily be explained with the variables used to calculate the CFs
- The reduction to a low number of input variables allows local recalculations of the CFs with high-quality input data. This enables a critical analysis of the underlying uncertainty.

However, several of the raised issues have limited influence on the daily practice since AWARE is not used in its most detailed form – partly because of the effort required for creating spatialized inventory datasets in matching resolution, and partly because of the lack of a complete and easy-to-use integration of the method in conventional LCA software (chapter 6).

4.7.6 Implementation issues

The varying degree of implementation in LCA software and LCIA methods leads to different issues that are further discussed in Chapter 6. Some of them are:

- Inventory databases might not be fully regionalized and spatialized, which either leads to a miscalculation of impacts due to inconsistent application of CFs to in- and outflows, or an application of CFs on inconsistent geographical scales. *For example: A global process for providing irrigation water (with the global default CF) might be used with an agricultural process specific to a certain country, where part of the irrigation water is returned to the watershed (with the country CF). The mismatch in CFs for the water-consuming irrigation water process and the return of water with the country CF leads to inconsistent results. Tools such as Regioinvent* (Agez, 2024) *aim to mitigate this issue.*
- LCIA methodologies that encompass several impact categories might not use the most up-to-date version of AWARE CFs. *For example, the country-level CFs of the Environmental Footprint methodology EF3.1 are outdated.*
- Inconsistent use of LCIA methods prescribing specific regionalization levels might lead to inconsistencies in characterization. *For example, the Product Environmental Footprint prescribes the geographic resolution of countries. Depending on the database implementation, elementary flows on other geographic scales such as continents sometimes are not characterized adequately (usually with the global average), even though more precise characterizations are available.*
- LCA software such as openLCA might allow the creation of customized spatial aggregations but does not follow the principle of weighting the watersheds by their overall freshwater consumption inventory. This misrepresents the spatiotemporal patterns of water extraction and could lead to inconsistencies with using other aggregations created by the AWARE developers.

5. Non-LCA water-related assessment methods and their comparison to LCA methods

This section first describes non-LCA water-related assessment methods, and then compares them to the LCA-based method WSF using AWARE. The choice of the methods studied is based on responses to the survey (section 6.1) and the most retrieved methods in the literature.

5.1 Description of non-LCA water-related assessment methods

5.1.1 Aqueduct Water Risk Atlas (WRI)

The Aqueduct Water Risk Atlas, developed by the World Resources Institute (WRI), is a web-based tool that enables users to map and analyze water-related risks globally. It utilizes high-resolution data to assess current and future water risks, including water stress, seasonal variability, and water quality. Designed for corporations, investors, and policymakers, it supports decision-making by highlighting regions most vulnerable to water-related challenges. The tool incorporates over a dozen indicators to provide a comprehensive picture of physical, regulatory, and reputational water risks.

Aqueduct allows users to input site-specific data, assess risks at different scales (from local watersheds to global comparisons), and visualize the outcomes through interactive maps. It integrates climate change scenarios and future water availability projections.

5.1.2 Global Water Tool (WBCSD)

The Global Water Tool, developed by the WBCSD, was an Excel-based resource that helped organizations map their water use and assess related risks. It combines site-specific water data with external datasets (e.g., water stress and quality indicators), allowing users to evaluate potential vulnerabilities across operations and supply chains. The tool was useful for high-level assessments and for identifying water-related hotspots in business activities.

The tool served as a precursor to more advanced solutions, such as WWF’s Water Risk Filter and WRI’s Aqueduct but it was discontinued in 2019.

5.1.3 Water Risk Filter (WWF)

The Water Risk Filter, created by the World Wide Fund for Nature (WWF), is a web-based tool designed to help companies and investors assess water-related risks. It includes a database with over 100 global datasets, covering physical, regulatory, and reputational risks. Users can conduct site-specific risk assessments and scenario analyses to assess current and future water challenges, including climate change impacts.

The tool is widely used for prioritizing water stewardship actions. It is integrated within reporting frameworks such as the Task Force on Climate-related Financial Disclosures (TCFD) making it an essential resource for aligning corporate sustainability goals with global standards.

5.1.4 Water Footprint Network (WFN)

The WFN provides a standardized methodology for quantifying the freshwater used and polluted during the production and consumption of goods and services. Its framework includes the green, blue, and grey water footprints, each addressing different aspects of water use:

- **Green water** footprint is water from precipitation that is stored in the root zone of the soil and evaporated, transpired or incorporated by plants. It is particularly relevant for agricultural, horticultural and forestry products.
- **Blue water** footprint is water that has been sourced from surface or groundwater resources and is either evaporated, incorporated into a product or taken from one body of water and returned to another, or returned at a different time. Irrigated agriculture, industry and domestic water use can each have a blue water footprint.

- **Grey water** footprint represents the virtual amount of fresh water required to assimilate pollutants to meet specific water quality standards. The grey water footprint considers point-source pollution discharged to a freshwater resource directly through a pipe or indirectly through runoff or leaching from the soil, impervious surfaces, or other diffuse sources.[4]

The WFN assessment uses a similar approach as the LCA based, with four differentiated phases:

- Goal and scope, that sets the objectives and indicate which data will be used, how each subsequent step of the assessment will be approached and the level of detail required to achieve the desired results.
- The accounting phase, where data are collected from primary sources or databases, with WaterStat the main one. Once data are collected, the volumes of the three types of water are calculated;
- The sustainability assessment phase assesses the level of sustainability of the volumes calculated. The level of sustainability is assessed through environmental sustainability, which looks at the exceedance of the sustainable limits of the resource, both in terms of scarcity and capacity to assimilate the pollution; the resource efficiency and the equitable allocation of the resources, by looking at the fair distribution of the resource among all users.
- The response formulation phase seeks to define strategies to reduce the total water footprint and increase the sustainability of the product based on the previous phases' analysis.

The WFN also maintains the WaterStat database, which offers global and country-level water footprint factors for crops, industries, and products. This database, along with the Water Footprint Assessment Manual, supports businesses, policymakers, and researchers in evaluating the sustainability of water use and developing strategies to reduce water-related impacts.

Boulay et al. (2013) studied the differences and complementarities between LCA-based WF and the WFN assessment. The main differences are identified in the objectives and the different phases of each method.

- The objectives are different since LCA-based WF looks at quantifying the potential impact of different water-related environmental problems while WFN assessment aims to assess the degree of sustainability and equitable use of the water used in the life cycle of the product or service.
- The phases of the methods are similar since both start with the definition of the goal and scope and a phase of accounting (life cycle inventory and accounting respectively). The main difference comes from the third phase, where LCA-based WF seeks to translate the volumes and substances inventoried into quantified potential environmental impacts, while the WFN assessment uses the volumes directly to perform a multicriteria analysis of the environmental sustainability, economic efficiency and social equity. Some potential aspects can be aligned, namely the water scarcity indicators.

5.2 Critical analysis

We have established different criteria to evaluate the methods presented in the previous section and compare them to AWARE. As it is the focus of the report, this comparison focuses initially on the calculation of a WSF (the nature of the water scarcity calculated, the approach and data used, the geographical level of detail, etc.) but it considers also other aspects such as the inclusion of other water-related indicators or the scope of the assessment. The elements and criteria used for the analysis are divided into general approach, application criteria and technical aspects.

5.2.1 General definition and approach criteria

The elements included in this section are:

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[4] https://www.waterfootprint.org/water-footprint-2/what-is-a-water-footprint/

- **Scope of the assessment:** if the assessment is intended for a company, a product, a region, etc.
- **Meaning/Most Appropriate Use of Results:** primary objectives of the tool and main uses
- **Recommendation by Standards/Guidelines:** is the method recommended by standards or guidelines?
- **Other indicators:** Indicates whether the method includes metrics beyond water scarcity, such as other water quantity, water quality or other issues.
- **Life cycle perspective:** the tool requires or recommends considering the whole life cycle of the studied object.

Table 8: Comparison of methods and tools. General definition and approach

Method	Definition	Scope of the assessment	Meaning/most appropriate use of results	Standards/ guidelines	Other indicators	Life cycle perspective :
AWARE	LCA-based WSF method	Products or services, (company, region)	Assessing water scarcity impacts at a regional level.	PEF GLAM FAO LEAP PCRs	Only water scarcity	Yes
Aqueduct Water Risk Atlas (WRI)	Tool to assess water risk across regions.	Companies, regions	Help stakeholders identify areas of high water-risk, and support decision-making processes.	No, but widespread use and recognition	Includes 13 indicators covering various risk categories: Physical risks (quantity), Physical risks (quality), Reputational risks	No
Global Water Tool (WBCSD)	Tool to map companies' water use and assess associated risks across their global operations and supply chains	Companies and their supply chain	Identify potential water-related risks	Compatible with reporting frameworks like the GRI and CDP Water	Sanitation, population, and biodiversity	Partial
Water Risk (WWF)	Tool for companies and investors to assess water-related risks across their operations, supply chains	Companies, regions	Identify and assess water-related risks	Task Force on Climate-related Financial Disclosures (TCFD)	60 risk indicators, including factors related to water quality, regulatory environments, and reputational considerations.	Partial
Water Footprint Network (WFN)	Methodology for evaluating the volume of freshwater utilized and polluted throughout the production and consumption processes of goods and services	Products, companies, regions	Evaluate the sustainability of water use.	FAO LEAP (only derived water scarcity indicator)	Blue water (freshwater), green water (rainwater), and grey water (pollution footprint).	Yes

AWARE is a method specifically developed to perform LCA-based water scarcity footprint, focusing on regional water scarcity and incorporating high levels of regional detail. As a consensual method, it is broadly recommended by guidelines and standards. WFN is the only one besides AWARE that incorporates a life cycle perspective and that provides a specific water scarcity indicator

Compared to AWARE, tools like the Aqueduct Water Risk Atlas and Water Risk Filter focus more broadly on assessing water risks (e.g., physical, regulatory, and reputational) rather than strictly quantifying water scarcity. These tools are designed for corporate decision-making, by identifying and assessing water-related risks across supply chains, but the life cycle perspective is not considered.

AWARE focuses on evaluating water scarcity impacts using water consumption and regional availability data. The WFN method evaluates also water use with a different approach, based on volumes and that seeks to assess the global sustainability of the water resources. The Aqueduct Water Risk Atlas (WRI), WWF's Water Risk and The Global Water Tool (WBCSD) assess potential water risks across supply chains.

Most of these methods (all but the WFN) are mainly designed for companies to understand the risks associated with their activities.

All methods but AWARE include complementary indicators covering physical, quality and, in some cases, reputational issues.

5.2.2 Technical characteristics

The elements included in this section are:

- **Water scarcity approach:** Explains how the method calculates water scarcity factors (methods presented in section 3.2.4.1), by stating whether assessments are based on withdrawals, total water availability, consumption, or other relevant factors.
- **Input data used:** data sources or databases utilized for calculations of water scarcity indicators (Aquastat, WaterGap…)
- **Level of geographical detail.** Specifies the geographical resolution at which the tool was developed (watershed, country, grid-cell resolution…)
- **Level of temporal detail.** Specifies the temporal granularity used in the tool (Monthly data for seasonal variations, annual averages, other)
- **Prospective analysis:** the tool provides future projections or scenarios, such as water scarcity per region based on consumption trends and climate change perspectives.
- **Uncertainty:** the tool accounts for or provides methods to assess the uncertainty of its results.

Table 9: Comparison of methods and tools. Technical characteristics.

Method	Water scarcity approach	Input data used	Level of geographical detail	Level of temporal detail	Prospective analysis	Uncertainty
AWARE	AMD.	WaterGap, Water use data	Watershed (sub-watershed in some cases. Country and global aggregations	Monthly with different annual aggregations (agri, non-agri)	Prospective values developed	Uncertainty values available, not implemented in LCA tools
Aqueduct Water Risk Atlas (WRI)	WTA	PCR-GLOBWB 2 model, which simulates global water supply and demand dynamics.	Sub-Basin Level	Monthly	Future projections, to provide users with a range of possible scenarios	Tool incorporates uncertainty analyses.
Global Water Tool (WBCSD)	Inventory level water stress indicators from the WRI.	AQUASTAT, World Health Organization, UNICEF Joint Monitoring Programme, and the United Nations Population Division	Country and watershed levels	Annual	Not included	Not included
Water Risk (WWF)	Qualitative score based on physical, regulatory, and reputational risks	Copernicus Climate Change Service and the European Environment Agency, to inform its risk assessments	Country and watershed levels, and offers high-resolution data for specific regions, such as Europe.	Annual	Scenario analysis to account for uncertainties in future water risks	Scenario analysis to account for uncertainties in future water risks
Water Footprint Network (WFN)	CTA	WaterStat database	Global, regional, country, and watershed levels are possible if data are collected (no data provided?)	Seasonal and annual variations.	Not included	No uncertainty information provided

The water scarcity indicators proposed by the methods differ all in the approach used, while AWARE, WFN and WRI rely on different quantitative approaches, the other methods use semi-qualitative methods or just inventory data (withdrawn).

Most of these tools (AWARE, Aqueduct, and Water Risk Filter) are developed at the subnational or watershed-level detail but in some cases, the operationalization is made at the country level. Equally, the temporal resolution of the developed methods for water scarcity indicators varies, with tools like AWARE and Aqueduct allowing for seasonal and monthly analysis, while others (e.g., WFN) rely on annual or aggregated data.

Few tools/indicators provide the data to perform uncertainty analyses. Tools like Aqueduct and the Water Risk Filter incorporate some sort of uncertainty analysis and prospective modelling, enabling scenario analysis for future water risks under different climate and socioeconomic conditions. AWARE uncertainty information is available but not implemented in LCA software. The Global Water Tool and WFN lack explicit frameworks for addressing uncertainty, which could limit their applicability in dynamic or uncertain contexts.

5.2.3 Operational characteristics

The elements included in this section are:

- **Operationalization:** how the method or tool is implemented (stand-alone tool, easily integrated into LCA software, web-based tools…)
- **Inventory**: types of input data required for the tool
- **Last Updated:** release of the most recent version

Table 10: Comparison of methods and tools. Operational characteristics.

Method	Inventory needed	Operationalization	Last update
AWARE	Water consumption data and regional water availability data.	Integrated into LCIA methods	2020
Aqueduct Water Risk Atlas (WRI)	Water withdrawals, consumption, availability, and quality, integrating outputs from the PCR-GLOBWB 2 global hydrological model.	Web-Based Platform	2023
Global Water Tool (WBCSD)	Water withdrawals, consumption, and discharge for each site, along with geographic coordinates	Excel-based tool	February 2015 Decommissioned in 2019
Water Risk (WWF)	Site locations and water usage metrics	Web-based tool	Version 6.0: 2021
Water Footprint Network (WFN)	Water withdrawals and consumption. Pollutant loads and concentrations. Production volumes and processes	Stand-alone tool (online Water Footprint Assessment Tool) or partially integrated in LCA software	2020-2022.

The Water Risks Atlas, WWF Water risk and the Global Water Tool as stand-alone tools (either Excel or web-based, while AWARE needs LCA software with its LCI databases to provide results. For the WFN, part of the approach is integrated into LCA software (namely the blue water as a measure of water scarcity), but there is an online tool to calculate the complete method.

Data needed are fairly similar for all the tools, including in and out volumes, location of sites and activities, and in the case of tools including other indicators, information about the quality (pollutant emissions and/or concentrations).

All these tools are kept updated by their developers but the Global Water tool, which was discontinued in 2015 and should be replaced by other tools.

6. Current practices and limitations

6.1 Current practices for assessing water-related issues in companies

A survey to know the current practices on water assessment of the ScoreLCA members was sent at the beginning of the project. The answers to the 14 questions (included in Annex 10.3) present a portrait of the current practices of companies from different sectors (including chemistry, mining, automotive, energy, or equipment), mainly based in France but with activities worldwide.

Most respondents identify direct consumption in manufacturing as a significant contributor to water use. Only 27% recognize the water consumption in the supply chain as one of the main contributors to the total life cycle water use.

The main reasons for assessing water-related issues include regulatory compliance, internal assessments for eco-design, and strategic decision-making. For this, companies frequently employ LCA-based tools (mainly AWARE as the water scarcity indicator), the Aqueduct Water Risk Atlas (WRI), and internally developed tools.

Primary data for the assessment include mainly the direct use in their facilities combined with ecoinvent and, in fewer cases, other LCI databases. Simapro and LCA for Experts (Gabi) are the most common tools for conducting LCAs.

The predominant challenges identified are data collection, modelling complexity, tool implementation, and result interpretation. In general, uncertainty is not calculated by companies in their assessments.

Besides these results, section 2.4.2 provides a portrait of how guidelines and standards at the regional or sectorial level assess water-related issues, namely water scarcity, and what are the main methods recommended.

6.2 Current practices for calculating a Water Scarcity Footprint

6.2.1 LCI databases

LCI databases are essential for performing an LCA calculation as they provide comprehensive datasets for background processes complement the foreground data collection and allow practitioners to complete the system model. LCI databases allow also the use of technology and region-specific processes that allow to increase the robustness of the results. In the case of WFs, which strongly depend on the geographical location of processes, the use of LCI databases representing multiple regions is crucial. Indeed, in other LCA-based assessments (e.g. carbon footprint) the use of non-region-specific data is not as important in the final result.

The main LCI databases were analyzed to understand their treatment water flows and other water information that would allow the complete calculation of water use impact scores. Table 11 summarizes these elements.

Table 11: Water flows included in LCI databases

LCI database	Are water flows balanced?	Flows included	Temporal and spatial differentiation	Other water information (flows, properties)
ecoinvent	Yes	Inflows: Water from surface and groundwater Outflows: emissions to different compartments	Only spatial (per country/region)	Water content in the product (partial)
Sphera LCA database	Yes	Inflows: Water from surface and groundwater	Only spatial (per country/region)	Additional flows not used in calculations

LCI database	Are water flows balanced?	Flows included	Temporal and spatial differentiation	Other water information (flows, properties)
		Outflows: emissions to different compartments		
Agribalyse	Yes	Inflows: Water from surface and groundwater Outflows: emissions to different compartments	Only spatial (per country/region)	
Agri-footprint	No	Inflows: Water from surface and groundwater, rainwater	Only spatial (per country/region)	
USLCI	No	Inflows: Water from surface and groundwater	No	

Ecoinvent, Sphera LCA database (Gabi) and Agribalyse ensure that water flows are balanced while Agrifootprint and US-LCI only include withdrawals in their processes.

Ecoinvent (and Agribalyse, which follows ecoinvent's data guidelines) mostly follows the framework proposed in the Quantis water database (explained in section 2.2.3) and in ISO 14046. Inputs of water include different types (groundwater, surface water, seawater, and rainwater) differentiated by their location while outputs, which should balance the inputs include water incorporated in the products, water transferred to other watersheds, and outputs to different environmental compartments (see section 4.6.1 for specific flows to be included for a WSF with AWARE). The water balance is completed by additional information to consider water incorporated in products from the technosphere or other extracted resources. Temporal differentiation is not provided.

Table 12 shows all water-related flows of ecoinvent 3.10 and whether they should be characterized with AWARE CFs. Note that in a watershed AWARE does not distinguish different freshwater bodies such as rivers, lakes, or groundwater – all are characterized with the same monthly CF. Marine or fossil water is out of the scope of AWARE (see edge cases of applying AWARE, section 4.6.5).

Table 12: Elementary flows of water in ecoinvent 3.10 and whether they require a characterization with AWARE.

type	flow name	compartment/ sub-compartment	characterized with AWARE
emission	Water	water, surface water	YES
	Water	water, fossil well	YES
	Water	water	YES
	Water	water, ground-	YES
	Water	water, ground-, long-term	YES
	Water	water, ocean	NO
	Water	air, non-urban air or from high stacks	NO
	Water	air, urban air close to ground	NO
	Water	air,	NO
	Water	air, lower stratosphere + upper troposphere	NO
	Water	air, low population density, long-term	NO

type	flow name	compartment/ sub-compartment	characterized with AWARE
natural resource	Water, cooling, unspecified natural origin	natural resource, in water	YES
	Water, lake	natural resource, in water	YES
	Water, river	natural resource, in water	YES
	Water, turbine use, unspecified natural origin	natural resource, in water	YES
	Water, unspecified natural origin	natural resource, fossil well	YES
	Water, unspecified natural origin	natural resource, in water	YES
	Water, unspecified natural origin	natural resource, in ground	YES
	Water, well, in ground	natural resource, in water	YES
	Water, in air	natural resource, in air	NO
	Water, salt, ocean	natural resource, in water	NO
	Water, salt, sole	natural resource, in water	NO

Sphera LCA database (Sphera, 2022) follows ISO 14046 to identify the water flows to be included in its processes, including:

- Inputs: freshwater, rainwater, lake water, river water and groundwater
- Outputs: water vapour, evapotranspiration, processed water, turbined water, cooling water and collected rain.

Besides, some additional water flows are accounted for in Sphera LCA database, namely sea water and water as a product from the technosphere (ex: tap water). No mention is made of the total water balance of processes in the documentation.

Spatial differentiation of flows is recognized as a key element and is provided in the database. While temporal differentiation is mentioned in the documentation as important since some LCIA methods provide specific characterization factors, this feature is not implemented due to the structure of the datasets and limited data availability (Sphera, 2022).

6.2.2 LCIA

The main LCIA methodologies are analyzed regarding the water scarcity indicator included in each method and the level of regionalization proposed. Table 13 summarizes these elements.

Table 13: Water scarcity category per LCIA method

LCIA method	Version	Water scarcity	Level of regionalization
EF3.1	3.1	AWARE	country
GLAM	beta	AWARE (recommended, not available in the beta version)	country
IMPACT World+	2.1	AWARE	country
ReCiPe (midpoint)	2016	Water use (Hoekstra & Mekonnen, 2012)	country

LC-IMPACT	0.5	WSI (used to calculate DALY and species.yr)	country

All the listed LCIA methodologies propose water scarcity indicators at the country level. Most of these methodologies use AWARE to assess water scarcity. LC-IMPACT, which is an endpoint method deviates by using the Water Stress Index (WSI), which is then used to derive impacts measured in DALY and species loss (species.yr), emphasizing a more direct link to human and ecological health outcomes.

In addition to water scarcity, each method incorporates other impact categories such as acidification and eutrophication, which are critical for a holistic understanding of environmental burdens. The EF3.1, GLAM, and IMPACT World+ methods include acidification and eutrophication indicators, while the ReCiPe (midpoint) method uses a different water scarcity indicator — Water Consumption Potential (WCP) — but similarly integrates acidification and eutrophication impacts. IMPACT World+ also extends its scope to include ecotoxicity, reflecting a broader assessment of chemical impacts on ecosystems. Section 3.2.3 provides details on the categories included in each LCIA method.

6.2.3 Operationalization of the calculation of water scarcity impact scores in LCA software

6.2.3.1 Estimation and characterization of net freshwater consumption

Unlike the calculation of carbon footprint, which can rely on a single emission factor without spatial information, the calculation of water scarcity impact scores requires spatially detailed flows. This implies the use of LCA tools capable of integrating spatially differentiated flows.

As mentioned in section 4.6.1, the calculation of water scarcity scores is made by multiplying the net freshwater consumed by the corresponding characterization factor for each process. Two approaches are identified:

- “Consumptive flows” approach the water flows effectively consumed (i.e. leaving the watershed) are added. Those flows are the water evaporated, and the net water incorporated in the product or the by-products.
- Watershed differential: the total water consumed is calculated by the differential between the withdrawal and the water discharged back to the biosphere.

This latter approach is the one implemented in all LCA tools due to its simplicity. Indeed, this approach estimates the net freshwater consumption using elementary flows that are easily available while the first approach requires additional information like the water content incorporated in products) that is not handled by LCA tools and would requires more complete LCI databases. Indeed, the water incorporated in the product is documented in ecoinvent as a property that can be consulted via ecoquery, but it does not appear in the implementation of the database in LCA tools as they only use elementary flows for calculations. A simplification could be done where the consumptive flows approach was used by approximating the total consumption by the water evaporated, which is an elementary flow present in the database.

Since all elementary flows (input and output) are positive in LCA tools, and contrary to what is theoretically explained in section 4.6.3, the calculation based on the differential is made by multiplying the input flows by a positive characterization factor and output flows – representing a decrease of the scarcity – by the same characterization factor in negative (a special case of freshwater replenishment occurs for reservoir operation in dry seasons, see section 4.6.5). The example box used in 5.5.3 is reproduced again here with the difference highlighted in red.

AWARE results of the tap water production:

Process inputs (water, from groundwater):	0.0005 m^3 x 14.7 m^3 world-eq./m^3
Process outputs (water, to surface water):	0.0001m^3 x -14.7 m^3 world-eq./m^3
Total:	0.006 m^3 world-eq.

6.2.3.2 Operationalization of the spatial differentiation

The geographical resolution implemented is equal for all the studied tools. All include characterization factors spatially differentiated at the country level. In the case of openLCA and Brightway, the use of native characterization factors or the calculation of new characterization factors for newly defined regions is technically possible but not well implemented yet as explained in section 4.7.6. All the tools allow the manual addition of new characterization factors in the LCIA method, but this implies the creation of new elementary flows and their inclusion in the studied processes.

6.2.3.3 Operationalization of the temporal differentiation

The temporal resolution is available in the implemented methods with agri and non-agri characterization factors, but LCI databases do not include this detail, so their use implies modification of processes. As for the temporal resolution, more precise temporal characterization factors (monthly values) could be included in LCIA methods.

6.2.3.4 Other aspects

Only openLCA and Brightway allow the inclusion of uncertainty data (available for AWARE) for LCIA methods that would be used in Monte-Carlo analyses. Nevertheless, the differential approach used to calculate the net consumption is problematic for Monte-Carlo analyses, as explained in section 6.3.

However, generating a single aggregated water scarcity score could be feasible if the impact scores for each process within the background system were precalculated and used outside the LCA tool.

Table 14 summarizes the implementation of previous aspects of AWARE in the most common commercial LCA tools. As mentioned above, all tools use the differential of flows as a method to calculate the AWARE scores.

Table 14: AWARE integration in commercial software

Method/Software	**Simapro**	**openLCA**	**PCA for experts**	**Brightway**
Calculation method	Differential of flows	Differential of flows	Differential of flows	Differential of flows
Spatial resolution by default	Country	Country	Country	Country
Spatial resolution refined	By hand	Geospatial* By hand	By hand	Geospatial* By hand
Temporal resolution	Agri-non-agri, average Available but no LCI to complete the calculation	Agri-non-agri, average Available but no LCI to complete the calculation	Agri-non-agri, average Available but no LCI to complete the calculation	Agri-non-agri, average Available but no LCI to complete the calculation

Uncertainty of LCIA	Not possible	Available	Not possible	Available

6.3 Interpretation

The approach of implementation by watershed differential presents some issues during the interpretation phase.

When one of the main in or out water flows is a technosphere flow, the calculation by differential can create an **imbalance in the final result if the process that produces this technosphere flow does not have the same geographical location as the studied process**. When using ecoinvent, this issue appears mainly with agricultural processes using irrigation, processes using tap water and processes using wastewater treatment processes. Figure 20 shows an example of this issue extracted from ecoinvent v3.10, where the inputs of water come from different regions that do not match the region of the output (wastewater treatment). Table 15 shows the detailed calculation for the flows presented in the figure with their respective characterization factors. Even if the water input and output are balanced, the result is negative due to the mismatch of locations.

Besides, the potential mismatch of regions, the use of stand-alone processes for activities such as irrigation creates a false portrait of the responsibility for the water consumption when performing contribution analysis.

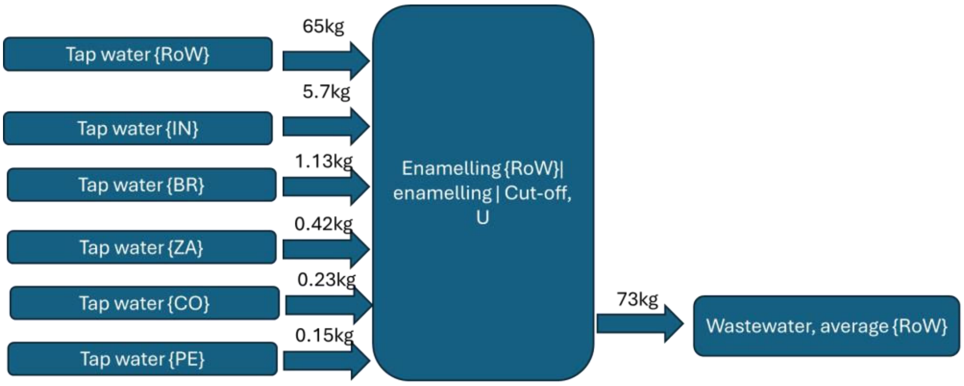


Figure 20: Enamelling {RoW} process from ecoinvent v3.10, cut-off. Main water flows.

Table 15 : Simplified calculation of AWARE score for Enamelling {RoW} process from ecoinvent v3.10, cut-off (outputs in red)

Flow	CF	Amount	AWARE (m3 world eq)
Tap water, RoW	42.95	65.35	2806.91
Tap water, IN	29.83	5.71	170.36
Tap water, BR	2.28	1.14	2.60
Tap water, ZA	38.35	0.42	16.21
Tap water, CO	1.42	0.23	0.32
Tap water, PE	27.78	0.15	4.13
Wastewater, average, RoW	**-42.95**	**73**	**-3135.35**
TOTAL		**0**	**-134.83**

The approach of implementation by watershed differential creates also a problem when analyzing the contribution to the impact score by elementary flows. As both negative and positive flows are included, the list of contributors is often dominated by flows that are balanced by the equivalent negative flow. This artificially extended list of elementary flows complicates the identification of the actual main contributors.

The calculation by differential presents also issues when performing Monte-Carlo analyses as the flows in and out are independent of each other when implemented in LCA tools. The independence of the two flows results in an imbalance of the total water of the process, which could lead to wrong results. Table

16 shows a simplified example of this issue based on the previous example assuming a probability distribution function of the total water in and out is uniform varying between 71 and 75 m^3. In some iterations (iterations 7 or 8), the aleatory value for the output is bigger than the value for the input, which leads to a negative balance that could be interpreted as if the process created water.

Table 16: Example of Monte-Carlo iterations with independent input and output water flows

Iteration number	Water in	Water out	Water balance
1	71	71	0
2	75	71	4
3	75	73	2
4	71	72	-1
5	72	73	-1
6	71	71	0
7	73	74	-1
8	73	75	-2

6.4 Other limitations

Besides the limitations explained in the previous section, other aspects can be identified of the water scarcity footprint. Most of the specific cases of use of AWARE detailed in section 4.6.5 apply also to other water scarcity methods, namely:

- How to account for the effects of water management infrastructures (dams and reservoirs) and how to handle the water availability over the year compared to the natural availability;
- How to consider the use of water resources not connected to the main available water system, such as fossil groundwater and water collected in artificial infrastructures such as ponds or reservoirs;
- The system boundary problem associated with the use of wastewater. The question of how to allocate the water withdrawal and later emission between the initial and the final used can affect the result of the water scarcity footprint.

7. Case studies for Water Scarcity Footprint

7.1 Description of case studies

The following sections present two case studies illustrating the applicability and challenges of using the AWARE method to perform a Water Scarcity Footprint (WSF):

Case Study 1: Application of the Water Scarcity Footprint to reservoir operations for hydroelectricity generation:

- ⇨ This case study explores the WSF of reservoirs in hydroelectricity generation, using the AWARE method to assess the influence of inventory spatialization and temporalization in WSF calculations. It emphasizes how different levels of spatiotemporal details can improve the accuracy of water scarcity assessments for reservoirs. The study also highlights challenges such as multifunctionality, the representativity of input data, and reservoir multifunctionality.

Case Study 2: Application of the Water Scarcity Footprint to an industrial process using bio-based inputs

- ⇨ This case study focuses on the ethanol production process from maize in Iowa, using a generic ecoinvent cradle-to-gate model. It aims to understand the importance of refining WSF results through regionalization, explores edge cases like the use of fossil groundwater, and compares WSF with other water-related impact categories, highlighting the limitations of relying solely on AWARE for water-related impacts.

7.2 Case study 1: Application of the Water Scarcity Footprint to reservoir operations for hydroelectricity generation

7.2.1 Overview of the case study

This case study explores the treatment of reservoirs for hydroelectricity to perform a WSF. First, the dynamics of a reservoir's water consumption are presented (section 7.2.2). Subsequently, section 7.2.3 presents an ecoinvent process for hydroelectricity generation that will serve as a starting point for WSF calculations. In section 7.2.4, the process is characterized by the AWARE method, using different levels of spatiotemporal detail to show the benefits of applying spatialization and temporalization of the WSF inventory in line with ISO/TR14073. A WSF in m^3 world-eq./kWh is calculated for the reservoir, respecting its monthly water consumption patterns. The final parts of the case study evaluate the relative importance of spatialization over temporalization for the reservoir case and provide an example of how to interpret the obtained WSF.

In addition to the main case study, section 7.2.5 discusses general challenges for implementing a WSF for reservoirs, namely reservoir multifunctionality, temporal representativity of the water balance input data and non-marginality of a reservoir's water consumption.

Data and tools used

Database:	*ecoinvent version 3.10 cutoff (Wernet et al., 2016)*
LCA software:	*openLCA version 2.4.0 (https://openlca.org)*
LCIA method dataset:	*openLCA LCIA method database version 2.7.0 (available on openLCA nexus: https://nexus.openlca.org/)*

7.2.2 Introduction: Water balance and net freshwater consumption of a reservoir

Reservoirs are unique in the context of AWARE since they are part of a water management scheme in a watershed but consume water themselves. The construction of a reservoir often leads to a lower annual discharge at the location downstream of the reservoir. The increased surface area of the surface water body increases evaporation losses from the watershed. However, reservoirs can help to mitigate droughts and make water available for human and environmental needs in the dry season.

To model the WSF of a reservoir with AWARE, relevant flows have to be identified and quantified, to establish the net water consumption of the reservoir (section 4.6.1, Inventory data collection). For a simple reservoir, it can be assumed that it receives water from upstream and from direct precipitation on its surface. The reservoir loses water due to evaporation and due to the release of water into the downstream river. Additionally, the reservoir has a storage capacity which is not represented in Figure 17 (*Water consumption in a simple LCA process*). This storage capacity separates reservoirs from other technological processes, where water in- and outputs of the process balance to zero. To be aligned with the Inventory data collection methodology presented earlier, we can interpret the storage function of the reservoir as an external process that receives water for storage or returns water to the reservoir operation but has no other in- or outputs (Figure 21). Accounting for all these flows balances to zero:

Equation 8

$$0 = IN_{inflow} - OUT_{release} + IN_{from\_storage} - OUT_{to\_storage} + IN_{precipitation} - OUT_{evaporation} \; [m^3]$$

Following this concept, two ways of establishing the net freshwater consumption of a reservoir are possible (see as well section 4.6.1.1):

1. The watershed differential approach: $IN_{inflow} - OUT_{release}$
2. The consumptive flows approach:
   $IN_{from\_storage} - OUT_{to\_storage} + IN_{precipitation} - OUT_{evaporation}$

Obtaining data for an entire water balance for a reservoir is often challenging, especially for the modelling of evaporation processes. Therefore, in this case study we focus on the watershed differential approach which only requires data on the inflow of the reservoir from upstream and its outflow to the downstream watershed.

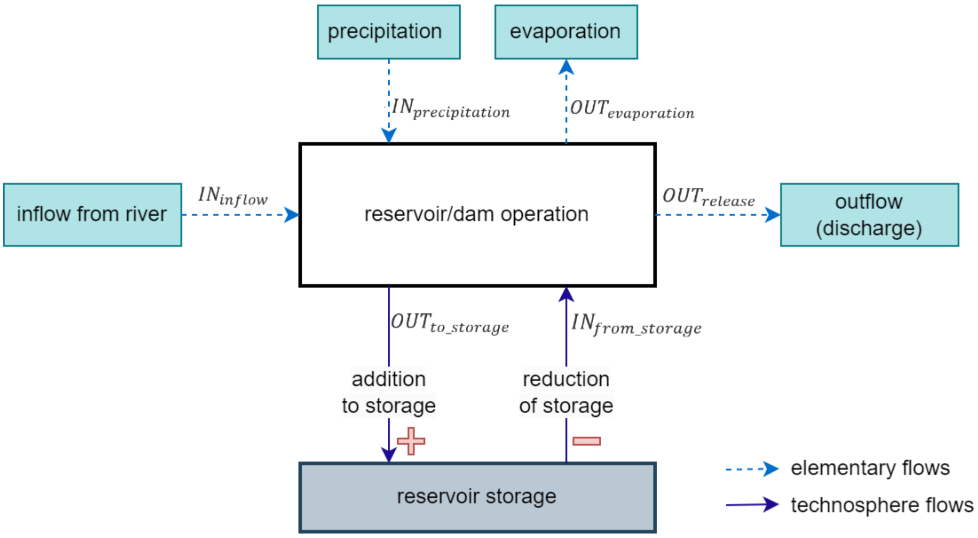


Figure 21. Relevant flows for assessing reservoir operations with AWARE.

7.2.3 Inventory: An ecoinvent hydropower generation process

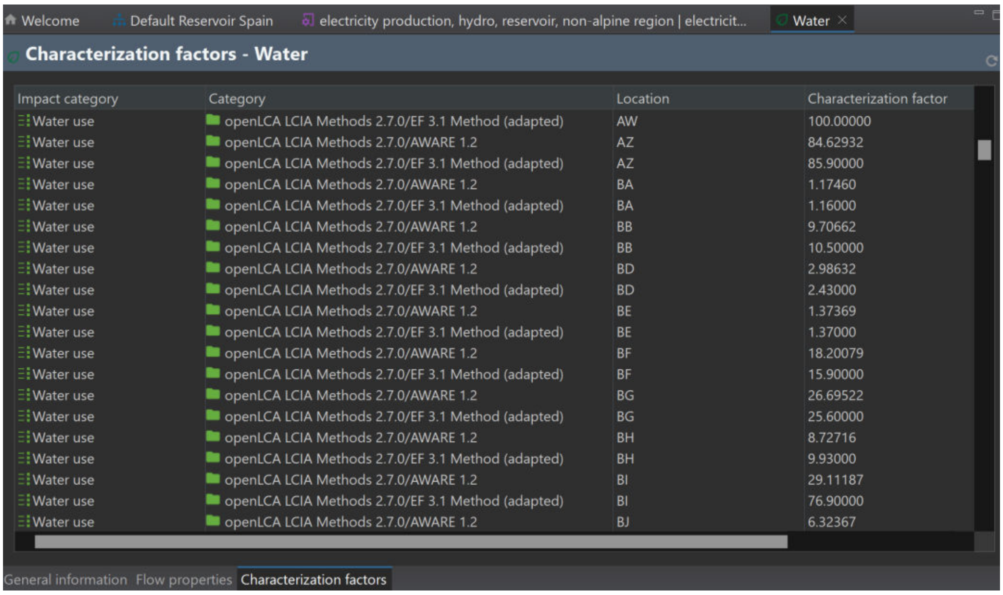
The hydroelectricity generation process “*electricity production, hydro, reservoir, non-alpine region* | *electricity, high voltage* | *Cutoff, U – ES“* is selected from the ecoinvent database. The process generates 1 kWh of high-voltage electricity and requires the flows shown in Table 17.

Table 17: In- and output flows of the selected hydroelectricity generation process. For licensing reasons, only the most water-relevant flows are displayed here.

INPUT		**OUTPUT**	
Flow	**Amount**	**Flow**	**Amount**
hydropower plant, reservoir, non-alpine regions	-	electricity, high voltage	1 kWh
lubricating oil	-	waste mineral oil	-

INPUT		OUTPUT	
Flow	**Amount**	**Flow**	**Amount**
Energy, potential (in hydropower reservoir), converted	-	Carbon dioxide, from soil or biomass stock	-
Occupation, lake, artificial	-	Methane, non-fossil	-
Transformation, from unspecified	-	Water (emission to air, unspecified)	0.03 m³
Transformation, to industrial area	-	Water (emission to water, unspecified)	8.07 m³
Transformation, to lake, artificial	-		
Volume occupied, reservoir	-		
Water, turbine use, unspecified natural origin	8.1 m3		

Of the three water elementary flows in the dataset, following the watershed differential approach implemented in openLCA, only the flows “Water, turbine use, unspecified natural origin” (IN_{inflow}) and “Water (emission to water, unspecified)” $(OUT_{release})$ need to be characterized with AWARE[5]. This can be tested by double-clicking the respective flow in the input/output view of the process: For the *Water (emission to air, unspecified)* flow, there is no AWARE CF listed, while for *Water (emission to water, unspecified)*, several AWARE CFs are listed, offering the possibility to spatialize the flow (Figure 22).



Impact category	Category	Location	Characterization factor
Water use	openLCA LCIA Methods 2.7.0/EF 3.1 Method (adapted)	AW	100.00000
Water use	openLCA LCIA Methods 2.7.0/AWARE 1.2	AZ	84.62932
Water use	openLCA LCIA Methods 2.7.0/EF 3.1 Method (adapted)	AZ	85.90000
Water use	openLCA LCIA Methods 2.7.0/AWARE 1.2	BA	1.17460
Water use	openLCA LCIA Methods 2.7.0/EF 3.1 Method (adapted)	BA	1.16000
Water use	openLCA LCIA Methods 2.7.0/AWARE 1.2	BB	9.70662
Water use	openLCA LCIA Methods 2.7.0/EF 3.1 Method (adapted)	BB	10.50000
Water use	openLCA LCIA Methods 2.7.0/AWARE 1.2	BD	2.98632
Water use	openLCA LCIA Methods 2.7.0/EF 3.1 Method (adapted)	BD	2.43000
Water use	openLCA LCIA Methods 2.7.0/AWARE 1.2	BE	1.37369
Water use	openLCA LCIA Methods 2.7.0/EF 3.1 Method (adapted)	BE	1.37000
Water use	openLCA LCIA Methods 2.7.0/AWARE 1.2	BF	18.20079
Water use	openLCA LCIA Methods 2.7.0/EF 3.1 Method (adapted)	BF	15.90000
Water use	openLCA LCIA Methods 2.7.0/AWARE 1.2	BG	26.69522
Water use	openLCA LCIA Methods 2.7.0/EF 3.1 Method (adapted)	BG	25.60000
Water use	openLCA LCIA Methods 2.7.0/AWARE 1.2	BH	8.72716
Water use	openLCA LCIA Methods 2.7.0/EF 3.1 Method (adapted)	BH	9.93000
Water use	openLCA LCIA Methods 2.7.0/AWARE 1.2	BI	29.11187
Water use	openLCA LCIA Methods 2.7.0/EF 3.1 Method (adapted)	BI	76.90000
Water use	openLCA LCIA Methods 2.7.0/AWARE 1.2	BJ	6.32367

Figure 22. Screenshot of the Characterization factors tab of the ecoinvent flow “Water (emission to water, unspecified)”, using openLCA LCIA Methods pack version 2.7.0

As a side note, even though the ecoinvent process claims that its location is Spain, this does not mean that the technology for the reservoir explicitly represents the reservoir technology used in Spain. A direct comparison shows that the inventory of the processes for Spain and Finland is identical, except from the different location attributed and thus CF applied. However, since Spain and Finland have different climates, the reservoir’s evaporation rate and thus water consumption should be different between both countries.

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[5] Ideally, the water flows should be named with their respective water compartment, such as “emission to water, river”, instead of using “emission to water, unspecified”. This would facilitate a correct selection of flows for the watershed differential approach. The input flow might contain precipitation over the reservoir, but this is not clear from the flow name.

7.2.4 AWARE scores: WSF results with AWARE

The AWARE score for the hydroelectricity process can be calculated on different spatiotemporal resolutions in openLCA. The following sections move from a characterization with the global default CF to a regionalized characterization, and a temporalized characterization (Figure 23).

Based on the hydroelectricity process from ecoinvent, the benefits of increased spatial representativity are shown by comparing three spatialization levels of the inventory: global default characterization (7.2.4.1), country resolution (7.2.4.2) and watershed resolution (7.2.4.3). Subsequently, the watershed resolution results are implicitly temporalized by using aggregated annual CFs which represent different seasonal water consumption patterns (7.2.4.4).

Since ecoinvent does not provide information on the seasonal water consumption pattern of the hydroelectricity process, the remainder of the case study is based on generic data created from ISO14073 and Spanish reservoir operation statistics. Here, the impact of temporalizing the inventory on monthly resolution is shown (section 7.2.4.5). Since the latter section is based on monthly absolute water consumption, the corresponding WSF has to be linked to the hydroelectricity generation again to be usable for WSF calculations of hydropower consumption (section 7.2.4.6). Finally, the priority of temporalization and spatialization are discussed (section 7.2.4.8) and a suggestion is made for interpretation of the results (section 7.2.4.9).

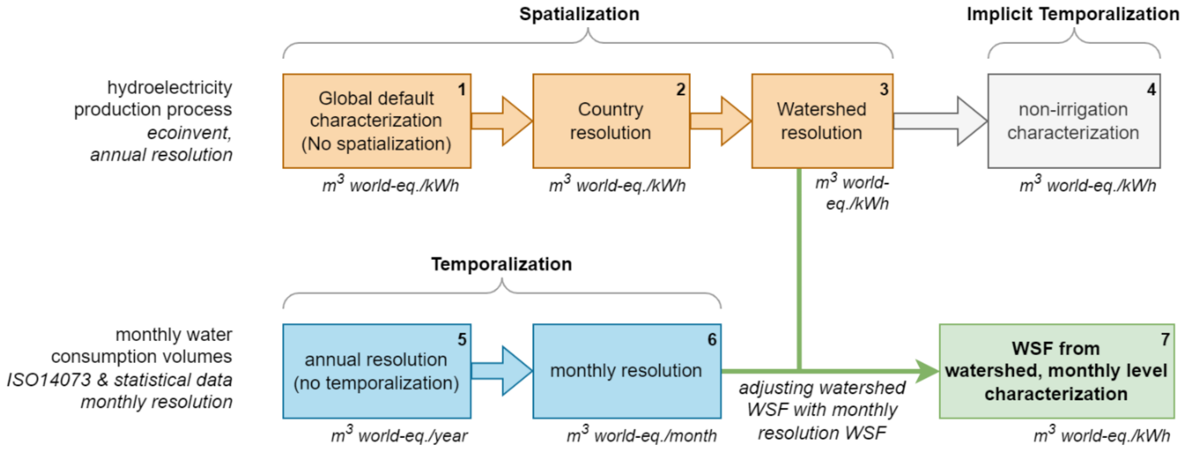


Figure 23. Roadmap for section 7.2.4, with its 7 individual steps. For a comparison of how the different steps affect the AWARE score of the hydroelectricity process, see Figure 30.

7.2.4.1 Step 1: No spatialization - Global default characterization

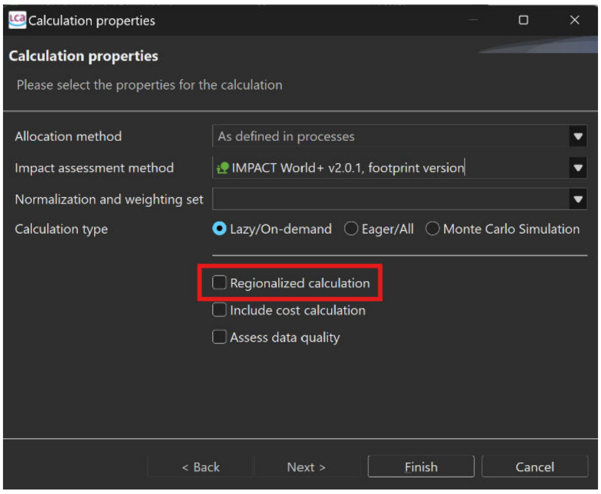
In the "default" LCIA calculation, no water flow is spatialized. Instead, all relevant flows are characterized by the global default CF of 42.95 m³ world-eq./m³. The resulting WSF for 1 kWh electricity production equals **1.26 m³ world-eq.** (Table 18).

This result includes the construction of the dam, its maintenance and decommissioning. However, the direct water consumption of the reservoir due to evaporation losses constitutes almost 100% of the entire impact – impacts from infrastructure are negligible (See Table 18, for the global default spatialization column). **The relevance of infrastructure to a reservoir WSF strongly depends on the order of magnitude of evaporative water loss from the reservoir**, which is determined by local climate. In high-latitude countries such as Norway, the water loss by evaporation is comparatively low and thus infrastructure impacts can become an important part of the overall reservoir WSF (Bakken, Modahl, Engeland, et al., 2016).

Table 18: Inventory results and AWARE score for the three most contributing processes in the system boundaries of the hydroelectricity process for different levels of inventory spatialization. Unit of CFs: m³ world-eq./m³. Unit of scores: m³ world-eq.

	inventory [m³]		impact assessment – spatialization level					
			Global default		Country		Watershed	
elementary flow	**amount**	**netC**	**CF**	**score**	**CF**	**score**	**CF**	**score**
main process		2.9E^{-2}	42.95	1.26	79.33	2.32	88.95	2.60
Water, turbine use, unspecified natural origin - ES	8.10							
Water - ES	-8.07							
hot rolling, steel		2.5E^{-6}	42.95	1.1E^{-4}	42.95	1.1E^{-4}	42.95	1.1E^{-4}
Water, cooling, unspecified natural origin - RoW	6.1E^{-6}							
Water - RoW	-4.9E^{-6}							
Water, unspecified natural origin - RoW	1.2E^{-6}							
lime production		2.2E^{-6}	42.95	9.6E^{-5}	41.02	9.2E^{-5}	41.02	9.2E^{-5}
Water, unspecified natural origin - Europe w/o CH	7.7E^{-6}							
Water - Europe w/o CH	-5.4E^{-6}							
total [m³ world-eq.]				1.26		2.32		2.60

7.2.4.2 Step 2: Spatialization – Country level (default openLCA approach)


Calculation properties

Calculation properties

Please select the properties for the calculation

Allocation method: As defined in processes
Impact assessment method: IMPACT World+ v2.0.1, footprint version
Normalization and weighting set:
Calculation type: ● Lazy/On-demand ○ Eager/All ○ Monte Carlo Simulation

☐ Regionalized calculation
☐ Include cost calculation
☐ Assess data quality

Figure 24. Screenshot of the "Calculation properties" dialogue in openLCA. The regionalized calculation box only leads to regionalized results for AWARE, if the appropriate LCIA methodology is selected.

While openLCA offers a method for spatializing processes and flows, it is not always straightforward to implement. For example, when using the IMPACT World+ v2.0.1 impact assessment method as provided on the openLCA nexus website, ticking "*regionalized calculation*" (Figure 24**Erreur ! Source du renvoi introuvable.**)[6] when calculating the LCA does not lead to a regionalized result. Instead, the global default CF is applied to all water flows provided they were not manually set to pre-generated spatialized elementary flows. However, using the AWARE v1.2 method as provided on the openLCA nexus website allows automated regionalization. The "*regionalized calculation"* works by selecting

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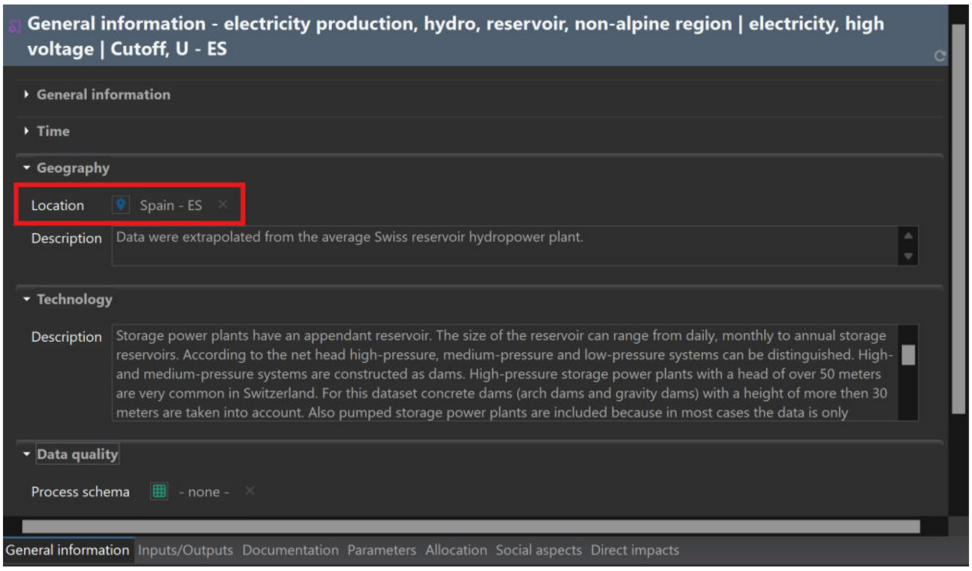
[6] openLCA's term "regionalized calculation" means "making use of regionalized CFs for spatialized inventory".

appropriate CFs for the elementary flows based on their “location” attribute[7] (Figure 25). In the used ecoinvent database version, the location attributes are already set, mainly at the country level. Evaluation of the hydropower process, ticking “*regionalized calculation*” provides a regionalized AWARE score of **2.32 m³ world-eq.**, 80% higher than without regionalization.



General information - electricity production, hydro, reservoir, non-alpine region | electricity, high voltage | Cutoff, U - ES

General information

Time

Geography

Location: Spain - ES

Description: Data were extrapolated from the average Swiss reservoir hydropower plant.

Technology

Description: Storage power plants have an appendant reservoir. The size of the reservoir can range from daily, monthly to annual storage reservoirs. According to the net head high-pressure, medium-pressure and low-pressure systems can be distinguished. High- and medium-pressure systems are constructed as dams. High-pressure storage power plants with a head of over 50 meters are very common in Switzerland. For this dataset concrete dams (arch dams and gravity dams) with a height of more then 30 meters are taken into account. Also pumped storage power plants are included because in most cases the data is only

Data quality

Process schema: - none -

Figure 25. Screenshot of the “General information” tab in openLCA for the selected process. The “Geography” section allows to set a location attribute for a process.

However, this openLCA regionalization of AWARE has two flaws: It is based on ecoinvent geometries (Spain, Europe without Switzerland,…) and therefore is highly uncertain when the spatial variability of watershed CF values inside countries or regions is large. For example, the annual watershed CFs for unspecified water use in Spain range from less than 1 to more than 90 m³ world-eq./m³ (Figure 26). In addition to not using watershed-level CFs, the calculation is not made on a monthly level and thus neglects the reservoir’s positive impact on water availability in the dry season.

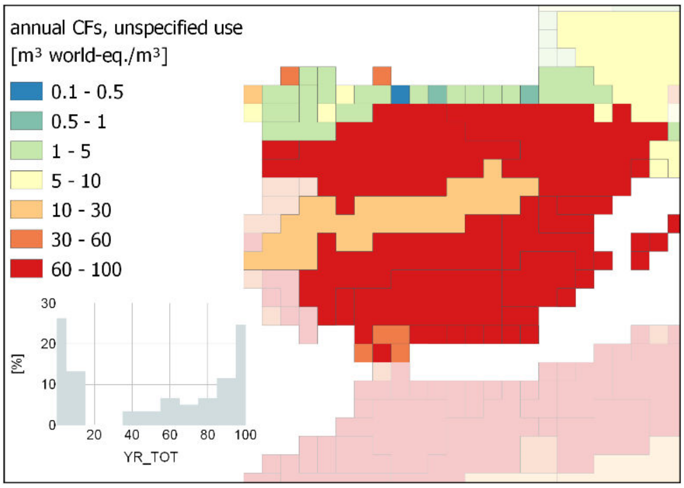


Figure 26. The spatial variability of annual CFs for unspecified water use in Spain. More than 30% of basins are classified with CFs <20 m³ world-eq./m³, while more than 20% of basins are classified with CFs close to 100 m³ world-eq./m³.

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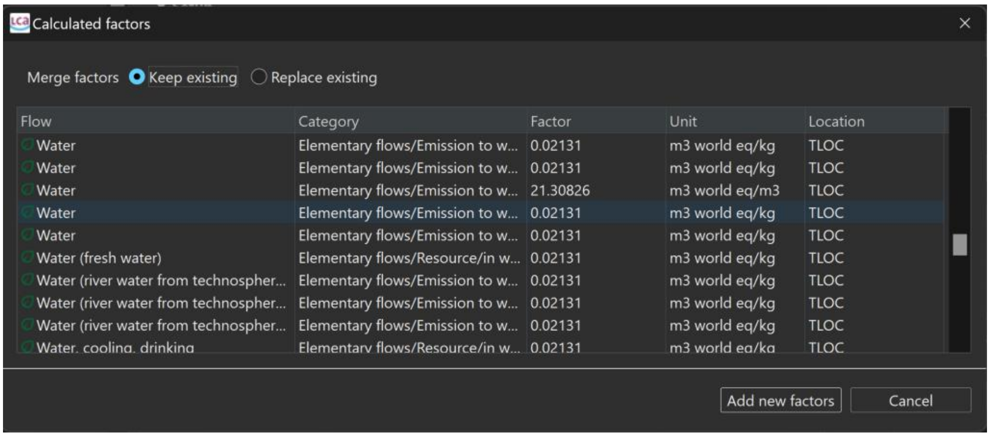
[7] The location attribute can both be set on process or flow level. Flow locations override process locations. For information about how to create custom locations in openLCA, see the ScoreLCA report on regionalization (ScoreLCA, 2024)

7.2.4.3 Step 3: Spatialization – Watershed level

To further refine the regionalized calculations, custom geographical regions and thus watersheds (which are the native resolution of AWARE CF) can be imported to openLCA using the in-built GIS feature. The corresponding approach is described in detail in the ScoreLCA report on regionalization, Annex 8.4 (ScoreLCA, 2024). Careful handling is required to not override the existing global CF for AWARE v1.2 when importing the new geometry (Figure 27).



Merge factors ● Keep existing ○ Replace existing

Flow	Category	Factor	Unit	Location
Water	Elementary flows/Emission to w...	0.02131	m3 world eq/kg	TLOC
Water	Elementary flows/Emission to w...	0.02131	m3 world eq/kg	TLOC
Water	Elementary flows/Emission to w...	21.30826	m3 world eq/m3	TLOC
Water	Elementary flows/Emission to w...	0.02131	m3 world eq/kg	TLOC
Water	Elementary flows/Emission to w...	0.02131	m3 world eq/kg	TLOC
Water (fresh water)	Elementary flows/Resource/in w...	0.02131	m3 world eq/kg	TLOC
Water (river water from technospher...	Elementary flows/Emission to w...	0.02131	m3 world eq/kg	TLOC
Water (river water from technospher...	Elementary flows/Emission to w...	0.02131	m3 world eq/kg	TLOC
Water (river water from technospher...	Elementary flows/Emission to w...	0.02131	m3 world eq/kg	TLOC
Water, cooling, drinking	Elementary flows/Resource/in w...	0.02131	m3 world eq/kg	TLOC

*Figure 27. When OpenLCA creates regionalized CFs from GIS data, a dialogue is displayed with the new CF for the specified location (here: TLOC) and **a new global default CF**. There is an option to keep or replace existing CFs. When only some new geometries are to be added to the database, it is important to select "keep existing". Otherwise, OpenLCA **overrides the global default CF with an incorrect value**.*

Instead of using Spain's country CF, the hydropower process is now spatialized on the watershed level. We assume that the reservoir is situated in the Ebro watershed of Northern Spain, a rather water-scarce region with a large number of reservoirs (Moreno & Ruiz, 2003). The annual CF for unspecified water use in the Ebro watershed equals 88.95 m³ world-eq., resulting in an AWARE score of **2.60 m³ world-eq./kWh** of hydroelectricity production. This is more than double the score obtained with global default CFs and 12% higher than the score obtained from country resolution.

Increasing the spatialization level of the inventory leads to an increase in the AWARE score (Figure 28) while reducing the associated uncertainty linked to spatial variability. The spatial variability of AWARE CFs inside Spain is smaller than the spatial variability across the globe. Nevertheless, 50% of the Spanish water consumption happens in watersheds which would result in a range of AWARE scores for the assessed hydropower production process between 1.8 and 2.8 m³ world-eq./kWh. **Selecting the watershed as the definitive location of the hydropower production eliminated this uncertainty source.**

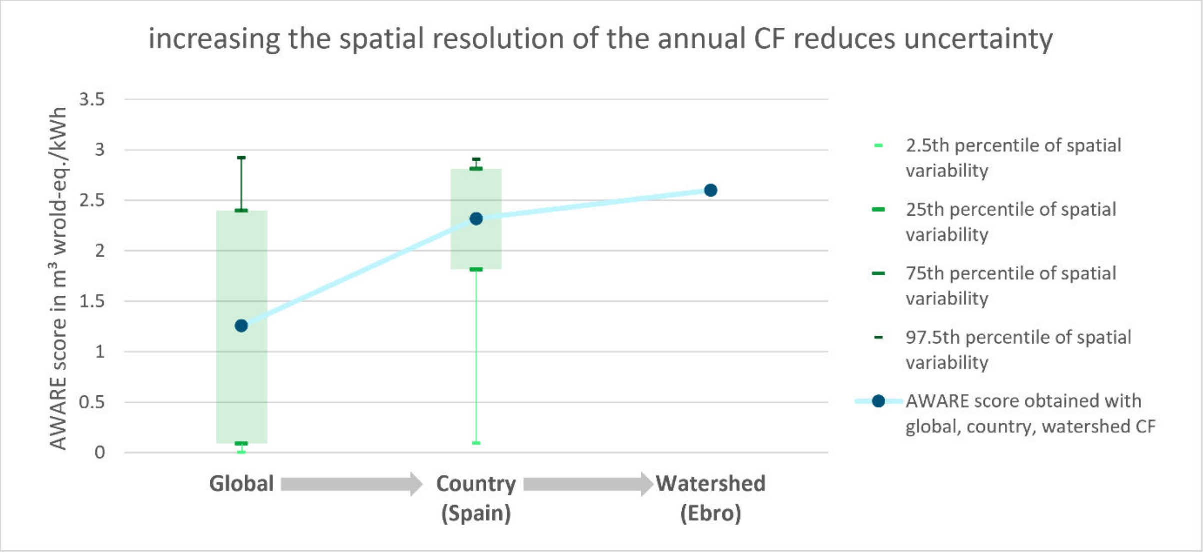


Figure 28. Potential AWARE scores considering the consumption-weighted variability of AWARE CFs across the globe and across Spain, compared with the AWARE scores obtained in this case study by spatializing on global, country and watershed levels. Only uncertainty due to spatial variability of spatially aggregated CFs is displayed.

7.2.4.4 Step 4: Temporalization – based on the type of water usage

The CF for unspecified water use does not distinguish between water use patterns of industry, agriculture or domestic water users. However, knowing that the reservoir is not an irrigation process, we can also use the non-agricultural water use CF for the watershed. The annual CF for non-agricultural water use equals 42.60 m³ world-eq., leading to an AWARE score of **1.24 m³ world-eq**. This is 47% lower than when using the Spain CF provided in the openLCA database, but close to the first result using the global default CF.

Table 19: Results for the Ebro watershed depending on the type of annual aggregation used. Due to the negligible impact of background processes, the results were calculated by multiplying the netC of the main reservoir process (0.029 m³) with the CFs.

annual aggregation for water consumption pattern of	**CF [m³ world-eq./m³]**	**result [m³ world-eq.]**
agricultural water use	90.00	2.63
non-agricultural water use	42.60	1.24
unspecified use	88.95	2.60

Annual CFs for non-agricultural water use are usually lower than the annual CF for unspecified water use since they do not emphasize irrigation-intensive months (see section 4.2.4). However, non-agricultural annual CFs assume that there is no seasonal change in water consumption. The real water consumption of the reservoir might not be static and thus deviate from this assumption. Consequently, only monthly evaluation of the WSF enables a robust interpretation of the reservoir's impacts on water scarcity. This is shown in Figure 29, which summarizes this section and the following one. **Moving from annual unspecified water use to annual non-agricultural water use CFs does not reflect well the water consumption pattern of the reservoir.** Most of the consumptive impact of the reservoir occurs in the winter months, which have considerably lower CFs than the summer months. Applying one constant CF to all the months as is implicitly done with the annual resolution neglects this issue and leads to results which wildly differ from the fully temporalized results.

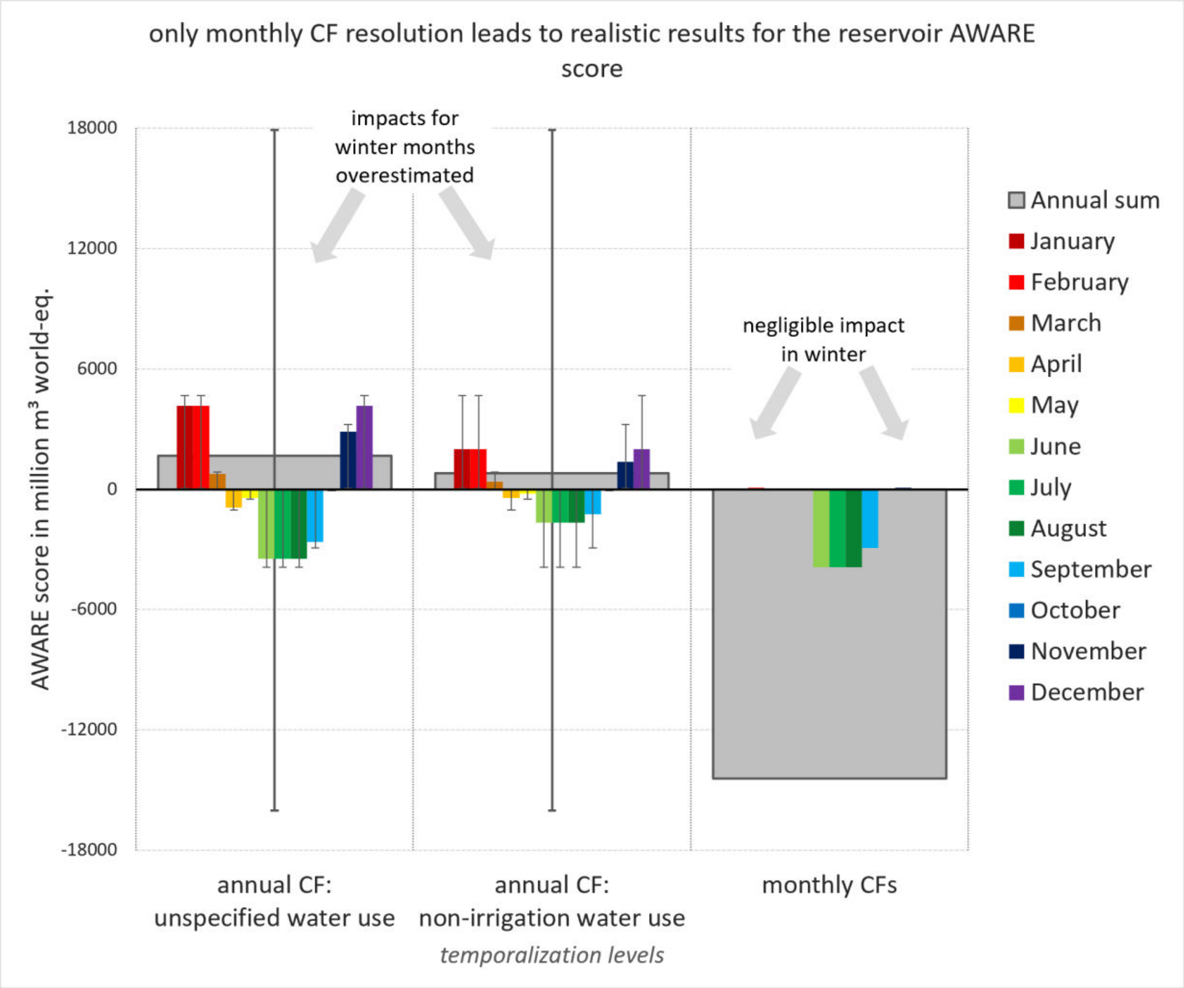


Figure 29. Monthly AWARE scores and their annual sum depending on the temporal characteristics of the CFs. The uncertainty indicates the maximum and minimum value obtainable depending on the monthly CF the monthly water consumption is allocated. Section 7.2.4.5 shows that winter months in the Ebro basin have low CFs, while summer months have rather high CFs.

7.2.4.5 Step 5 & 6: Temporalization – monthly resolution

For a monthly resolution of the impact assessment in the Ebro basin, monthly data is required for the water consumption of the reservoir. The following elaborations are based on a case study provided in ISO/TR 14073, transferred to a real reservoir and combined with the data provided in the ecoinvent dataset studied before. The example shows how to calculate the AWARE score of the 12-month operation of the reservoir.

On an annual basis, the water consumption of a reservoir is defined by increased direct evaporation, assuming that water storage in the reservoir at the beginning and end of the year is equal (section 7.2.2). For monthly data, simply relying on monthly evaporation is not adequate, because the water evaporated in month A does not directly reduce water availability downstream of the reservoir in month A – the reservoir can use its storage to counterbalance evaporation. Instead, the watershed differential approach (section 4.6.1.1) should be used to calculate the reservoir's water consumption. Therefore, inflow and outflow data of the reservoir are required. Inflow is defined as the inflow of water from upstream, excluding precipitation on the reservoir boundaries, while outflow is the outflow that is provided to downstream water users by the release of water through the outlet of the reservoir.

The ISO/TR 14073 provides a monthly balance of inflows and outflows for a generic reservoir. Table 20 shows this balance adjusted to the reservoir Canelles in the Ebro watershed, by scaling all values in the example by the ratio between the example's annual outflow (610.7 million m^3) and the annual outflow of the Canelles reservoir (580.7 million m^3)[8].

The monthly water balance (MBW) in TR/ISO14073 assumes a constant outflow of the reservoir, but seasonally varying water inflow. This leads to a seasonally distributed pattern of water consumption for the reservoir: In winter months, inflow exceeds outflow and the reservoir "consumes" water. In summer months, the water outflow exceeds inflow, resulting in higher water availability to water users downstream compared to the situation without a reservoir. The total annual water consumption equals 18.9 million m^3.

Table 20: Hypothetical water balance for a reservoir in the Ebro basin, based on TR/ISO14073 and data for the Canelles reservoir. Unit: million m^3.

Month	Water inflow	Evaporation	Precipitation	Water outflow	Water volume in the reservoir	Monthly Water balance (MBW)
January	95.1	0.2	1.0	48.4	237.6	**46.7**
February	95.1	0.2	1.9	48.4	286.0	**46.7**
March	57.0	0.5	2.2	48.4	296.4	**8.7**
April	38.0	1.4	1.9	48.4	286.5	**-10.4**
May	43.4	2.9	1.2	48.4	280.0	**-4.9**
June	9.5	5.7	0.3	48.4	235.8	**-38.9**
July	9.5	6.7	0.1	48.4	190.3	**-38.9**
August	9.5	5.7	0.1	48.4	145.8	**-38.9**
September	19.0	3.8	0.1	48.4	112.7	**-29.4**
October	47.5	1.0	0.1	48.4	110.9	**-0.9**
November	80.8	0.3	0.2	48.4	143.3	**32.4**
December	95.1	0.3	0.5	48.4	190.1	**46.7**
Total	599.6	28.5	9.5	580.7	--	**18.9**

Multiplying the annual non-agricultural CF (42.60 m^3 world-eq./m^3) with the annual water consumption, results in an AWARE score of 806 million m^3 world-eq. However, grace to the monthly water consumption data, the AWARE score can be calculated for individual months. This temporalization provides further insight into the impacts of the reservoir operation and will lead to a different annual total AWARE score.

The monthly scores can be calculated by multiplying the MBW with the monthly CFs (Table 21). The annual total AWARE score amounts to -14,450 million m^3 world-eq. **This example shows that there is a significant difference in results whether the seasonal water consumption pattern of the reservoir is modelled and characterized explicitly (-14,450 million m^3 world-eq.), versus the use of the annual total water consumption (806 million m^3 world-eq).**

Table 21: Monthly CFs for the Ebro watershed (BAS34S_ID 32963). The monthly AWARE score is obtained by multiplication with the reservoir's MBW.

	CF [m^3 world-eq./m^3]	MBW [million m^3]	score (CFxMBW) [million m^3 world-eq.]
January	1.13	**46.7**	52.7
February	1.41	**46.7**	65.8
March	1.40	**8.7**	12.1
April	1.39	**-10.4**	-14.5
May	2.02	**-4.9**	-9.92

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[8] Note that this is not suitable to calculate the actual WSF of the Canelles reservoir, because its real monthly water balance could differ strongly from the patterns provided for the unknown basin in the TR/ISO14073!

	CF [m³ world-eq./m³]	MBW [million m³]	score (CFxMBW) [million m³ world-eq.]
June	100	-38.9	-3890
July	100	-38.9	-3890
August	100	-38.9	-3890
September	100	-29.4	-2940
October	100	-0.9	-90
November	2.50	32.4	81.1
December	1.33	46.7	62.2
total	-	-	-14,450.4

7.2.4.6 Step 7: Connecting the reservoir WSF to 1 kWh produced

Since the functional unit of hydropower reservoir operations is the production of electricity, the WSF of a reservoir should be communicated per 1kWh electricity produced. In the previous section, the WSF was calculated for each month of the reservoir operation, but not per kWh. An allocation of the monthly WSF to the electricity production of the respective month is not easily possible, as will be explained further below. Therefore, the most straightforward approach is to relate the annual $\mathrm{WSF}_{\mathrm{total}}$ of the reservoir (-14,450.4 million m^3 world-eq.) with the annual electricity production in kWh, resulting in the WSF_{kWh}. For this approach, the total generated electricity of the reservoir is required. We assume that the reservoir produces approximately 647GWh of electricity per year. Since the functional unit of the hydropower process is 1 kWh, we can calculate the average impact per kWh by dividing the AWARE score by the total electricity production (Equation 9):

Equation 9

$$WSF_{kWh} = \frac{\mathrm{WSF}_{\mathrm{total}}}{647.442\mathrm{x}10^6 kWh} = -22 \frac{m^3\ world - eq.}{kWh}$$

Instead of using the annual WSF_{total} for deriving an impact per kWh, one might desire to calculate impacts per kWh for each month explicitly. This is because hydroelectricity production fluctuates seasonally. For example, in Spain, total electricity generation from reservoirs is lower in summer and higher in winter (RED ELÉCTRICA DE ESPAÑA, 2020). Naturally, it might be interesting to calculate the WSF per kWh for a specific month to respect this seasonality. However, this is not as straightforward as it might seem at first. The water consumed and thus the AWARE score of a certain month is not a direct result of the electricity generation in that month. Instead, only the water returned to the environment is a direct function of the electricity generation, while storing inflow to the reservoir and thus the net water consumption is done to provide potential energy for electricity production in later months. Consequentially, a simple breakdown of the $WSF_{reservoir}$ into month-specific WSFs expressed in m³ world-eq./kWh is of limited use.

The knowledge about which flows are directly resulting from hydroelectricity generation in a certain month could be used for a temporal distribution of the impacts. By attributing the reservoir's elementary flows to different temporal periods (monthly versus entire year), an estimation of the impact of hydroelectricity production of a specific month could be made. However, this approach is, to the knowledge of the authors, not sufficiently discussed in the literature.

To summarize, the WSF of the hydroelectricity process is reduced significantly by accounting for the seasonality of the reservoir's water consumption (see Figure 29). **While any application of annually aggregated CFs led to results between 1.2 and 2.6 m^3 world-eq./kWh, the fully temporalized characterization results in a WSF of -22 m^3 world-eq./kWh, expressing a net benefit of operating the reservoir.**

7.2.4.7 Applying the temporalized approach in LCA software

Most LCA software tools do not provide a straightforward implementation of temporally resolved LCA. For LCA software to calculate the correct AWARE score, an appropriate annual aggregated CF ($CF_{reservoir}$) for the Ebro watershed is required, which indirectly accounts for the seasonal water consumption pattern of the reservoir. This CF can be calculated as a *netC*-weighted annual average of the monthly CFs of the Ebro watershed[9]:

Equation 10
$$CF_{reservoir} = \frac{\sum_{month} CF_{month} \cdot netC_{month}}{\sum_{month} netC_{month}} = -765 \frac{m^3\ world - eq.}{m^3}$$

$CF_{reservoir}$ can be imported into OpenLCA using a custom location (e.g. "Reservoir Ebro") as an identifier. Setting the relevant water flows in the ecoinvent hydroelectricity process to this location and conducting a regionalized LCA calculation will result in the correct result[10]:

Equation 11
$$WSF_{kWh} = \frac{2.9\text{x}10^{-2}\ \text{m}^3}{kWh} \cdot -765 \frac{m^3\ world - eq.}{m^3} = -22 \frac{m^3\ world - eq.}{kWh}$$

7.2.4.8 Prioritizing temporalization or spatialization?

When calculating a WSF, a prioritization of tasks might be helpful for increased work efficiency. Assessing whether temporalization or spatialization of the WSF inventory is more relevant might help in focusing on the most important determinants of the WSF. When starting without any spatialization or temporalization (i.e. using the annual global CF), spatializing the inventory on the country level has a higher potential to reduce uncertainties than temporalizing the inventory. This is because the geographical variability of annual CFs across the globe is higher than the variability of the twelve monthly global CFs.

However, country-level resolution can still obscure high spatial variabilities inside a country. As mentioned in section **Erreur ! Source du renvoi introuvable.**, the country-level CF Excel file at https://wulca-waterlca.org/aware/download-aware-factors/ shows which of the two is more relevant for each country based on their associated variability. It can help to decide whether improving spatial resolution (watershed instead of country) or temporal resolution (monthly instead of annual CFs) should be prioritized.

The Excel file reports a standard deviation of 32.0 for the temporal variability of the Spanish CFs and a standard deviation of 39.9 for spatial variability in Spain[11]. Following these values, spatialization is slightly more important than temporalization for an average Spanish LCA inventory. However, temporalization is extremely important for reservoirs with their exceptional seasonal water consumption pattern. This can be illustrated with the annual WSF for the above reservoir. Calculation for different combinations of temporalization and spatialization yields:

- Country-level, annual resolution: 594 million m³ world-eq.
- **Watershed-level**, annual resolution: 806 million m³ world-eq.
- Country-level, **monthly resolution**: -7,222 million m³ world-eq.
- **Watershed-level, monthly resolution**: -14,450 million m³ world-eq. (Table 21)

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[9] (Karimpour et al., 2021) did this for hydropower in the US, but on annual level and thus obtaining a positive aggregated CF: 19.57 m³ world-eq./m³

[10] We assume that the ecoinvent process selected in this case study already states the correct *netC* per kWh (2.9E-2 m³/kWh).

[11] The standard deviation for annual CFs across the globe equals 30.4! Therefore, the step from global to country resolution did not reduce the uncertainty linked to spatial variability. Note that a similar message results when respecting the importance of individual basins by accounting for their water consumption. The consumption-weighted standard deviations are 38 (global) and 33 (Spain).

Temporalization (monthly resolution of inventory and CFs) results in a closer match to the target of -14,450 million m³ world-eq. than spatialization since it accounts for the extra water supply in the dry season. Therefore, inventory temporalization might often be a better priority for reservoir WSFs than inventory spatialization. While the implicit temporalization by actively choosing between unspecified, agricultural and non-agricultural CF might increase the accuracy of the results (section 7.2.4.4), it is not nearly equivalent to a full temporalization using monthly CFs, since it does not result in the negative AWARE score (Figure 30).

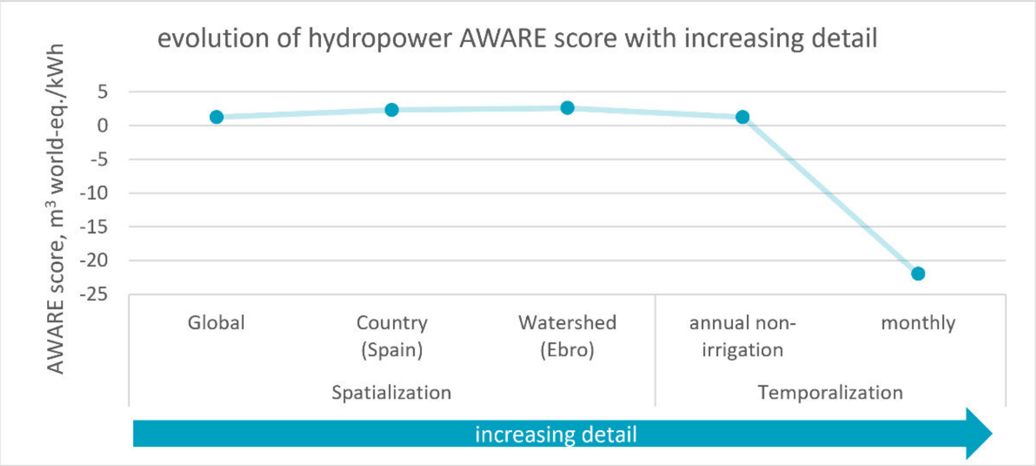


Figure 30. Evolution of hydropower AWARE score with increasing detail as shown in this case study. Note that steps 5 & 6 are skipped since they are calculated for a different unit (not per kWh).

7.2.4.9 Interpretation of the result

The WSF score of -22 m³ world-eq./kWh (section 7.2.4.6) can be interpreted as follows: **The production of electricity in the studied reservoir on annual average decreases water scarcity in the watershed where it operates.** The magnitude of this beneficial impact per kWh of electricity is equal to the consumption of 22 m³ of water in a world average location. In cases where the reservoir infrastructure or maintenance contributes a significant part of the WSF (e.g. Norway, see section 7.2.4.1), impacts might as well be distributed between different watersheds and the interpretation would require differentiation between these watersheds.

This however requires the assumption that the electricity production is the sole reason for the reservoir construction and operation. For example, some reservoir operators might ensure an environmental base flow independent of whether electricity is generated or not, or reservoirs might need to allow emergency discharge in times of high reservoir levels. Using different allocation methods to account for the multifunctionality of the reservoir might lead to deviating results. This is discussed in the following sections, taking the case of Lake Mead (United States) as an example.

7.2.5 Implementation challenges for real reservoirs

Real reservoirs and their water consumption data can deviate from the characteristics of the idealized case study. The following section presents two challenges which might arise when implementing a WSF with AWARE for real reservoirs. First, the challenge of more complex functions of a reservoir, specifically when it provides water for direct withdrawal by municipal or industrial water users while producing hydropower. Second, ensuring temporal validity of the reservoir data and its potential influence on AWARE scores.

7.2.5.1 Dealing with reservoir multifunctionality: additional functions to hydropower generation

The above case study uses generic data. In reality, in- and outflows of reservoirs can occur in many different ways. For example, a report on the water balance of Lake Mead (Moreo & Swancar, 2013) lists a set of flows different from the above case study (Figure 31), including direct water withdrawal from the reservoir for municipal water supply.

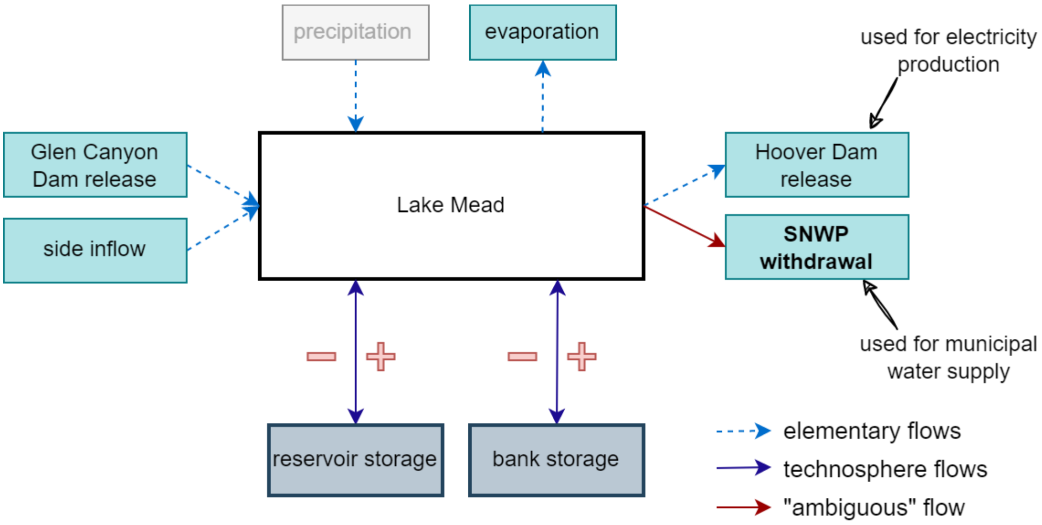


Figure 31. Water mass balance elements of Lake Mead (United States) according to (Moreo & Swancar, 2013). Note that precipitation inflow is insignificant and as such not included in their water balance. The Glen Canyon Dam release represents the river inflow to Lake Mead since the Glen Canyon Dam is situated right upstream of Lake Mead. SNWP withdrawal is the water withdrawal by the Southern Nevada Water Project, supplying Las Vegas with water.

In the water balance of Lake Mead, the water withdrawal for the Southern Nevada Water Project (SNWP) is listed, which supplies the city of Las Vegas with water. The SNWP withdrawal leads to lower annual outflows from the reservoir and is exemplary of why reservoirs are an edge case for WSFs: they can have multiple functions at the same time, which makes the WSF calculation for one isolated function challenging.

The SNWP water withdrawal can be classified into two different cases:

- Case 1: If the water withdrawal is independent of the reservoir operation, i.e., it does not require the reservoir to store the water to be withdrawn, the withdrawal could be considered as elementary flow, like for any other water withdrawal in the watershed. This case means that the water withdrawal for the municipal water supply would have been possible even without the reservoir and the reservoir does not change how much of the water is withdrawn from the water body.
- Case 2: If the reservoir is paramount to enabling the water withdrawal, i.e. in summer months where otherwise not enough water would be available, the water withdrawal could be considered as technosphere flow leaving the reservoir operation process. In this case, water withdrawal for municipal water supply and the dam operation for electricity production are both functions of the reservoir and the impact of reservoir operation must be allocated between both functions.

Case 1

If the water withdrawal is independent of the reservoir operation and thus an elementary flow, Equation 12 could be used for calculating the *netC* of the reservoir operation at Lake Mead (applying the watershed differential approach):

Equation 12

$$netC_{LakeMead} = Glen\ Canyon\ Dam\ release + side\ inflow - Hoover\ Dam\ release - SNWP\ withdrawal\ [m^3]$$

The entire *netC* would be allocated to the hydropower generation which is the only function of the reservoir assumed here. The water consumption linked to the reservoir operation is considered independent of the water withdrawal for the SNWP, which is why it is removed from the reservoir water consumption. In a month in which the reservoir does not change the river flow (when the inflows equal the Hoover Dam outflow), this would result in a negative $netC_{LakeMead}$, since the reservoir compensates the SNWP withdrawal with water from its reservoir storage.

Case 2

However, if the reservoir is required for hydropower **and to sustain the water withdrawal**, its entire water consumption needs to be allocated between water withdrawal and hydropower production.

In this case, it might make sense to calculate the water consumption of the reservoir (not yet separating municipal withdrawal from hydropower generation) by using Equation 13. Since the withdrawal is not represented in the equation, it is not defined whether the withdrawal is satisfied from the reservoir storage or the monthly inflow. The only relevant variables are the flows of water received (Glen Canyon release & side inflow) from and released (Hoover Dam release) to the watershed.

The obtained *netC* is the water consumption of the reservoir resulting from reducing or increasing the water availability in the downstream watershed compared to the baseline without a reservoir (see section 4.6.1.1):

Equation 13

$$netC_{LakeMead} = Glen\ Canyon\ Dam\ release + side\ inflow - Hoover\ Dam\ release\ [m^3]$$

This reduction or increase must be allocated between the reservoir's functions "hydropower production" and "water supply".

ISO 14044 prescribes a stepwise approach to allocation (also known as "allocation hierarchy"). First, allocation should be avoided, either by subdividing larger processes into smaller processes which serve only the intended function or by expanding the system scope to include the additional functions. If that is not possible, allocation of the process flows can be performed, using weights that represent their underlying physical relationship. Only as a third solution, other allocation weights can be used, such as economic allocation.

The avoidance of water consumption allocation by subdivision or system expansion does not apply to multi-purpose reservoirs, since the reservoir functions can not be completely separated from each other (Bakken, Modahl, Raadal, et al., 2016). For example, if the reservoir storage is required for the municipal water supply, it is not possible to separate it from the hydroelectricity production which also requires the reservoir storage as a storage of potential energy. Instead, two allocation approaches are possible: volume allocation and energy allocation. Using energy allocation implies attributing energy amounts to hydropower production and water supply. For hydropower production, the required variable is the power production, while for water supply it is the power production lost by withdrawing water for water supply. Consequentially, the water withdrawal's impact on hydropower generation is directly represented in the allocation. Volume allocation instead uses as keys the water volume processed in the hydropower generation and the water volume withdrawn for water supply.

Bakken et al. (2016) also present non-physical allocation methods – economic allocation and societal prioritization. Economic allocation is based on the income from hydropower production and the monetary value of the water supply (alternatively: the monetary value of the power generation loss). Societal prioritization can be based on government policies. Some countries define allocation rules based on the societal value of the reservoir functions, e.g. prioritizing domestic water supply and therefore allocating a larger share to it.

Following the ISO allocation hierarchy and preferring scientific robustness, the volume allocation approach was finally recommended for reservoir multifunctionality in the study of Bakken et al. (2016). To apply this approach to Lake Mead, the water volumes used for power generation and the withdrawn water volume for the SNWP have to be used as keys for allocating the impacts. The volume approach could additionally be used to allocate the built dam infrastructure between both reservoir functions.

7.2.5.2 Dealing with other services of reservoirs

In addition to providing water for irrigation and enabling power generation, reservoirs can have multiple other functions. The construction of a reservoir is an intervention into an ecosystem and affects the ecosystem services that are supplied by it. In general, ecosystem services can be divided into provisioning services *(PS)*, regulating and maintenance services *(RMS)* and cultural services *(CS)*. All three types can be affected by reservoirs. Some of them are improved, while others (e.g. provision of wood or crops on now inundated lands, supporting food production by enabling fish migration along a river, providing spiritual value) can be lost.

Mácová and Kozáková (2023), Zhuo et al. (2019), and Hogeboom et al. (2018) list potential functions of reservoirs and thus improved ecosystem services as

- Flood protection *(RMS)*
- Water supply *(PS)*
- Hydropower generation *(PS)*
- Recreation *(CS)*
- Sediment management *(RMS)*
- Fishing grounds *(PS)*
- Prevention of ice formation *(RMS)*

Hogeboom et al. (2018) attempted to reflect multifunctionality in their WF study, by allocating the WF according to the economic value of the provided functions. Globally, the largest monetary value of reservoirs was found in hydroelectricity generation, followed by water supply for residents and industry, and water supply for irrigation. Recreational use, flood control and fishing only represented a smaller part of the global monetary value of reservoir functions. Scherer and Pfister (2016) allocate the impacts to different reservoir functions based on their priority. Bakken et al. (2016) point out that multipurpose reservoirs are too diverse to allow for a definition of generic solutions and rather recommend the volume allocation method already presented in section 7.2.5.

7.2.5.3 Temporal representativeness of reservoir water balance

With the temporal scope of the reservoir balance data, WSF results can change. The water balance of the above Spanish case study is a loop: After one year, the reservoir storage is at the same volume it was one year ago. However, real-world measured data always is representative of a specific temporal period, e.g. a certain year or the average of certain years. This can pose challenges in calculating the WSFs of reservoirs.

Real reservoirs can show long-term trends in storage. The reservoir balance can be positive for several years in a row, indicating an increasing storage. This additional storage is used in dry years. Consequentially, the water balance, especially on a monthly scale, can be highly sensitive to the year assessed. This can be illustrated with the approach presented for Lake Mead in Equation 12, applied to its water balance from March 2010 to February 2012 (two years, data in Table 40). Results show that in year 1 most months are assigned negative WSFs, while in year 2 the WSFs are almost always positive (Figure 32). The annual total for year 1 equals -94 km³ world eq., while for year 2 it equals 324 km³ world-eq. The WSF per kWh would therefore differ substantially between year 1 and year 2, but would also be influenced by differences in electricity production between both years.

As a result of the WSF's possible sensitivity to the temporal validity of primary data, practitioners need to determine and communicate the temporal validity of the data they use for WSF calculations and consider potential interannual variations in their uncertainty assessments. Note that even though the ecoinvent process used at the beginning of this case study claims to represent 2012, this does not mean that the water consumption is specific to Spanish conditions in 2012 since the process is rather generic.

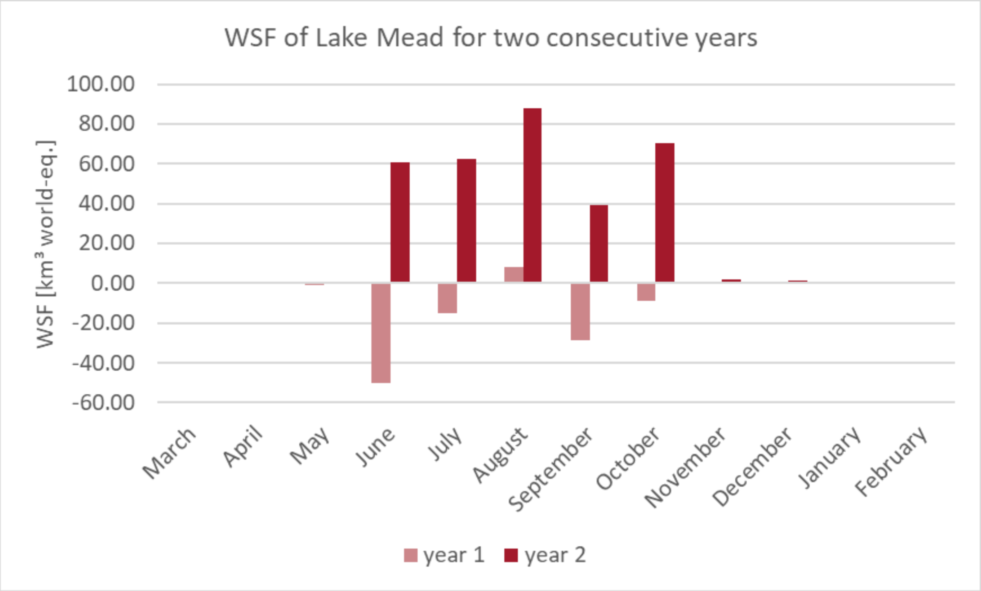


Figure 32. Monthly AWARE score for Lake Mead's water consumption (using the Ebro watershed CFs). The underlying data is in Table 40.

7.2.5.4 Reservoirs as an irrigation water source

When establishing the monthly water balance, the monthly outflow of the reservoir is determined. This outflow represents the amount of water a reservoir releases for use by humans and the downstream ecosystem. Sometimes, the discharge downstream is intentionally increased to satisfy irrigation water requirements, or the reservoir was built to enable irrigation in the first place. When a WSF is calculated for an irrigation activity in month A that is supplied by water from a reservoir, it could be argued that the water is not consumed from month A, since the water was specifically made available for the irrigation activity by the reservoir. Thus, if a reservoir is only used for irrigation purposes and a WSF is to be calculated for the irrigation process, the water consumption for irrigation results from the reservoir's water consumption, even though the water might be taken from a river.

The literature does not provide a standard approach for this issue. In most cases, a WSF modeller will simplify the calculations by characterizing the direct water consumption of irrigation in month X with the Water Scarcity CF of month X. This does not account for the water loss of the reservoir (Figure 33) and neglects that the irrigation water consumption is no burden to the downstream water users.

More sophisticated approaches are possible, e.g. by calculating the annual WSF of the reservoir as described in the Spain case study above. Subsequently, the amounts of water withdrawn for different irrigation purposes could be used as keys, allocating the annual WSF to the irrigation processes. This allocated reservoir WSF is then added to the direct WSF of the irrigation. The increased outflow from the reservoir and the irrigation water withdrawal would cancel themselves out However, for different cases, there might be different applicable solutions and there is no widely accepted approach in literature for this issue. Their discussion is therefore out of the scope of this report.

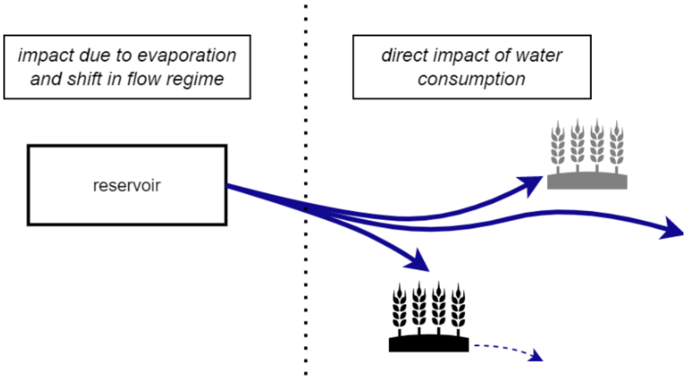


Figure 33. Impacts of irrigation water use considering multiple water users downstream of an irrigation water reservoir. The impact of the irrigation reservoir operation has to be allocated between the downstream water users.

7.2.5.5 Non-marginality of reservoir water consumption

Pfister et al. (2020) point out that for a majority of hydropower reservoirs globally, water consumption is non-marginal. This warrants the use of non-marginal CFs (section 4.5.1) in WSFs of hydropower generation. However, in the above case study, marginal CFs were used, since these are the CFs available in LCA software.

Since marginal and non-marginal AWARE CFs are related, **the use of non-marginal CFs would not change the conclusions of the case study** (Figure 34) but would decrease the absolute value of the WSFs. Using non-marginal CFs could however be relevant for WSF studies of larger systems, to not overestimate hydropower impacts where the hydropower generation is only a part of the assessed product system.

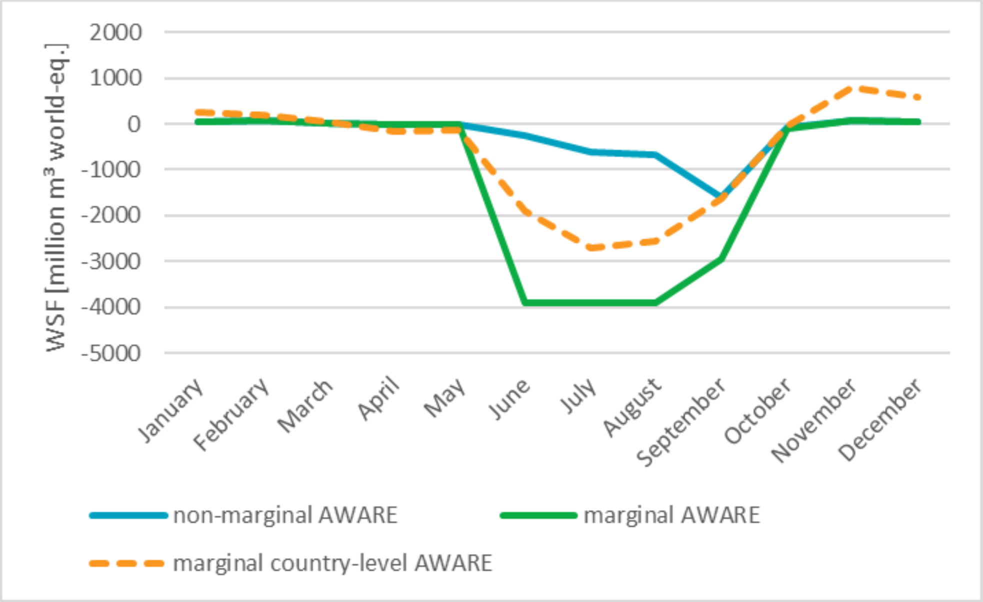


Figure 34. Comparing monthly WSFs of the reservoir in the Ebro watershed using non-marginal and marginal AWARE CFs. While the absolute values of the non-marginal CFs are lower than the absolute values of the marginal CFs, the overall seasonal pattern is similar. Therefore, with either of the two approaches the annual total WSF is negative (marginal CFs: -14450 million m³ world-eq., non-marginal CFs: -2,965 million m³ world-eq.).

7.3 Case study 2: Application of the Water Scarcity Footprint to an industrial process using bio-based inputs

7.3.1 Overview of the case study

The goal of the case study (intended learning)

This case study examines an industrial process. Since water use in agriculture presents challenges (mainly due to seasonality), we choose to use an industrial biobased process. To avoid intensive data collection, a generic cradle-to-gate process from ecoinvent was selected, namely the ethanol production from maize in the US. The analysis focuses on several key aspects:

- Data collection: The study identifies the relevant flows to be collected, addressing both the main elementary flows (cooling, process water...) and the flows from the technosphere, such as irrigation, tap water or wastewater treatment.
- Water scarcity footprint (WSF) is calculated using AWARE as the main impact method. Special attention is given to the geographical and temporal resolution of the CFs used by default and the refining of the results that can be performed through the regionalization of the inventory or the spatialization of the elementary flows. To take into account these aspects, the location of the industrial site is set in the state of Iowa, one of the main states producing maize in the US. Model refinement is prioritized based on hotspot analysis and potential variability.
- Exploration of edge cases: Additional scenarios are explored, such as the use of fossil groundwater and potential impacts near coastal regions, including wetlands.
- Comprehensive WF: The WSF scores using AWARE are put into perspective to other water-related LCIA categories. This is done by evaluating results at the endpoint or the single score level (using methods such as EF) to reveal the relative contribution of the water consumption categories compared to others contributing to the total score, namely those addressing water quality issues. To show possible trade-offs between impact categories, another baseline scenario is explored. The impacts associated with water degradation (loss of quality) are explored in this part.

Data and tools used

- Database: ecoinvent version 3.10 cutoff (Wernet et al., 2016)
- LCA software: Simapro 9.6.0.1
- LCIA method: AWARE 1.2, Impact World 2.1

7.3.2 Data collection and inventory

The production of ethanol includes input and output flows of water both from the biosphere (elementary flows) and from the technosphere (intermediate flows).

Elementary flows include water withdrawal for industrial uses (mainly cooling), evaporation of part of the water and water emissions to freshwater bodies after its use. Technosphere flows include tap water and wastewater treatment after its use in the industrial process. Besides these flows, water flows through the process via the water content of other intermediate flows, namely the maize used in ethanol production and the products of the process (ethanol and distiller's dried grains with solubles-DDS). Figure 35 presents a schema of the main flows of water in the industrial process. Technosphere flows are represented by red arrows. The dotted arrows represent flows with a water content while full arrows represent technosphere water flows (water content=1). Elementary flows appear in green.

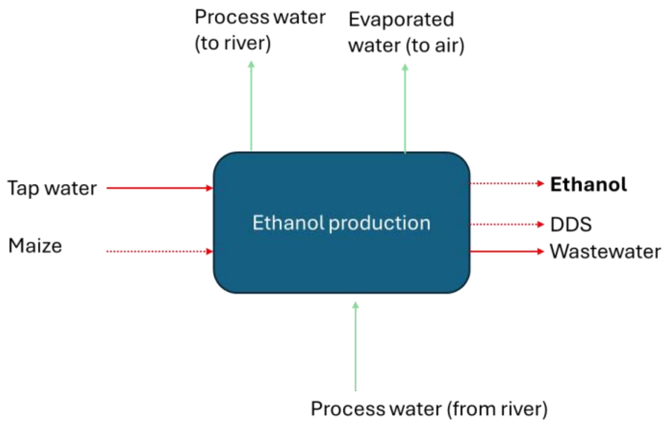


Figure 35: Schema of the industrial process of ethanol production from maize (elementary flows in green, water via technosphere flows in red, water via water content in technosphere flows in dotted red).

The first step to model this industrial process is to complete a water balance of the industrial process. Table 22 shows the water balance, including both elementary flows and technosphere flows for the ethanol production process already allocated to ethanol (the unallocated process and its issues are treated in Box 2). For technosphere flows that are not forms of water (tap water, wastewater), the amount needs to be combined with the water content to obtain the total water entering or outing the process via technosphere flows.

Table 22: Water balance of ethanol production process (from ecoinvent 3.10-cut off)

Flow	**Amount**	**units**	**Water content (kg/kg)**	**Water in (m^3)**	**% total in**	**Water out (m^3)**	**% total out**
Inputs							
Water, cooling	4.37E-03	m3	1	4.37E-03	48%		
Maize grain	3.23E+00	kg	0.14	4.52E-04	5%		
Tap water	4.22E+00	kg	1	4.22E-03	47%		
Outputs							
Ethanol (ref product)	1	kg	0			0	
Water to air	2.88E-03	m3	1			2.88E-03	34%
Water to water	2.76E-03	m3	1			2.76E-03	32%
Wastewater	2.95E-03	m3	1			2.95E-03	34%
			TOTAL in	**9.05E-03**	**TOTAL out**	**8.60E-03**	

The first remark in this table is that the inflows and outflows do not balance. The amount entering the process (9.05 kg of water/kg of ethanol) is 5% higher than the amount leaving the process (8.6 kg of water/kg of ethanol). As explained in section 4.6.1.1, water consumption is calculated by most software and LCIA methods using the watershed differential approach, so this imbalance results in an overestimated impact (as withdrawals are higher than the returns to the environment). The unbalance can be due to incomplete data collection or caused by allocation issues (as seen in Box 2).

Box 1: Unbalanced processes

Unbalance between inputs and outputs in a process (either after allocation or not) is problematic as net consumption is calculated using the watershed differential approach. An unbalance would mean that net consumption is either over or underestimated because inputs are higher than outputs or the opposite respectively.

The unbalance that overestimates the water consumption should be corrected by a more comprehensive data collection if the process does not represent the reality (for example an electric production from hydropower that only has a cooling water input flow). In some cases, as the example shown in Table 22, the unbalance does not affect significantly the representativity of the process and it can be assumed that the missing water is effectively consumed. In that case, an evaporation flow could be added to balance inputs and outputs even if this operation does not affect the final result as evaporation flow is not used in the calculation using the watershed differential approach.

The unbalance where the outputs are higher than the inputs is more problematic as the result would imply that water is "created" by the process, so it should be corrected in priority by identifying the missing inputs of water. In some cases, such as desalinization processes, this unbalance can be explained as the inputs come from the ocean (flows not included in the freshwater net consumption calculation) and the outputs would return to the watershed. In those cases, the unbalance does not need to be corrected, but the AWARE results should be treated carefully as they would be part of the edge cases explained in section 4.6.5.

Inputs come mainly from the cooling water and the tap water used in the process. The water entering the industry via the maize grain accounts only for 5% of the total freshwater input. Outputs of water are shared equally between evaporated water (water to air), water returned to the ecosystem (water to water), and water going to a water treatment plant (wastewater). Assuming that water for cooling is released directly to the environment and tap water exists through the sewage to a wastewater treatment plant, the two main flows entering the process are divided almost equally between the evaporation and the return to the technosphere or the environment; about 2/3 of the water used for cooling (2.88 l/kg of ethanol) returns to the environment (ration between water to water and cooling water) while the remainder is evaporated. In the case of tap water, 70% returns to the technosphere (ratio between wastewater and tap water). The amount of evaporated water is often estimated from the values that are more easily collected. Indeed the inflows and outflows should balance at the end, so the assumption that water unbalance is emitted through evaporation can be used. As mentioned in Box 1, this correction is not needed since the watershed differential approach is used and the net consumption would not be affected by the correction. This would not be the case for situations such as chemical reactions where part of the water reacts and is transformed into another substance.

Box 2: *Water balance and allocation*.

As mentioned in section 7.3.1, the ethanol production process is multifunctional, as a coproduct (DDS) is produced. The ecoinvent version used for the case study (ecoinvent 3.10-cut-off) uses the economic allocation to deal with multifunctionality. This allocation method can lead to an unbalance on the water flows in the final allocated processes.

In the multifunctional process studied, the allocation factors for ethanol and DDS are 98.8% and 1.2% respectively and the water content of the two coproducts are 0 kg of water/kg for the ethanol and 0.08 kg of water/kg for the DDS.

These differences in the allocation factor and the water content result in unbalanced allocated processes, namely for the DDS, where more water outs the process than the water that enters it. As shown in Table 23, the balance in the multifunctional unallocated process is not fully respected (inputs of water are 4% higher than outputs).

Table 23: Water balance of multifunctional ethanol production process (from ecoinvent 3.10-unallocated)

Flow	**Amount**	**units**	**Water content (kg/kg)**	**Water in (m^3)**	**Water out (m^3)**
Inputs					
Water, cooling	1.36E-03	m3	1	1.36E-03	
Maize grain	1.00E+00	kg	0.14	1.40E-04	
Tap water	1.31E+00	kg	1	1.31E-03	
Outputs					
Ethanol (ref product)	3.06E-01	kg	0		0.00E+00
DDS (coproduct)	3.21E-01	kg	0.08		2.57E-05
Water to air	8.94E-04	m3	1		8.94E-04
Water to water	8.56E-04	m3	1		8.56E-04
Wastewater	9.15E-04	m3	1		9.15E-04
			TOTAL	**2.81E-03**	**2.69E-03**

When using the allocation factors and analyzing the water balance of each allocated coproduct, the unbalance is increased due to the allocation, namely in the case of DDS, where the water content is higher. Table 24 shows the results of the water balance for DDS. It can be observed that outputs are more than 50% higher than inputs due to the accounting of the water content of the DDS.

Table 24: Water balance of DDS production process (from ecoinvent 3.10-cut off)

Flow	**Amount**	**units**	**Water content (kg/kg)**	**Water in (m^3)**	**Water out (m^3)**
Inputs					
Water, cooling	5.08E-05	m3	1	5.08E-05	
Maize grain	3.63E-02	kg	0.14	5.08E-06	
Tap water	4.76E-02	kg	1	4.76E-05	
Outputs					
DDS (ref product)	1	kg	0.08		8E-5
Water to air	3.25E-05	m3	1		3.25E-05
Water to water	3.11E-05	m3	1		3.11E-05
Wastewater	3.32E-05	m3	1		3.32E-05
			TOTAL	**1.03E-04**	**1.76E-04**

The same balancing approach can be done for maize production as it is the main ethanol ingredient and it is an agricultural process, which can present several challenges. **Erreur ! Source du renvoi**

introuvable. presents the main flows contributing to the water balance in the maize production process: the irrigation process (technosphere flow similar to tap water), the water contained in the manure as inputs and the output of water as elementary flows (emissions of water to river and groundwater). In this case, the balance is being done between the irrigation and the two elementary flows (to freshwater and to air) without considering the water input through manure and the water output in the main product. The case of water contained in manure is difficult to model for several reasons: the cut-off approach considers these wastes from animal production as burden-free, and the animal production modelling is not fully balanced.

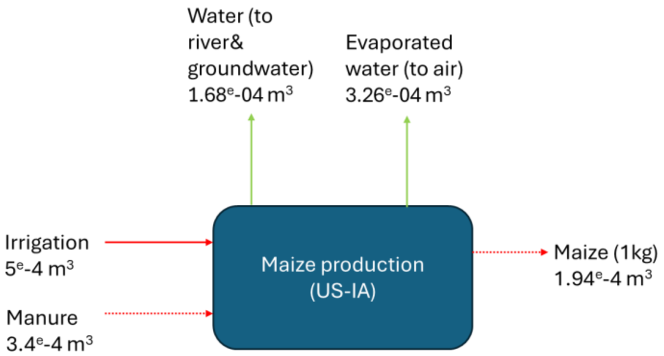


Figure 36: Schema of the maize production main water flows (amounts of water in m^3) (elementary flows in green, water via technosphere flows in red, water via water content in technosphere flows in dotted red).

7.3.3 WSF results with AWARE

Once the inventory is complete and the balance is solved, the results can be calculated. Several steps of modelling refining are presented in this section:

- Baseline scenario: the industrial process as it is included in ecoinvent, i.e., modelized at the country level and using water flows that are characterized by the average annual CF of the country;
- Scenario 2- Regionalized scenario: the main contributing processes are regionalized at a finer level (state level);
- Scenario 3- Spatialized scenario: the water elementary flows of the regionalized processes are spatialized at the watershed level;
- Scenario 4-Temporalized scenario: The temporal dimension is considered for the water elementary flows of the regionalized processes
- Scenario 5- Seawater scenario: seawater is used for cooling in the ethanol production process.

The different scenarios are conpared in section 7.3.3.6.

7.3.3.1 Baseline case: Regionalization and spatialization by default: Hotspot identification

In the baseline case, the model uses default geographies in ecoinvent, namely the US for ethanol production and a US group market for the production of maize used in the ethanol production process. The method available by default in Simapro is applied by using CF differentiated by country and larger regions (Europe, North America, etc.) based on the flow location as identified by ecoinvent.

Process contribution analysis

Figure 37 presents the contribution to the total impact score of the different processes in the life cycle of ethanol production. The production of maize grain appears as the main contributor (more than 80%

of the total score). This large contribution is mainly explained by the amount of water consumed for irrigation during the agricultural phase.

The tap water consumption and the wastewater treatment are the following contributors in absolute importance, but the scores of both cancel each other out. Indeed, the wastewater treatment process is modelled with one water input from the technosphere (wastewater to be treated) and one water output to the environment (freshwater). As AWARE is implemented using the watershed differential approach (explained in section 4.6.1.1), where only elementary flows are used to calculate the water consumption, the result is negative for the wastewater treatment process. The tap water process is modelled with one water input from the environment (freshwater) and one water output to the technosphere in the reference product.

The direct water consumption, which contributes to less than 3% of the total score, corresponds to the balance between the inputs of cooling water (4.37E-03 m^3/kg of ethanol) and the output back to the freshwater (2.76E-03 m^3/kg of ethanol) detailed in Table 22. The category "other" corresponds to the contribution of all the other elements included in the process (chemicals, electricity and heat).

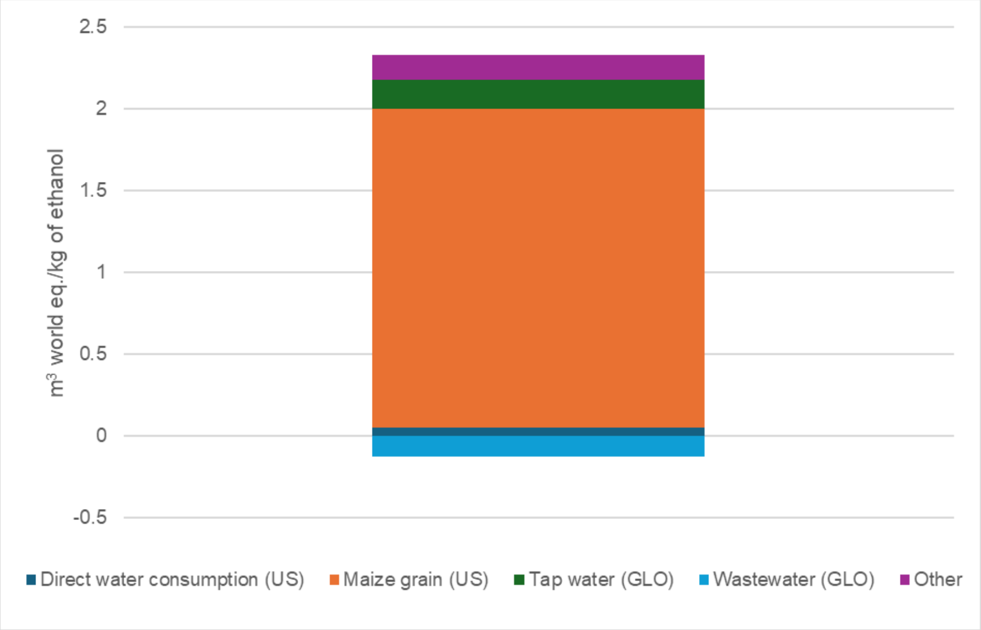
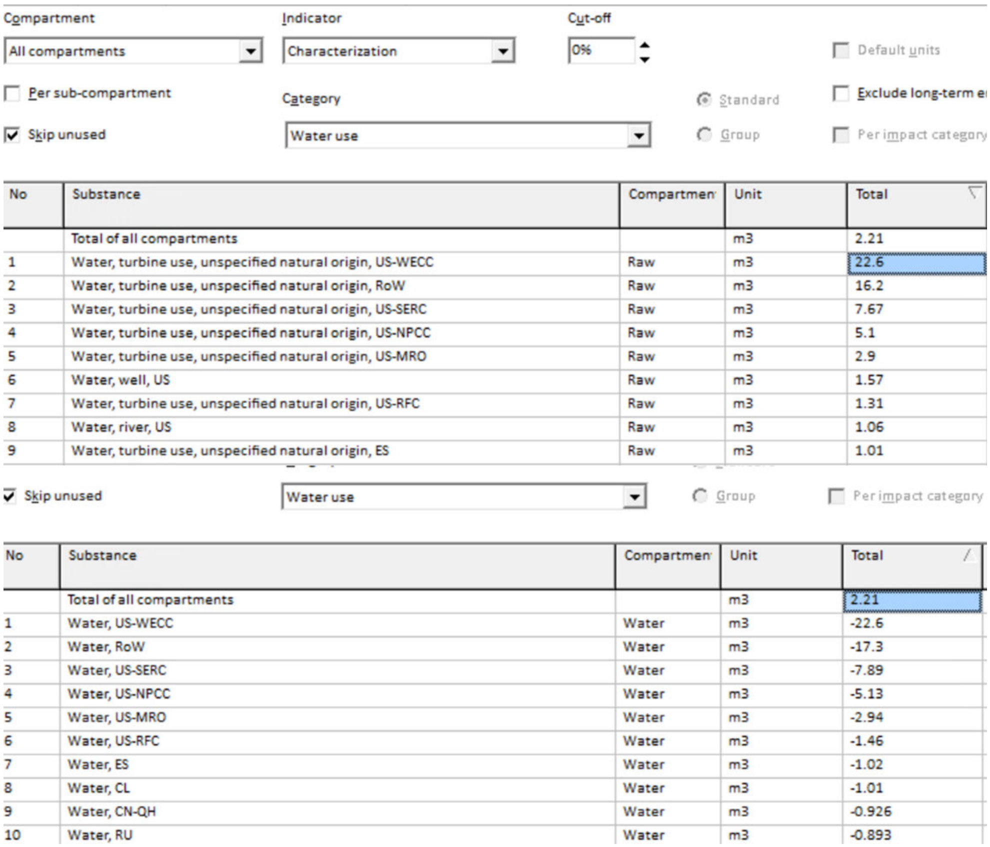


Figure 37: Results for 1kg of ethanol produced in the US (Baseline scenario) using AWARE 1.2. Main process contributors.

Elementary flow contribution analysis

One big challenge in interpreting the AWARE results and identifying the main contributors is the analysis of the main elementary flows' contribution to the impact. As the calculation of the water consumption implemented by most software uses the watershed differential approach, the main contributors list does not represent the water consumption but the main water inputs and outputs. Most of those water inputs and outputs cancel each other out and do not provide useful information about real water consumption. Figure 38 shows an example of this issue. The highest contributor (positive value) is "Water, turbine use, unspecified natural origin, US-WECC", but the contribution of this elementary flow cancels with the elementary flow with the lowest contribution (negative value) "Water, US-WECC".



Compartment: All compartments
Indicator: Characterization
Cut-off: 0%
☐ Default units
☐ Per sub-compartment
Category: Water use
● Standard
☐ Exclude long-term e
☑ Skip unused
○ Group
☐ Per impact category

No	Substance	Compartmen	Unit	Total
	Total of all compartments		m3	2.21
1	Water, turbine use, unspecified natural origin, US-WECC	Raw	m3	22.6
2	Water, turbine use, unspecified natural origin, RoW	Raw	m3	16.2
3	Water, turbine use, unspecified natural origin, US-SERC	Raw	m3	7.67
4	Water, turbine use, unspecified natural origin, US-NPCC	Raw	m3	5.1
5	Water, turbine use, unspecified natural origin, US-MRO	Raw	m3	2.9
6	Water, well, US	Raw	m3	1.57
7	Water, turbine use, unspecified natural origin, US-RFC	Raw	m3	1.31
8	Water, river, US	Raw	m3	1.06
9	Water, turbine use, unspecified natural origin, ES	Raw	m3	1.01

☑ Skip unused
Water use
○ Group
☐ Per impact category

No	Substance	Compartmen	Unit	Total
	Total of all compartments		m3	2.21
1	Water, US-WECC	Water	m3	-22.6
2	Water, RoW	Water	m3	-17.3
3	Water, US-SERC	Water	m3	-7.89
4	Water, US-NPCC	Water	m3	-5.13
5	Water, US-MRO	Water	m3	-2.94
6	Water, US-RFC	Water	m3	-1.46
7	Water, ES	Water	m3	-1.02
8	Water, CL	Water	m3	-1.01
9	Water, CN-QH	Water	m3	-0.926
10	Water, RU	Water	m3	-0.893

Figure 38: Contribution to total score per elementary flow. Higher contribution (positive values) and lower contribution (negative values).

7.3.3.2 Refined results - Regionalized scenario

As maize grain is the main contributor to the total score, the priority is to deepen the analysis to identify its main contributors and possible refinements of the model. The process used to model the maize grain production corresponds to the market of maize grain in the US, with a combination of productions from different states. The diversity in the amount of inputs, irrigation and yield results in different scores for each region (Figure 39), varying by a factor of 4 between the maximum score (NE, with a score of 2.8 m3 world eq./kg) and the minimum score (IA, with a score of 0.077 m3 world eq./kg). Refining the model by regionalizing this input would result in a more robust result even if the elementary flows are not spatialized at the state or watershed level. The choice of the right region for the production of the crop, Iowa (US-IA) in the case study, changes significantly the final score of the ethanol production.

It must be noted that the differences between these processes come uniquely from the amount of input, as the water flows are all modelled at the country level. Differences would be higher if more refined CFs were used for each state (either state level or watershed level).

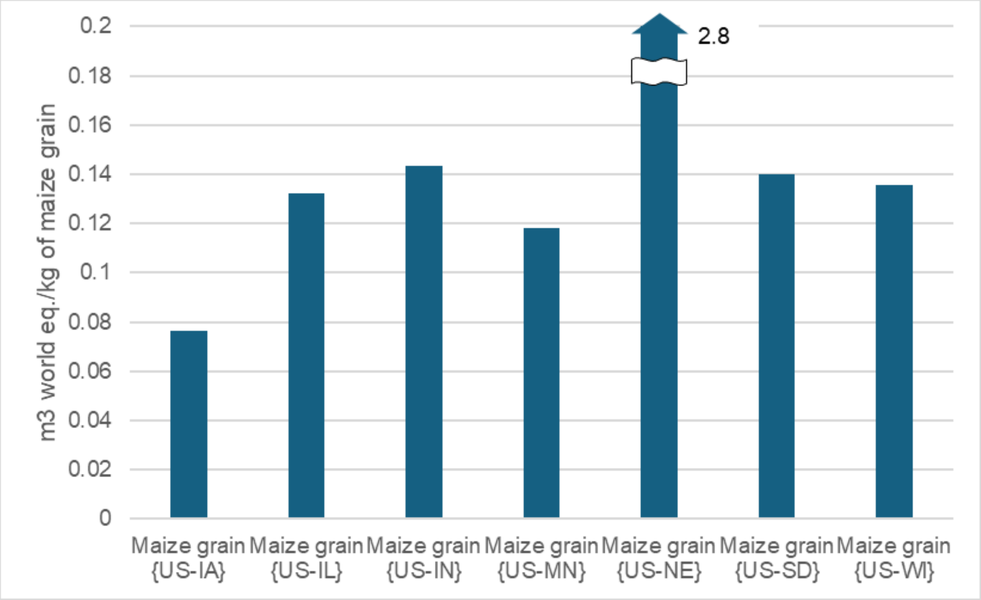
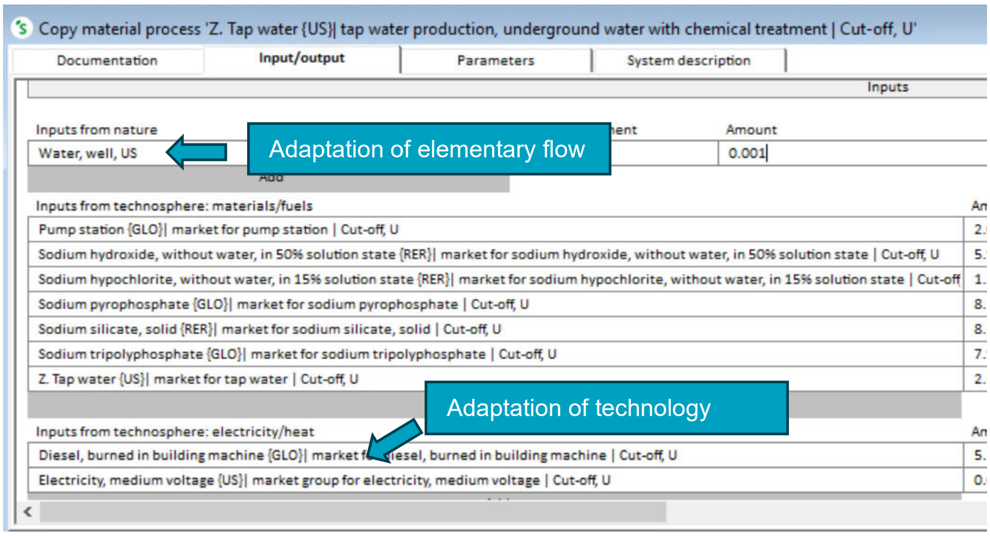


Figure 39: AWARE scores of maize grain production per state in the US.

Additionally, the processes to model the tap water and wastewater treatment correspond to the Rest-of-the-world (RoW) geography. This means that the water flows are tagged as global (GLO) and the CF used is the global average instead of the specific to the country. Although less contributing processes and so with a lower priority, those processes can be regionalized for more accurate modelling as they can vary substantially depending on regions. To regionalize those processes, quantities, technologies (if available) and the geography of the processes can be adapted. In addition, in the case of Simapro, the water elementary flows need to be adapted (spatialized) to consider the right region as shown in Figure 40. For this case study, only the electricity and the water elementary flows were adapted for tap water and wastewater treatment.



Inputs from nature	ent	Amount
Water, well, US		0.001

Inputs from technosphere: materials/fuels	An
Pump station {GLO}| market for pump station | Cut-off, U	2.
Sodium hydroxide, without water, in 50% solution state {RER}| market for sodium hydroxide, without water, in 50% solution state | Cut-off, U	5.
Sodium hypochlorite, without water, in 15% solution state {RER}| market for sodium hypochlorite, without water, in 15% solution state | Cut-off	1.
Sodium pyrophosphate {GLO}| market for sodium pyrophosphate | Cut-off, U	8.
Sodium silicate, solid {RER}| market for sodium silicate, solid | Cut-off, U	8.
Sodium tripolyphosphate {GLO}| market for sodium tripolyphosphate | Cut-off, U	7.
Z. Tap water {US}| market for tap water | Cut-off, U	2.

Inputs from technosphere: electricity/heat	An
Diesel, burned in building machine {GLO}| market for diesel, burned in building machine | Cut-off, U	5.
Electricity, medium voltage {US}| market group for electricity, medium voltage | Cut-off, U	0.

Figure 40: Regionalization of processes. Adaptation of technologies and spatialization of water elementary flows.

These refinings of the system result in changes in the final score of the studied system. Figure 41 presents the contribution to the total score of the processes in the life cycle of ethanol production once the regionalization is performed. The total score is reduced by a factor of 4 when compared to the baseline scenario, mainly due to the adaptation of the source of maize grain, whose score is reduced from 1.95 m^3 world eq./kg in the default process to 0.24 m^3 world eq./kg in the adapted one. With this reduction, the relative contribution of other elements, such as the production of urea used as fertilizer, increases significantly (it becomes the main contributor to the impact of maize production before the water is consumed through irrigation).

Tap water and wastewater scores are reduced by 20% each after the regionalization of the processes. Direct water consumption and other inputs scores remain the same as no adaptations were performed but their relative contribution increased thanks to the reduction of the total score.

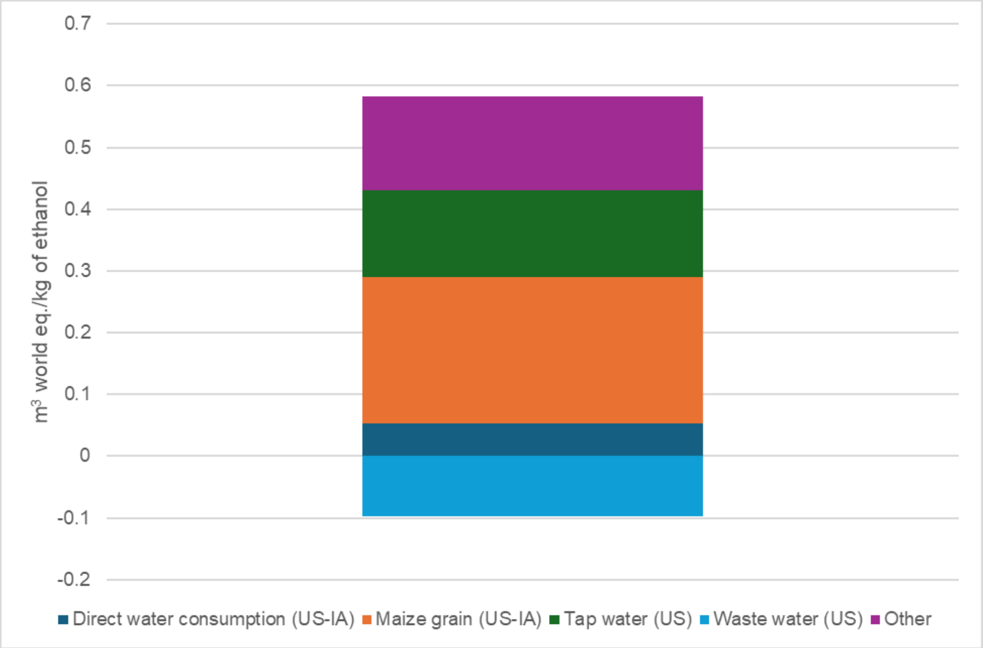


Figure 41: Results for 1kg of ethanol produced (Scenario 2- Regionalized scenario) in the US using AWARE 1.2. Main process contributors.

7.3.3.3 Refined results - Spatialization at watershed level

Further refining can be performed for the main processes by using CFs closer to the native resolution. In the case of AWARE two elements can be refined: the geographical scale, defined at the watershed level, and the temporal scale, calculated per month but available only as an annual average in the software implementation. Among those two elements, the priority can be set by looking at the geographical and temporal variability in each country, available in the Excel file on the WULCA website[12] (Boulay et al., 2018). In the case of the US, the geographical variability is higher, so this is the first refining performed. CFs between watersheds in the US vary from values around 0.2 m^3 world eq./m^3 (Mississippi watershed in Louisiana) to 100 m3 world eq./m^3 (in Arizona) while the aggregated value used is 33.12 m^3 world eq./m^3. The native CF for Iowa, where the production plant is located is 1.3 m^3 world eq./m^3. As most of the state is covered by one watershed, it was assumed that the elementary flow for the state could be used for the adaptation.

To refine the results by increasing the geographical representativity, an adaptation (spatialization) of the water flows to represent their location at the native scale[13] (in the case of AWARE, watershed level) is made.

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[12] https://wulca-waterlca.org/wordpress/wp-content/uploads/AWARE_country_regions_Corrected_online_20230113-1.xlsx

[13] Native spatial resolution corresponds to the spatial resolution of CF maps in a LCIA method, as chosen by the method developers (ScoreLCA, 2024).

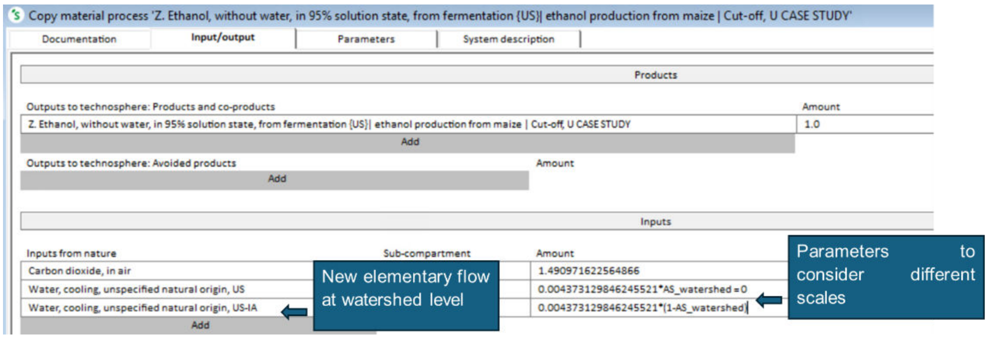
For this model refining, several processes can be adapted in priority order based on their impact contribution:

- The maize production process, which is the main contributor to the impact (49% of the total score).
- The tap water and wastewater treatment processes, whose contributions were 29% and -20% respectively;
- The ethanol production process, where the direct water consumption contributes to 10% of the total score;

Using native CFs in Simapro involves two operations described in the previous ScoreLCA reports (ScoreLCA, 2024):

- Creating new spatialized flows with a specific name for the native scale;
- Creating a copy of the LCIA method to include the CFs corresponding to the native scale (watershed);
- Replacing the original flows, which are spatialized at the country level by the flows created at the watershed level.

Figure 42 presents an example of the elementary flow spatialization for the ethanol production process. In this case, the elementary flows spatialized per US state are already present in Simapro, so the first step described above (creating new spatialized elementary flows) was skipped. The process shown in the figure includes both the original flows and the newly created spatialized ones. A switch parameter ("AS_watershed") is used to select one or the other option when calculating the results. The parameter has a value of 1 or 0 depending on the option that is calculated.


Copy material process 'Z. Ethanol, without water, in 95% solution state, from fermentation {US}| ethanol production from maize | Cut-off, U CASE STUDY'

Outputs to technosphere: Products and co-products	Amount
Z. Ethanol, without water, in 95% solution state, from fermentation {US}| ethanol production from maize | Cut-off, U CASE STUDY	1.0

Inputs from nature	Sub-compartment	Amount
Carbon dioxide, in air		1.490971622564866
Water, cooling, unspecified natural origin, US		0.004373129846245521*AS_watershed =0
Water, cooling, unspecified natural origin, US-IA		0.004373129846245521*(1-AS_watershed)

New elementary flow at watershed level

Parameters to consider different scales

Figure 42: Spatializing water elementary flows in Simapro at the watershed level. Parameters are used to compare results at different scales.

As shown in Figure 36, two main water flows contribute to the water balance in the maize production process: the output of water as elementary flows (emissions of water to river and groundwater) and the irrigation process (technosphere flow similar to tap water). These two elements need to be spatialized too at the same geographical scale, in this case, the native watershed scale, as they are used to calculate the total water consumption of the process.

These refinings of the system result in changes in the final score of the studied system. Figure 43 presents the contribution to the total score of the elements in the life cycle of ethanol production once the spatialization at the watershed level for most contributing water flows is added to the regionalization performed in the previous section. The total score is reduced by 25% when comparing scenario 2 (Regionalized) with scenario 3 (Spatialized at the watershed level). In this case, reductions are mainly due to the reduction of the scores of direct water consumption, tap water and wastewater treatment, since the CF used for the elementary flows in those processes was reduced from 33.12 m^3 world eq./m^3 to 1.3 m^3 world eq./m^3. The score of maize production remains quite stable as its main contributors (production of urea and other fertilizers) were not spatialized. Regionalization and spatialization of these processes could increase the representativity and accuracy of the result but there were no precise data on their origin.

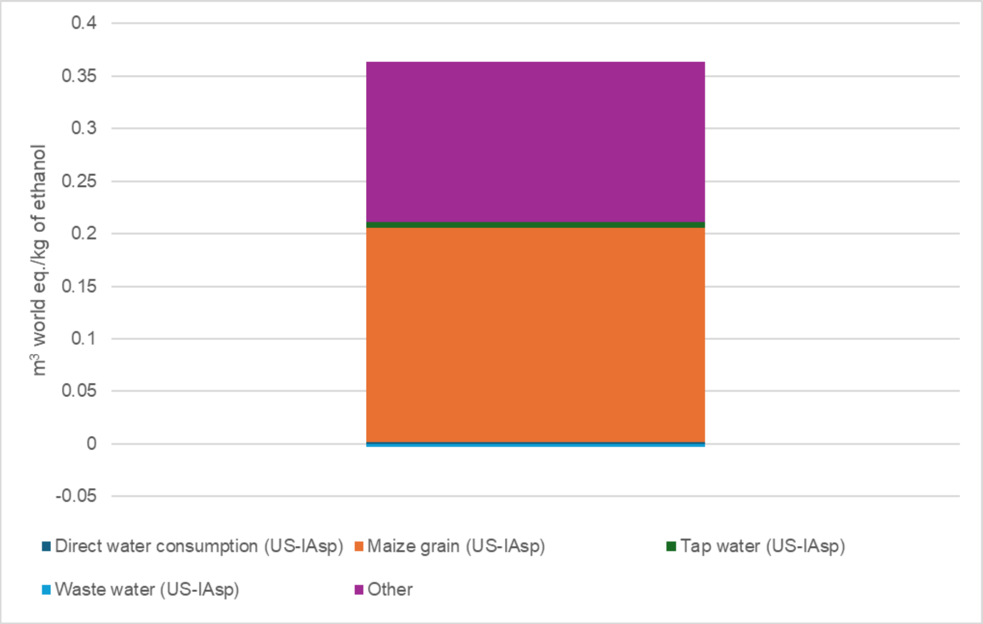


Figure 43: Results for 1kg of ethanol produced (Scenario 3- Spatialized scenario) in the US using AWARE 1.2. Main process contributors.

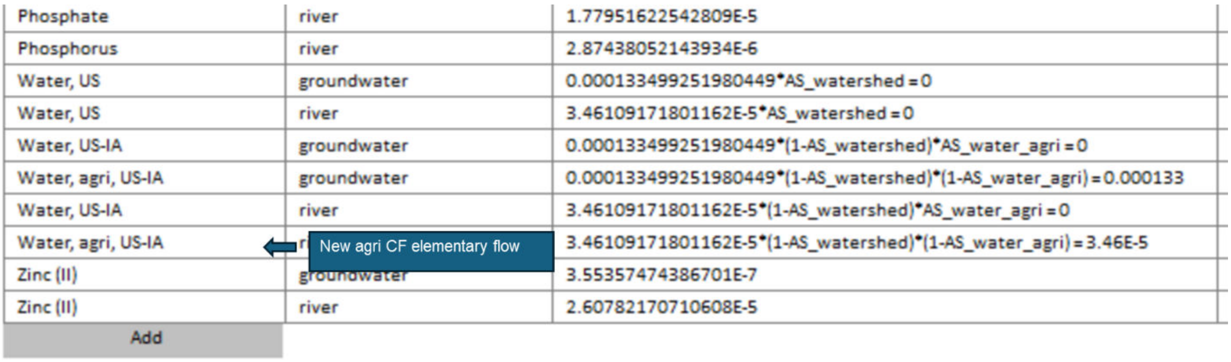
7.3.3.4 Refined results - Temporalization based on type of water usage

A step beyond the refining of the modelled system consists of accounting for the temporal variations of the CFs as explained in section 4.4.1. As some consuming water activities do not occur equally during the year and water scarcity varies also over the year, this refinement of the modelling could be relevant and result in major changes in the final score. In this case study, it is assumed that the ethanol production is constant over the year, so no temporal refinement is judged necessary for that process.

The first step for temporalization is to use the agricultural CF (explained in section 4.2.4) for maize production. To include this agricultural CF, the refining is made as in the previous section for the spatialization:

- Creating new water-agri flows for the studied watershed;
- Including in the LCIA method the agri CFs corresponding to the studied;
- Replacing the original flows, by the agri flows created at the watershed level.

Figure 44 presents an example of this refinement of the elementary flows for the maize production process.



Phosphate	river	1.77951622542809E-5
Phosphorus	river	2.87438052143934E-6
Water, US	groundwater	0.000133499251980449*AS_watershed=0
Water, US	river	3.46109171801162E-5*AS_watershed=0
Water, US-IA	groundwater	0.000133499251980449*(1-AS_watershed)*AS_water_agri=0
Water, agri, US-IA	groundwater	0.000133499251980449*(1-AS_watershed)*(1-AS_water_agri)=0.000133
Water, US-IA	river	3.46109171801162E-5*(1-AS_watershed)*AS_water_agri=0
Water, agri, US-IA	r	3.46109171801162E-5*(1-AS_watershed)*(1-AS_water_agri)=3.46E-5
Zinc (II)	groundwater	3.55357474386701E-7
Zinc (II)	river	2.60782170710608E-5

Figure 44: Including agri elementary flows in Simapro at the watershed level. Parameters are used to compare results at different scales.

Figure 45 presents the contribution to the total score of the elements in the life cycle of ethanol production once the agricultural elementary flows are added to the refined model of the previous section. In this case, the total score remains unchanged as the difference between the agricultural and the unknown CF is low (1.2 m^3 world eq./m^3 and 1.3 m^3 world eq./m^3 respectively). A step beyond would use the monthly CFs and the actual irrigation per month to calculate a more precise result. (Boulay et al., 2019) propose crop-specific CFs that consider the irrigation over the year per country. However, as these values are calculated per country, they are not useful in the case of the US, where the geographical variability is higher than the temporal one.

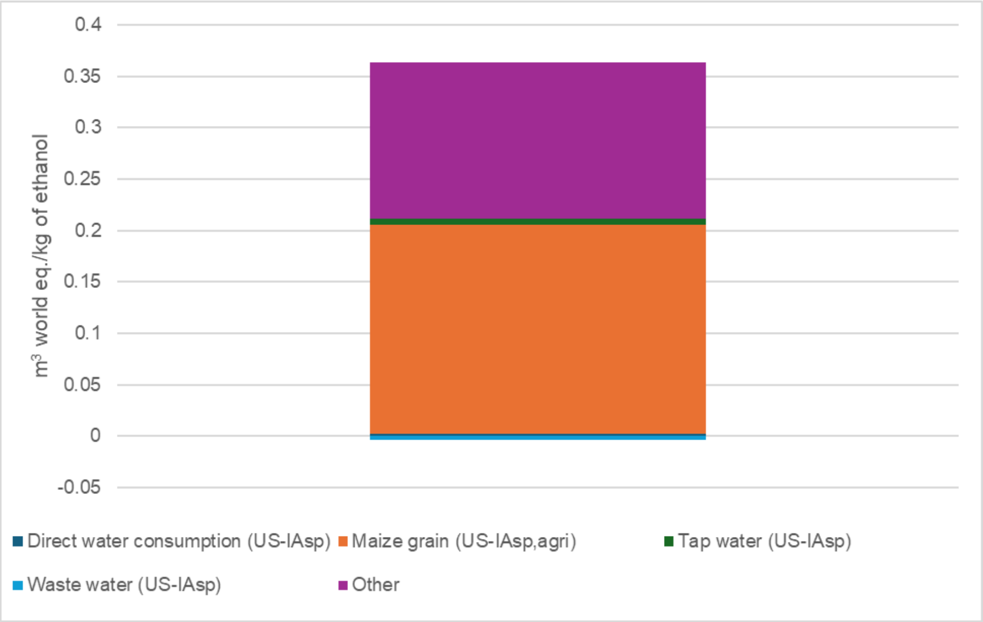


Figure 45 Results for 1kg of ethanol produced (Scenario 4-Temporalized scenario) in the US using AWARE 1.2. Main process contributors

7.3.3.5 Edge cases - Use of seawater

As presented in section 4.6.5, some cases present challenges in the modelling and the interpretation of the results calculated with AWARE. The use of seawater in an industrial process for cooling or to produce tap water (via reverse osmosis) can lead to results difficult to interpret as seawater is not accounted for in AWARE results' calculation, which can lead to an unbalance as water is rejected in freshwater ecosystems and consequently, accounted in the calculation. Using the same case study, we assume that both the cooling water and the tap water used in ethanol production use seawater as an input of water. As the original case study was located in Iowa, a generic location in the US is used for this example (country-level CFs are used).

Figure 46 presents the contribution to the total score of the elements in the life cycle of ethanol production using seawater for cooling and tap water production. This result is to be compared with the results in Figure 41. In this case, the use of seawater, which is not accounted for in the consumption calculation (as it is not a freshwater flow), results in negative values for direct consumption and tap water production. These results, while valid from a calculation point of view, remain disputable as the water used close to the sea as the cooling water in the example, should be modelled also as an emission to the ocean and not to the freshwater. In the case of tap water, the emission after the wastewater treatment process assumes that the water is available for other users in the watershed, but as the consumption occurs close to the sea, only a few additional users would benefit before running into the ocean.

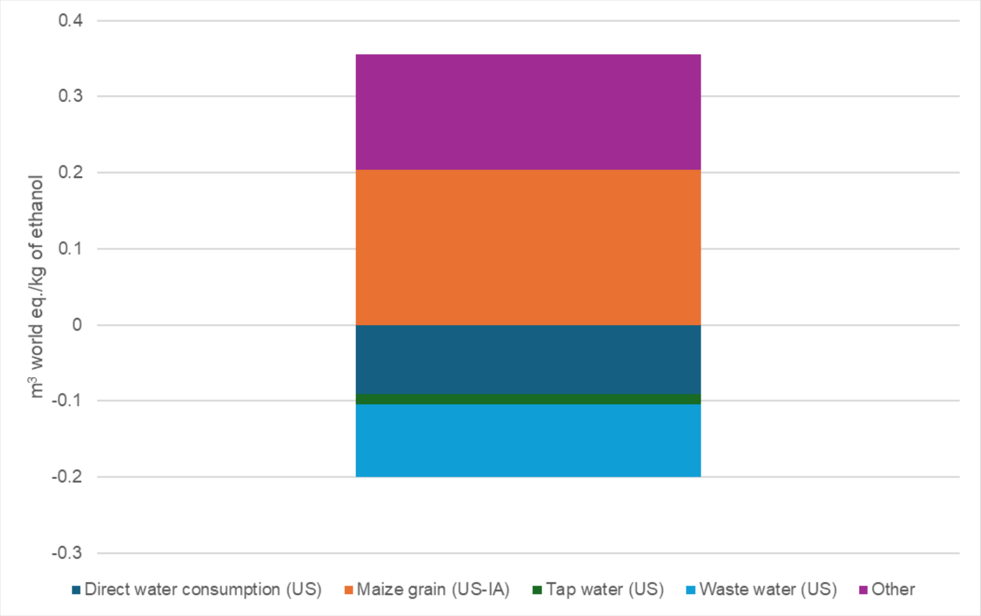


Figure 46 Results for 1kg of ethanol produced (Scenario 5- Seawater scenario) in the US using AWARE 1.2. Main contributors

7.3.3.6 Scenarios comparison

Figure 47 resumes the comparison of the refining steps scenarios developed in previous sections. The baseline scenario presents the highest score among all the scenarios compared, which shows that the regionalization process (i.e. using the most representative technologies of the studied region) is the most important refining step in this case. Indeed, the amount of water used for irrigation appears as the main contributor to the final score and the regionalization step results in a significant reduction (see Figure 39).

The spatialization (scenario 3) results also in a reduction as the CF of the watershed studied has a notably lower value than the US country average. Scenario 4 does not present differences compared to scenario 3. As explained in section 7.3.3.4, unknown CF and agricultural CF present close values in the studied watershed, so no differences are found with the temporalization step. However, this step could be performed more precisely by collecting the actual water consumption per month and using the CFs per month.

Due to the inputs of seawater not included in the calculation, the edge case (scenario 5) presents negative values (i.e. diminishing the water scarcity) for the tap water and the direct use of water. This results in a total value lower than the previous scenarios.

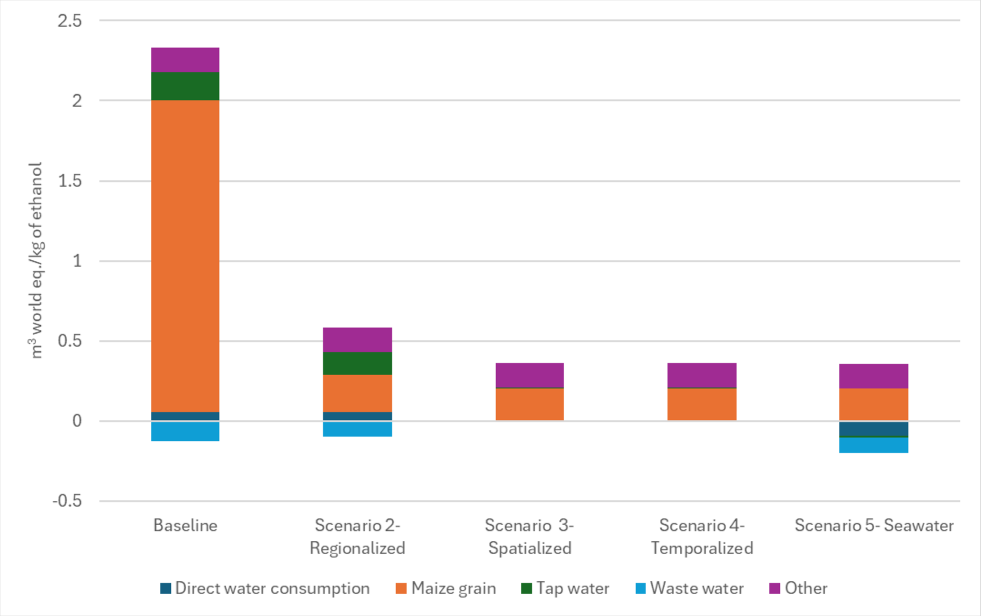


Figure 47: Results for 1kg of ethanol produced in the US using AWARE 1.2. Scenarios comparison.

7.3.4 Comprehensive water footprint beyond water scarcity footprint with AWARE

As mentioned in section 3.1, a water footprint should include all water-related impacts. The use of AWARE as a single indicator is only useful when calculating a WSF and not a comprehensive water footprint. Burden shiftings could occur between water-related environmental issues if only AWARE is used to measure the water footprint of a product.

To illustrate potential burden shifting, two different comprehensive LCIA methodologies are used in this section: The Environmental Footprint methods developed by the European Commission and Impact World+. Both methodologies calculate results beyond water-related impacts, so for the example, only water-related categories are included. Table 25 summarizes the categories considered as water-related categories for each LCIA methodology. To calculate the relative contribution of each impact category and highlight the importance of water scarcity (represented by Water use in EF 3.1 and Water availability in Impact World+), two different approaches are used. For EF, the weighting factors proposed in the method are used to calculate the category contribution to a single score. For Impact World+, the scores are calculated at the damage level, so category contribution can be analyzed for each area of protection (Human health and Ecosystem quality).

Table 25: Categories of LCIA methods considered as water-related for the analysis (Water use-related categories in blue)

EF 3.1	Impact World+	
Acidification Ecotoxicity, freshwater Eutrophication, freshwater Human toxicity, cancer Human toxicity, non-cancer Ionizing radiation **Water use**	**Human health**: Human toxicity cancer, long term Human toxicity cancer, short term Human toxicity non-cancer, long term Human toxicity non-cancer, short term Ionizing radiation, human health **Water availability, human health**	**Ecosystem quality:** Freshwater acidification (damage) Freshwater ecotoxicity, long term Freshwater ecotoxicity, short term Freshwater eutrophication Ionizing radiations, ecosystem quality Thermally polluted water **Water availability, freshwater ecosystem** **Water availability, terrestrial ecosystem**

Figure 48 and Figure 49 show the results for the two LCIA methods presented above. In both cases, the contribution of the water consumption categories is low compared to other categories. It should be noted that some of the included categories, namely human toxicity and ionizing radiation, are only partially water-related as only part of the emissions occur in freshwater environments and only a part of the impacts via freshwater ecosystems (via fish eating for example). Even if we exclude these categories completely, the relative contribution of the water consumption categories would be minor.

This result is just an example of the importance of considering the water footprint as a whole and to consider other categories than water scarcity and it can not be extrapolated to all situations and analyses. In other studies, the contribution of water scarcity could be major.

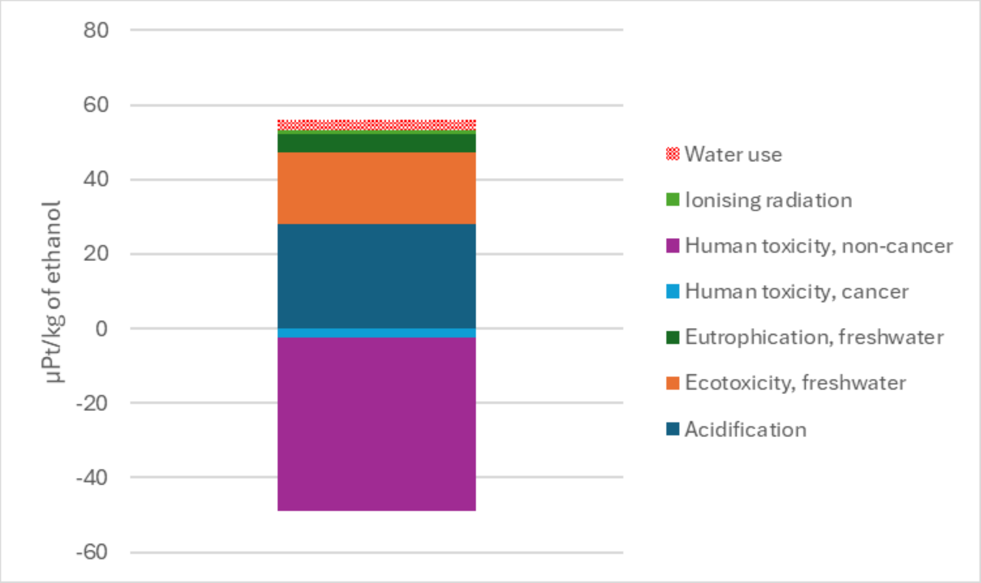


Figure 48: Results for 1kg of ethanol produced in the US using EF 3.1 (single score, selected categories).

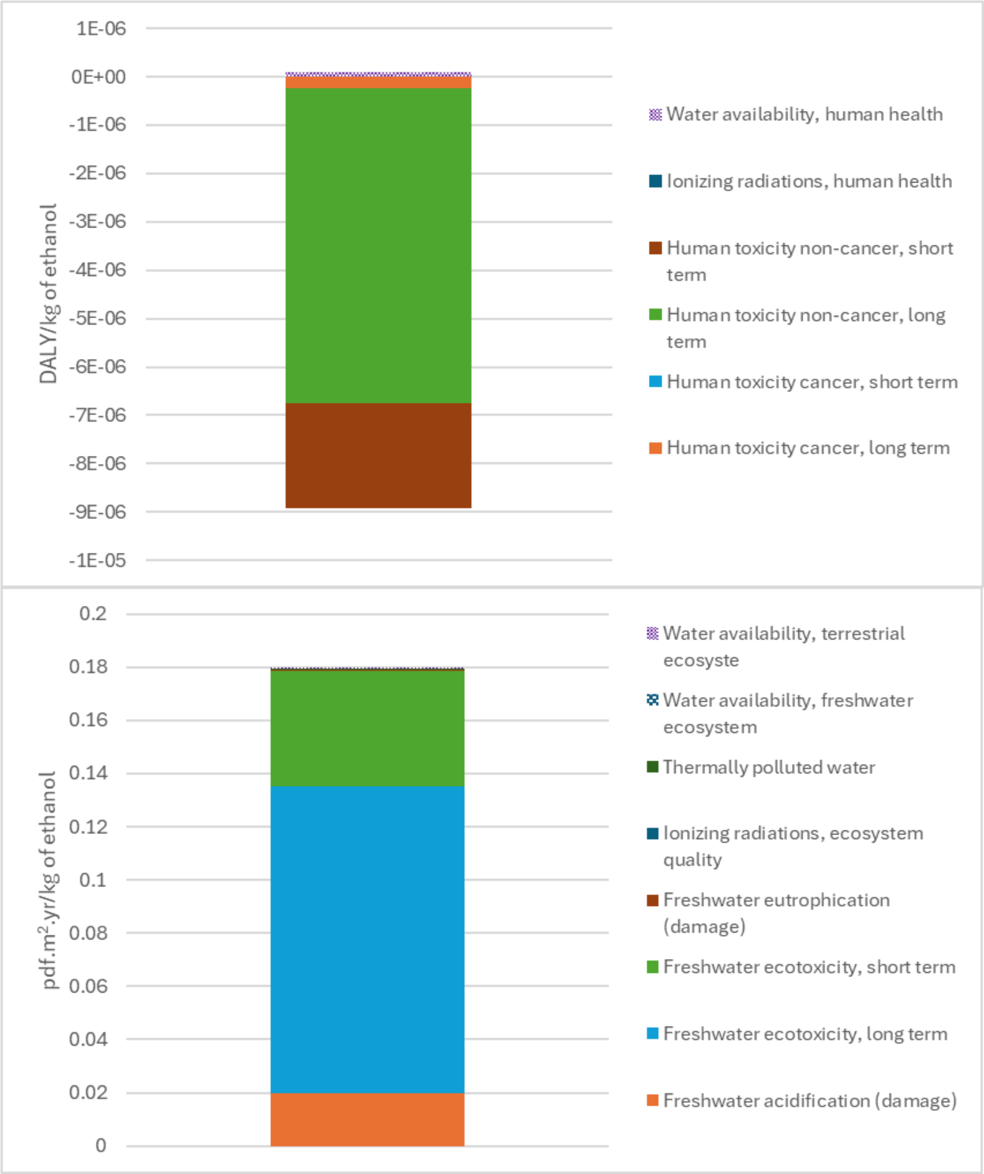


Figure 49 Results for 1kg of ethanol produced in the US using Impact World+ (endpoint, selected categories).

7.3.5 Main conclusions and challenges

The example above shows the main steps to calculate a WSF using AWARE with Simapro. The first steps include calculating the water balance to see if the main processes are well balanced or if further data collection (or using another LCI database) is needed. This is important particularly to ensure that there are no more water outputs than water inputs so that no water is "created" in a process due to poor data.

Once the model is balanced, or at least ensuring that the unbalance does not affect the net consumption calculation (for example with outputs lower than inputs), the calculation of results presents two main challenges:

- The interpretation and identification of the main contributors to the impact, that is not easy due to the watershed differential approach used in the calculation of the water consumption of each process;
- The refining of the results using more precise CFs, both from a geographic (spatialization) and temporal (temporalization) point of view. This step can be challenging and time-consuming due

to Simapro's configuration, but the increase in the representativity and robustness of the results can be worth it. Prioritizing these two refining steps depends strongly on the variability of the CFs from the geographical and temporal points of view. As mentioned in section 7.3.3.3, the variability depends on the country but also the type of activity. The refining should be done iteratively only on the main contributors to the impact that are poorly represented.

Another main challenge is to check for any burden shifting between impact categories due to the use of a single-category method.

8. Recommendations and conclusion

8.1 Summary of challenges and associated recommendations

This report aims to provide recommendations for affected stakeholders in the LCA community to overcome or mitigate challenges in the context of the WF. Therefore, four stakeholders were defined:

1. Practitioners **(P)**
2. LCI database developers **(DB)**
3. LCIA method developers **(MD)**
4. LCA software developers **(SD)**

The following sections collect challenges these groups can face in the context of the WF. Since this report focuses on the AWARE method, the challenges are divided into

- General challenges arising for WFs (Performing a Water Footprint according to ISO14046), and
- Challenges specific to AWARE and other Water Scarcity Impact assessment methods (Performing a Water Scarcity Footprint with AWARE).

The recommendations are divided into two groups (columns in the following tables):

- Recommendations to practitioners, which are practical recommendations that can already be implemented, and
- Recommendations to the general LCA community, including the other three stakeholders defined above. The latter type of recommendations mostly targets improvements that could be implemented in the long term and would finally benefit the work of WF practitioners.

8.1.1 Performing a Water Footprint according to ISO14046

ISO 14046 establishes a framework to calculate water-related environmental impacts following the basis of the 14040/44 series on LCA. This framework includes the different phases and the elements to include, but there are no clear recommendations on how to perform the assessment. The main challenges identified per LCA phases are described below. Table 26, Table 27, and Table 28 list the individual challenges with their recommendations. Note that this report focuses on the Water Scarcity Footprint. Therefore, the lists might not cover some challenges that might arise around other topics of the ISO WF, e.g. Water Degradation impacts.

1. Goal & Scope (Table 26)

- **Defining the G&S (functional unit with spatial and temporal context, system boundaries) with a temporal and geographical resolution adequate to the aim of the project.** As water-related issues are highly geography and time-dependent, defining the elements of the G&S is necessary to obtain robust results and conclusions.

- **Choice of the LCIA methodology and impact categories.** The aim of the study can also determine the choice of the LCIA methodology and the impact categories selected to perform the WF. A single-issue method, such as AWARE, can be justified, but the risk of burden shifting between other water-related impact categories should be considered. Apart from AWARE and USETox, no consensus exists on which LCIA methods to use for a comprehensive WF according to ISO 14046. To cover all relevant water-related impacts as mandated by the standard, first, suitable impact assessment methods must be available. However, the set of impact assessment indicators is still evolving, which means that some water-related impacts can not be covered yet, while other indicators exist but without a general endorsement by the scientific community.

2. Life Cycle Inventory (Table 27)

- **Primary data collection.** It should be comprehensive, including temporal and geographical information, and including all the quantity and quality information to allow the calculation of results for the impact categories chosen. Such detailed data are rarely available, so secondary data should be used and the uncertainty of this choice considered when interpreting the results.

- **Secondary data (LCI databases)**. According to the objectives, the tools used to model the system and calculate the inventory can differ. Missing water flows, disaggregation of the processes, the lack of temporal information or insufficient geographical aggregation are the main challenges when selecting an LCI database.

- **Calculation tools (LCA software).** The choice of LCA software determines also the level of detail in the results, particularly for the geographical aspects, and the flexibility in the modelling and its refinement. The geographical and temporal dimensions of the water footprint complicate the use of simplified tools, such as those used in carbon footprint calculation.

3. Impact Assessment (Table 28)

- **Geographic resolution mismatch.** WF methods provide regionalized CFs at a native scale that does not always match the scale provided in LCI databases. The adjustment of the WF methods by calculating aggregated CFs to ensure compatibility increases the uncertainty and decreases the robustness of the results. While some tools allow regionalized calculation at different levels, it is not yet a wide practice.

- **Temporal aspects.** WF methods, namely AWARE provide CFs considering the temporal variability in water availability and use over the year. Using those temporally resolved CFs involved a temporalization of the inventory, but this feature is not implemented either in LCI databases or software.

- **WF scope and LCIA categories**. Some categories are only partially water-related, but no differentiation is available in LCIA methods. For example, impact methods for Human Toxicity in USEtox by default include different exposure pathways, which are not all water-related. The use of these methods in the context of a WF might therefore overestimate the actual Human Toxicity impacts related to water.

- **Uncharacterized issues.** Some water flows such as rainwater harvesting, fossil groundwater and water collected in artificial infrastructures such as ponds or reservoirs are not well characterized by impact assessment methods, which affects the comprehensiveness of the assessment.

4. Interpretation (Table 28)

- **Contribution analysis.** Several issues affect the capability of diving into the contribution of processes and flows, namely the use of the watershed differential approach to calculate the water consumption and the use of aggregate CFs.

- **Burden shifting between impact categories.** The choice of a single category such as water scarcity can sometimes lead to missing possible burden shifting between categories.

- **Uncertainty analysis.** Most LCIA methods do not provide uncertainty information on the CFs. Besides, the watershed differential approach to calculating the consumption complicates the calculation as inputs and outputs are wrongly modelled as independent.

Table 26: General challenges and recommendations for performing a Water Footprint according to ISO14046 – Goal and Scope.

Nr	Challenge	Recommendation - practitioners	Recommendation – general LCA community
	Goal and Scope – Setting objectives		
C1	Deciding between the use of the ISO approach or other approaches, e.g. WFN	**P**: Often ISO approach resulting from regulatory requirements; clarify intention: if broad focus on environmental impacts, use ISO WF. If no detailed environmental assessment is required: choose WFN	
C2	Allow comparability with other studies	**P**: Adhere to regulatory requirements	General: Create community consensus on methods to use
	Goal and Scope – Defining the system		
C3	Definition of and adhering to spatial and temporal system boundaries.	**P:** Collecting process-specific location data and temporal data for the foreground system, evaluate the importance of the background system (sensitivity analysis) and do additional regionalization	**DB:** provide parametrized processes that can be adjusted to product system requirements
	Goal and Scope – Selecting an LCIA methodology		
C4	Selection of impact categories and LCIA methodologies	**P**: Clarify the objective of assessment (level of details required in interpretation phase, comprehensive or non-comprehensive WF,...) and adhere to regulatory requirements; compare different methods in sensitivity analysis	General: Create community consensus on a set of indicators and impact categories to use for the different types of WF
C5	Select a Water Scarcity Footprint method	**P**: Clarify the objective of assessment and adhere to regulatory requirements (e.g. for Water Scarcity impacts in the context of the European Environmental Footprint use AWARE); use different methods for sensitivity analysis	
C6	Use or not: Emerging indicators without many examples in literature/other studies, e.g. impacts of turbine water use as provided in (Dorber et al., 2024)	**P**: Justify choice: How relevant is this method for the specific impact category or a specific mechanism that is important for the product system; Be transparent about the limitations of the new indicator; check whether there are community standards and compare new results with the results obtained using community standard methods.	**MD**: develop consensual indicators covering gaps in water-related issues

Table 27: General challenges and recommendations for performing a Water Footprint according to ISO14046 – Life Cycle Inventory.

Nr	Challenge	Recommendation - practitioners	Recommendation – general LCA community
	Life Cycle Inventory - primary data collection		
C7	Collecting the required data attributes (time, space) for the elementary flows to correctly assign regionalized and temporalized CFs	**P**: Identify from the beginning the required data to apply the selected LCIA methodologies used, to be able to collect data attributes while collecting other data	**MD**: Clearly state data requirements and potentially create harmonized WF LCIA methods, stating data requirements **DB**: increase alignment of databases with widely used WF data requirements
C8	Finding the required data along an entire supply chain (data collection and supply chain modelling)	**P**: Ensure water inflows and outflows balance in your foreground processes **P**: Model water-related data using parameters to facilitate sensitivity analyses and subsequent refinement of the model if supply chain data appears to be relevant	
C9	Handling low-quality or missing data in the LCI	**P**: Clearly state where data is missing (transparency in reporting); use literature values; perform a data quality assessment; **P**: Using parameters for water-related data to facilitate sensitivity analyses and refinement of the model	
C10	Ensuring the required temporal representativeness of the LCI for the study's objectives e.g., reservoir water consumption might differ drastically from year to year	**P**: Clarify objective: Is the study a "snapshot" or should it allow for generalizable conclusions? Perform sensitivity analysis on different temporal periods if generalizable conclusions are desired	
C11	Prioritization of LCI model refinement (e.g., for which process to increase regional details)	**P**: If possible, prioritize according to which aspects or processes contribute most to overall uncertainty (requires Monte-Carlo simulation) **P**: Use the impact contribution of individual processes as a proxy of uncertainty contribution	**SD**: Allow for automated uncertainty contribution analyses in the software tools.
	Life Cycle Inventory - secondary data use		
C12	Background LCI database selection: Suitable quality for intended use	**P**: Ensure suitability according to criteria such as elementary flows required for the selected LCIA methods and an appropriate balance of water resources;	**DB**: Clearly state the compatibility of DB with LCIA methods
C13	Handling LCI database deficiencies: Mass imbalances	**P**: Ensure water inflows and outflows balance in your main contributor processes. Correct in priority when unbalance affects the net consumption calculation (outputs>inputs) **P**: Early on starting to determine LCIA methodologies used and the required data	**MD**: Clearly state data requirements and potentially create harmonized WF LCIA methods, stating data requirements **DB**: increase alignment of LCI databases with widely used WF data requirements

C14	Handling LCI database deficiencies: inconsistent spatialization and regionalization (elementary flows and technology) e.g., when LCI databases provide seemingly regionalized processes but the technology is not representative of the region represented (see reservoir example)	**P**: (Manually) ensure matching regionalization between foreground and background; check impact contributions on a map (e.g. map view in openLCA); check whether technologies are location-dependent but the LCI database duplicated the same technology for different countries; correct regionalization of process or spatialization of flows if needed. **P**: If possible, use tools such as regioinvent for postprocessing LCA databases (section 4.7.6)	**MD**: Clearly state data requirements and potentially create harmonized WF LCIA methods, stating data requirements **DB**: Provide options to ensure simplified but coherent regionalization (e.g. country-specific market processes); Provide parametrized models that can be adjusted with characteristics of local technology **DB**: include temporal resolution in databases, at least as archetypes (ex: agri, non-agri) **SD**: Create workarounds that adjust the used background processes' regionalization and spatialization
	LCA software		
C15	LCA software selection	**P**: Adapt the software choice to the level of detail needed for the objectives: need of refining results, uncertainty analysis… Most LCA software use the country level included in LCI databases and more accurate results depend on the easiness of adapting processes (spatialization, temporalization) **P**: Excel-based calculators could be used with precaution to ensure the background calculations correspond to the geographical and temporal boundaries defined in the G&S (section 6.2.3.1)	**SD**: Develop software to facilitate refining of results (ex: inclusion of geospatial approach for geographical refining)

Table 28: General challenges and recommendations of performing a Water Footprint according to ISO14046 – Impact Assessment and Interpretation.

Nr	Challenge	Recommendation - practitioners	Recommendation – general LCA community
	Life Cycle Impact Assessment		
C16	Treating impacts without corresponding LCIA method (e.g. ecosystem services)	**P**: Discuss additional impacts or benefits in the study	**MD** & **DB**: increase coverage of environmental issues
	Interpretation		
C17	Interpret results from water-related impact methods which also contain non-water-related impacts	**P**: Be aware and transparent about this issue, avoid double-counting of impacts;	**MD**: Provide WF-specific versions of impact methods where non-water related impacts are neglected; Provide LCIA methodologies specifically tailored for WF without double-counting;
C18	Interpret multi-indicator results (compared to standalone indicator results)	**P**: Avoid double-counting of impacts; Be aware of implicit weighting in standalone indicators; **P**: Be aware of and transparent about your own value choices (such as: “water scarcity impacts are most important to us”) when using these to interpret multi-indicator results; Acknowledge “ties” if multi-indicator results are inconclusive **P**: Test whether indicators at damage level (endpoint indicators) reduce ambiguity of the results (since they reduce the indicators to HH, EQ, Resources and Ecosystem Services)	
C19	Interpret regionalized impacts	**P**: Focus on main contributors or assessing regional hot spots; use map plots; avoid the use of Rest-of-World or non-regionalized processes **P**: Be transparent about that these are not local impacts but impacts of the local emission (LCIA methods are usually not spatialized, see section 4.4.2)	
C20	Perform uncertainty analysis	**P**: Be aware and transparent about the impossibility of performing proper Monte-Carlo analysis for LCIA due to software constraints **P**: Be aware that in the default Monte-Carlo analysis, common LCA software usually only assesses the uncertainty of the inventory, not of the LCIA method.	**MD**: Provide uncertainty information on CF (uncertainty of CF at native scale + additional uncertainty of aggregated CF due to spatial or temporal variability) **SD**: Improve the functionality for CF uncertainty representation, e.g. by allowing more diverse uncertainty distributions **MD**, **DB** & **SD**: use parameters to link water inputs and outputs to make them dependant; modify the approach to calculate water consumption to avoid relying on flow differential

8.1.2 Performing a Water Scarcity Footprint with AWARE

The main challenges identified when performing a WSF with AWARE per LCA phase are described below. Table 29, Table 30 and Table 31 list all identified challenges and their respective recommendations to practitioners, method developers, database and software developers.

I. Goal & Scope (Table 29)

Choice of the AWARE version. Versions of AWARE contained in different recommended LCIA methods are not always the most updated version of AWARE, which leads to different results with different methods claiming to use AWARE.

II. Inventory analysis (Table 29)

Data collection. Unclarities can arise about which types of water flows to collect and evaluate with AWARE and especially monthly resolution data or data in high spatial resolution can be difficult to find. The prioritization between spatialization and temporalization can be challenging in some cases, even though it might help to only put efforts where necessary.

Secondary data sources. In secondary data sources like LCI databases, geographical information is rarely available at the native scale (watershed), while temporal information is never available. Also, LCI databases do not always contain datasets for all the geographies included in a study.

III. Characterization of elementary flows with AWARE (Table 30)

Native temporal and spatial scales: Current software tools allow different scales of elementary flow spatialization, but do not provide these by default. LCI databases do not include location information at AWARE's native spatial scale or temporal (monthly) resolution. Those refinements need to be done manually.

IV. Interpretation (Table 30)

Interpreting of the AWARE score. Technical as well as conceptual aspects might make the interpretation of AWARE results challenging, especially considering their uncertainty. This includes the technical difficulty of a contribution analysis when using watershed differential.

Burden shifting between categories. The choice of a single category such as water scarcity can sometimes lead to missing possible burden shifting between categories and there is no accepted standalone indicator that would represent both Water Scarcity and Water Degradation impacts.

V. Compatibility of tools with AWARE (Table 31)

Software limits. LCA software lacks support for the seasonality of LCI and LCIA and in some cases provides erroneous implementations of AWARE concepts such as spatial aggregations by consumption-weighting.

VI. Advanced applications of AWARE (Table 31)

Uncertainty modelling. AWARE provides uncertainty information on the CFs, but this uncertainty information is not provided in LCIA methods or well implemented in LCA software. Besides, the watershed differential approach to calculating the consumption complicates the calculation as water inputs and outputs are often modelled as independent. Therefore, uncertainty modelling with AWARE is not mature in LCA software, even though uncertainty can be an important aspect of the AWARE score.

VII. Edge cases

Note that here we do not list again the challenges and recommendations for AWARE edge cases and implementing AWARE for reservoir operations, since these are described in detail in sections 4.6.5 and 7.2.

Table 29: Challenges and recommendations linked to implementing the AWARE method – AWARE versions and constructing an inventory for AWARE

Nr	Challenge	Recommendation - practitioners	Recommendation – general LCA community
	AWARE versions (Goal and Scope)		
C21	Identification of current version of AWARE, AWARE updates (section 4.7.6 & 4.2.3)	**P**: Use WULCA website (https://wulca-waterlca.org/) as the main source of information about the current AWARE version and updates.	**MD**: Provide clear guidance on which version of AWARE is currently recommended; provide information on potential changes in results due to updates;
C22	Out-of-date or modified versions of AWARE in third-party recommendations (e.g. the Product Environmental Footprint, PEF) (section 4.7.6)	**P**: Be aware of and transparent about the issue. Test whether using the recent version of AWARE would change the results. Do not report the result as having been calculated with the AWARE method, but specifically with the methodology used, e.g. PEF.	**MD**: Frequently check for AWARE updates; reduce modifications of AWARE to a minimum; allow for smooth integration of updated CFs in their method;
	Constructing an inventory for AWARE		
C23	Identification of the types of water flows to be collected	**P**: If possible, collect all water flows to set up a consistent mass balance of the processes **P**: Else, focus on processes required for watershed differential or consumptive flows approach. Ensure correct interpretation by LCA software (since the software will not consider consumptive flows as water consumption according to AWARE)	
C24	Unclarities about the consumption of which water types (or which elementary flows) can be evaluated with AWARE (see also 4.3.2)	**P**: Ensure that only elementary water flows from and to watersheds are characterized with AWARE CFs;	**MD**: Provide clear guidelines on the use of the AWARE method;
C25	Lack of monthly water use data for the use of native AWARE CFs (section 4.6.1.3)	**P**: Test whether proxies such as water pump energy consumption patterns could help reconstruct the temporal pattern of the water consumption; **P**: Use sector- or crop-specific (spatio-)temporal aggregations of the AWARE CFs when available (sections 4.2.4 & 4.2.5); **P**: Use an iterative approach with different temporalization levels: step 1 temporalizes by using the agricultural/non-agricultural annual aggregated CF for main contributors; step 2 temporalizes main contributors at the monthly resolution if remaining temporal variability is important	**DB**: Provide monthly resolution of LCI databases or at least archetypes for temporal distinct uses (agri, non-agri) **MD**: Create further sector-specific aggregated CFs
C26	Lack of spatial data for the use of native AWARE CFs (section 4.6.1.3)	**P**: Use sector- or crop-specific spatial aggregations of the AWARE CFs when available; Use the agricultural/non-agricultural or unspecified annual aggregations; **P**: Iteratively increase the spatial resolution for processes mainly contributing to AWARE score;	**MD**: Create further sector-specific aggregated CFs

C27	Prioritize efforts between spatialization or temporalization (section 4.4)	**P**: Use the provided standard deviations to identify the dimension to prioritize as described in 7.2.4.8;	**MD**: Provide information about the impreciseness of aggregated CFs due to spatiotemporal variability which helps to prioritize practitioners' efforts.
C28	Identifying and dealing with non-marginal water use (section 4.5.1)	**P**: Compare water consumption order of magnitude for main water consuming processes to the basin's total water consumption provided in the AWARE CF files, if non-marginality seems likely;	**MD**: Improve guidelines on when to use non-marginal CFs; provide thresholds for when water consumption is not marginal;
C29	Spatializing tap water processes (section 4.6.1.3)	**P**: Investigate locations of tap water withdrawal (sometimes, approximate location is provided by water supplier) and use these; **P**: Use the location of tap water use as the location of water withdrawal; **P**: Use the existing processes in databases to regionalize processes and include the spatialized flows	**DB**: Increase the representativity of tap water processes (further regionalization)

Table 30: Challenges and recommendations linked to implementing the AWARE method – Retrieval of the correct AWARE CF and Interpretation of the AWARE score.

Nr	Challenge	Recommendation - practitioners	Recommendation – general LCA community
	Retrieving the correct AWARE CF		
C30	Possibly wrong values in automated retrieval of AWARE CFs using coordinates due to grid-cell-based AWARE input data (section **Erreur ! Source du renvoi introuvable.**)	**P**: Be aware of the issue and manually check whether the correct watersheds have been identified (Google Earth file available)	**MD**: Provide a mapping of coordinates to appropriate watersheds. Provide updated Google Earth file for AWARE.
C31	Identification of the correct watershed (section 4.6.1.3)	**P**: Aim to always record the appropriate location of collected data; With the Google Earth file provided on the WULCA website: identify the location of water use and assess which watershed would correspond to this location;	**MD**: Provide an updated Google Earth file for AWARE **MD**: Provide GIS files compatible with LCA software **SD:** Allow the use of native resolution in the calculation
	Interpretation of the AWARE score		
C32	Interpreting AWARE scores (section 4.6.4 & 4.3.3)	**P**: Use phrases similar to the ones provided in section 4.6.4 and section 4.3.3;	
C33	Interpreting AWARE scores considering their uncertainty (section 4.5.2)	**P**: Be aware of AWARE's uncertainty sources; accept and communicate indecisive results if they are indecisive; use sensitivity analyses to assess the influence of potential uncertainties; test water consumption impacts on endpoint level as well **P**: Perform data quality assessment and use an iterative approach to refine modelling	
C34	Accounting for spatiotemporal variability when using aggregated CFs (section 4.2.4)	**P**: Always use the finest spatiotemporal resolution possible; **P:** Use sensitivity analyses to assess the resulting variability (the range of possible results if using watershed instead of country values) and refine the modelling if the variability is high or prevents a conclusion;	**MD**: Provide GIS files compatible with LCA software **SD:** Allow the use of native resolution in the calculation
C35	Dealing with incomplete water use cascades, e.g. for wastewater treatment plants which seem to "generate" freshwater (section 4.6.5.4)	**P**: Use sensitivity analyses and discuss the implications of not considering the entire water use cascade; ensure a well-defined baseline scenario (in alternative scenarios, would the water withdrawal or discharge happen anyway?) **P**: In some cases, switching to cradle-to-grave systems mitigates the issue; otherwise, it could be acceptable to correct the water balance in a (well documented!) post-processing step	
C36	Lack of standalone indicators for comprehensive WF with AWARE (since AWARE only addresses water scarcity, not degradation)	**P**: Use endpoint water degradation LCIA methods to obtain a low number of indicators additional to the WSF with AWARE;	**MD**: Integrate AWARE with water degradation impact methods to provide a standalone midpoint indicator encompassing WSF and water degradation (see section 3.2.4.3)

C37	Dealing with methodological limits of AWARE (section 4.7), e.g. the neglect of inter-basin water transfers	**P**: Identify limits that might be most relevant for the study; discuss these and their potential relevance in the WSF study;	**MD**: Improve AWARE method to reduce methodological limits, provide information on these limits and their relevance

Table 31: Challenges and recommendations linked to implementing the AWARE method – Compatibility of tools with AWARE and Advanced applications of AWARE.

Nr	Challenge	Recommendation - practitioners	Recommendation – general LCA community
	Compatibility of tools with AWARE		
C38	Lack of technical know-how for using spatial data and maps	**P**: Geospatial skills are only required for watershed-level characterization; watershed identification is easily possible by loading the AWARE .kmz file into free tools such as GoogleEarth (desktop or browser)	**MD**: Provide online tools where the CFs are already integrated into maps **SD:** Allow the use of native resolution in the calculation
C39	Finding the most contributing flows when using watershed differential (section 6.3)	**P**: Always manually check whether the order of magnitude is close to the expected net freshwater consumption **P**: Compare max and min contributors to impact per elementary flow. Look at the network result to understand the net consumption	**SD**: Provide functions to assess the net elementary flow balance associated with a process **MD, DB & SD**: modify the approach to calculate water consumption
C40	Software: lacking support for seasonal elementary flow changes and monthly resolution CFs	**P**: Calculation of custom weighted annual CFs (see sections 7.2.4.7 and 4.4.1) and manual insertion of this CF in the LCA model **P**: Use an iterative approach to refine main contributors manually	**SD**: Support monthly CFs and functions to assign these to (seasonally varying) elementary flows
C41	CF weighting for custom geospatial units in LCIA software is sometimes not consumption-based (section 4.7.6)	**P**: Check the plausibility of automatically aggregated CF; Do not use automated weighting in LCA software if it is not using consumption-weighted averages; **P**: Use tested AWARE aggregations available for this case (avoid creating your version);	**MD & SD**: Work together to implement AWARE at native scale in software with the appropriate aggregation process. **SD**: Provide advanced functions for custom spatial aggregations based on water consumption weighting **MD**: Provide information on water consumption to perform the weighted average
	Advanced applications of AWARE		
C42	Modelling uncertainty of AWARE in LCA software	**P**: Use sophisticated tools such as Brightway for advanced LCA uncertainty modelling	**MD**: Provide uncertainty information for spatially and temporally aggregated CFs; **SD**: Allow for diverse sets of uncertainty distributions in LCA software **MD, DB & SD**: Modify the approach to calculate water consumption
C43	Implementing Monte-Carlo simulations for inventory uncertainty (section 6.3)	**P**: Ensure that all water consumption relevant elementary flows are parametrized	**DB**: Provide parametrized background databases where water inputs and outputs are mathematically linked **MD, DB & SD**: Modify the approach to calculate water consumption
	Implementing AWARE for edge cases		
C44	General: see section 4.6.5		

C45 (Hydropower) reservoirs: see section 7.2

8.2 Conclusion

This study, commissioned by ScoreLCA and carried out by CIRAIG, had several main objectives. The first objective was to review the state of the art of water footprint calculation with a special focus on the AWARE method for WSF and its differences and similarities with other methods and metrics (inside and outside the LCA framework). Secondly, case studies were completed to identify issues of application of AWARE with different tools and interpretation of its results. A set of recommendations was proposed based on the state of the art and the results of the case studies.

The state of the art describes the main framework to perform a WF, defined in ISO 14046, with its specificities compared to the LCA framework followed by a historic overview of the water-related categories and the development of methods up to the consensual recommendation of AWARE. A deeper description of AWARE, the calculation principles, the input data used and its implementation in LCA software is done, identifying the challenges and limitations in each step. The current practices and available tools (databases, impact assessment methods, software) were analyzed too.

Two case studies were conducted to identify issues of application and interpretation of AWARE using different tools: a reservoir, where the intended objectives were to identify the challenges of calculation linked to multifunctional processes with high spatial and temporal variability; and an industrial process producing a bio-based product, where the intended objectives were to identify the challenges linked to the data collection of an industrial site, deal with the spatiotemporal variability of agricultural processes, refine the results and to put into perspective the AWARE results to other water-related LCIA categories.

Recommendations seek to provide practitioners with elements to overcome the challenges of calculating WSF with AWARE using the tools available. Besides, recommendations for other stakeholders (method developers, inventory data developers, software developers) were provided to improve the ease and robustness of the calculations in the future. The main recommendations concern the inclusion of all the relevant information needed to calculate a water balance, including temporal and geographical data, the adaptation of the inventory to the native scale of the methods and the improvement of the tools to adapt the variability of the scales depending on the objective of the study and the available data.

In summary, this study provides a basis for a deep understanding of the calculation of WSF with AWARE, while calling for further research to refine the methods, the data needed to perform the calculation, and the tools used while providing practical recommendations to practitioners to deal with present limitations in the calculation of water footprints.

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10. Annex

10.1 Water-related LCIA methodology content

10.1.1 IMPACT World+

Note that (Bulle et al., 2019) mentions the categories of Water stream use and management and Water Availability, Resources and Ecosystem Services. However, these never became operationalized.

Impact categories covered on midpoint level:

Table 32: Midpoint impact categories related to water in IMPACT World+ (Bulle et al., 2019)

Impact category	Main reference to method	Method version
Water Scarcity	(Boulay et al., 2018)	2.0.1
	(Seitfudem et al., 2025)	2.1
Freshwater Acidification	(Roy et al., 2012, 2014)	2.0.1
	(Roy et al., 2012, 2014)	2.1
Freshwater Eutrophication	(Helmes et al., 2012; Tirado-Seco, 2005)	2.0.1
	(Helmes et al., 2012)	2.1
Freshwater Ecotoxicity	(Rosenbaum et al., 2008) and follow-ups	2.0.1
	(Rosenbaum et al., 2008) and follow-ups	2.1
Human Toxicity, cancer	(Rosenbaum et al., 2008) and follow-ups	2.0.1
	(Rosenbaum et al., 2008) and follow-ups	2.1
Human Toxicity, non-cancer	(Rosenbaum et al., 2008) and follow-ups	2.0.1
	(Rosenbaum et al., 2008) and follow-ups	2.1
Ionizing radiations	(Frischknecht et al., 2000)	2.0.1
	(Frischknecht et al., 2000)	2.1

Endpoint impact categories related to water:

Table 33: Endpoint impact categories related to water in IMPACT World+. (Bulle et al., 2019)

Impact category	Main reference to method	Method version
Water Availability, Human Health	(Boulay, Bulle, Bayart, et al., 2011)	2.0.1
	(Debarre et al., 2024)	2.1
Water Availability, Freshwater Ecosystem	(Hanafiah et al., 2011)	2.0.1
	(Hanafiah et al., 2011)	2.1
Water Availability, Terrestrial Ecosystem	(van Zelm et al., 2011)	2.0.1
	(Jasechko & Perrone, 2021; van Zelm et al., 2011)	2.1
Thermally Polluted Water	(Verones et al., 2010)	2.0.1
	(Verones et al., 2010)	2.1
Freshwater Acidification	(Roy et al., 2012, 2014)	2.0.1
	(Roy et al., 2012, 2014)	2.1
Freshwater Eutrophication	(Helmes et al., 2012; Tirado-Seco, 2005)	2.0.1
	(Helmes et al., 2012)	2.1
Freshwater Ecotoxicity (short term & long term)	(Rosenbaum et al., 2008) and follow-ups	2.0.1

Impact category	Main reference to method	Method version
	(Rosenbaum et al., 2008) and follow-ups	2.1
Human Toxicity, cancer (short term & long term)	(Rosenbaum et al., 2008) and follow-ups	2.0.1
	(Rosenbaum et al., 2008) and follow-ups	2.1
Human Toxicity, non-cancer (short term & long term)	(Rosenbaum et al., 2008) and follow-ups	2.0.1
	(Rosenbaum et al., 2008) and follow-ups	2.1
Ionizing Radiation, Ecosystem Quality	(Garnier-Laplace et al., 2009)	2.0.1
	(Garnier-Laplace et al., 2009)	2.1
Ionizing Radiation, Human Health	(Frischknecht et al., 2000)	2.0.1
	(Frischknecht et al., 2000)	2.1

10.1.2 ReCiPe2016

Table 34: Midpoint impact categories related to water in RECiPe2016 (Huijbregts et al., 2017)

Impact category	Main reference to method
Water Use	(Hoekstra & Mekonnen, 2012)
Freshwater Ecotoxicity	(van Zelm et al., 2009)
Freshwater Eutrophication	(Helmes et al., 2012)

Table 35: Endpoint ("damage") impact categories related to water in RECiPe2016 (Huijbregts et al., 2017)

Impact category	Main reference to method
Water consumption, Human Health	(Pfister et al., 2009)
Water consumption, Terrestrial Ecosystems	(Pfister et al., 2009)
Water consumption, Aquatic Ecosystems	(Hanafiah et al., 2011)
Freshwater Ecotoxicity	(van Zelm et al., 2009)
Freshwater Eutrophication	(Azevedo, Henderson, et al., 2013; Azevedo, van Zelm, et al., 2013; Helmes et al., 2012)

10.1.3 EF3.0

Table 36: Midpoint impact categories related to water in the EF3.0 (Fazio et al., 2018)

Impact category	Main reference to method
Water Use	(Boulay et al., 2018)
Ecotoxicity Freshwater	(Rosenbaum et al., 2008)
Aquatic Freshwater Eutrophication	(Struijs et al., 2013)
Acidification	(Posch et al., 2008; Seppälä et al., 2006)

10.1.4 LC-IMPACT

Table 37: Endpoint impact categories related to water in LC-IMPACT (Verones et al., 2020)

Impact category	Main reference to method
Water Stress (Human health)	(Pfister et al., 2009; Pfister & Bayer, 2014)
Human toxicity, cancer	(Fantke & Jolliet, 2016; Rosenbaum et al., 2008, 2015)
Human toxicity, non-cancer	(Fantke & Jolliet, 2016; Rosenbaum et al., 2008, 2015)
Ionising Radiation	(Frischknecht et al., 2000)
Freshwater Eutrophication	(Azevedo, Henderson, et al., 2013; Helmes et al., 2012; Scherer & Pfister, 2015)

Freshwater Ecotoxicity	(Dong et al., 2014; Gandhi et al., 2010; Rosenbaum et al., 2008)
Water Stress (Ecosystems)	(Verones, Pfister, et al., 2017)

10.1.5 GLAM (beta version)

Table 38: Midpoint impact categories related to water in GLAM (Life Cycle Initiative, 2023)

Impact category	Main reference to method
Human Toxicity	(Fantke et al., 2021; Rosenbaum et al., 2008)
Ionizing Radiation	(Paulillo et al., 2020, 2023)
Freshwater Ecotoxicity	(Douziech et al., 2024; Oginah et al., 2023; Owsianiak et al., 2023; Rosenbaum et al., 2008)

Table 39: Endpoint impact categories related to water in GLAM (Life Cycle Initiative, 2023)

Impact category	Main reference to method
Human Toxicity	(Fantke et al., 2021; Rosenbaum et al., 2008)
Ionizing Radiation	(Paulillo et al., 2020, 2023)
Water Scarcity, domestic	(Debarre et al., 2022, 2024)
Water Scarcity, agriculture	(Motoshita et al., 2018), additional paper submitted
Freshwater Eutrophication	(Zhou et al., 2023, 2024)
Water Consumption, Ecosystem Quality	(Pierrat, Barbarossa, et al., 2023)
Freshwater Ecotoxicity	(Douziech et al., 2024; Oginah et al., 2023; Owsianiak et al., 2023; Rosenbaum et al., 2008)

10.2 AWARE CFs in native resolution

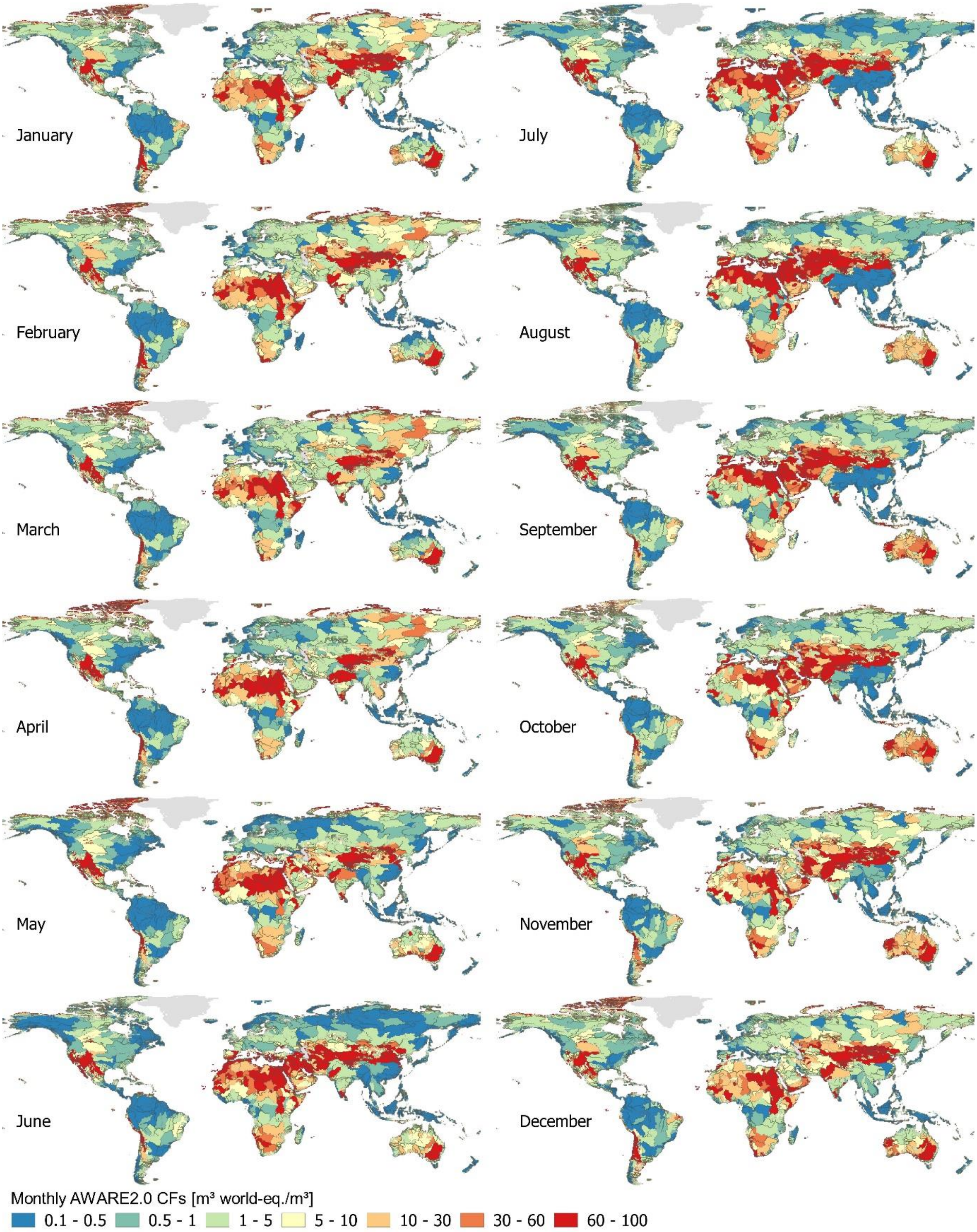


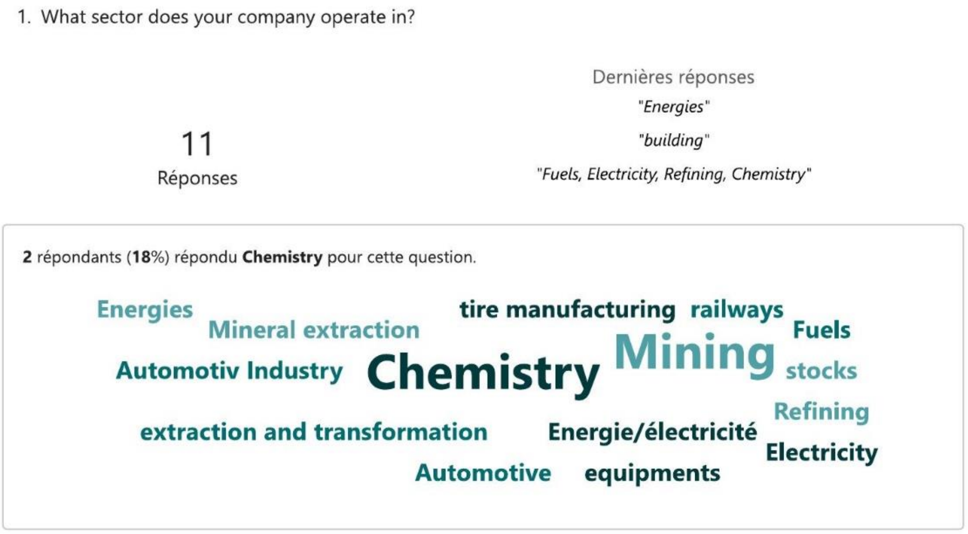
Figure 50. Map of the AWARE CFs on watershed scale in monthly resolution.

10.3 Additional material for case studies

Table 40 : Monthly AWARE score for Lake Mead's water consumption (using the Ebro watershed CFs).

		year 1		***year 2***	
	CFs [m^3 world-eq./m^3]	**netC [km^3]**	**WSF [km^3 world-eq.]**	**netC [km^3]**	**WSF [km^3 world-eq.]**
March	1.13	-0.24	-0.34	0.10	0.15
April	1.1	-0.26	-0.36	-0.01	-0.02
May	1.77	-0.34	-0.69	0.33	0.67
June	100	-0.50	-50.10	0.61	61.00
July	100	-0.15	-15.30	0.63	62.50
August	100	0.08	8.10	0.88	87.70
September	100	-0.29	-28.50	0.39	39.00
October	100	-0.09	-9.00	0.70	70.10
November	2.39	0.02	0.06	0.69	1.72
December	1.05	0.52	0.70	0.99	1.32
January	0.88	0.64	0.73	0.23	0.26
February	1.11	0.50	0.71	-0.11	-0.15
Sum	-	**-0.11**	**-94.01**	**5.43**	**324.25**

10.4 Survey answers

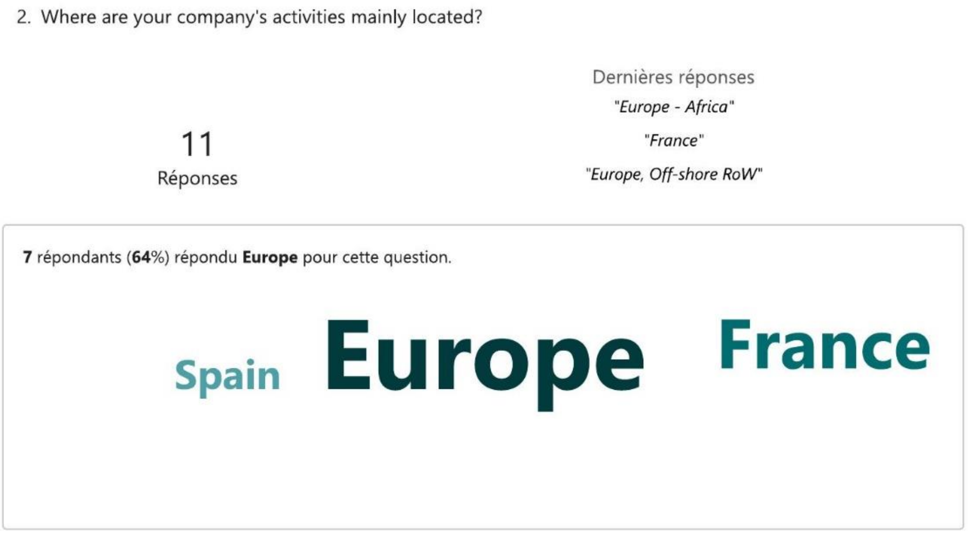


1. What sector does your company operate in?

11
Réponses

Dernières réponses
"*Energies*"
"*building*"
"*Fuels, Electricity, Refining, Chemistry*"

2 répondants (**18**%) répondu **Chemistry** pour cette question.



2. Where are your company's activities mainly located?

11
Réponses

Dernières réponses
"*Europe - Africa*"
"*France*"
"*Europe, Off-shore RoW*"

7 répondants (**64**%) répondu **Europe** pour cette question.

3. According to your knowledge,what are the main contributors to water use in your company's value chain? (direct consumption/pollution, supply chain..)

11

Réponses

Dernières réponses

"direct consumption"

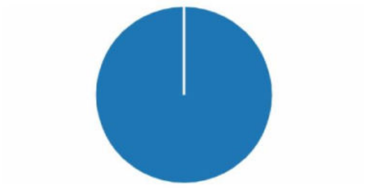
"direct consumption"

"direct consumption for our processes"

10 répondants (**91**%) répondu **direct consumption** pour cette question.

4. Does your company assess water-related issues in its operations?

● Yes	11
● No	0
● I don't know	0



5. Why does your company assess water-related issues?

● Regulatory issues	8
● SRC Reporting	5
● Internal assessment (eco-desing...	8
● Strategic decision-making	5
● Autre	2

6. What methods/tools does your company use?

🔵 Aqueduct Water Risk Atlas (WRI)	4
🟠 Corporate Water Stewardship in...	1
🟢 Global Water Tool (WBCSD)	1
🔴 Water Risk (WWF)	0
🟣 Water Footprint Network (WFN)	0
🟤 LCA-based assessment (ex: AWA...	8
● Internally developed tools	2
● Autre	4

7. Does your company collect water use data on a regular basis to apply these tools/methods?

🔵 Direct use and from supply chain	2
🟠 Only direct use	8
🟢 Only supply chain	0
🔴 No data are collected on a regul...	1
🟣 Autre	0

8. Does your company calculate or report the LCA-based water footprint of its products or activities?

🔵 Yes	8
🟠 No	1
🟢 I don't know	2

9. What is the scope of the assessment do you perform?

🔵 Product-based	9
🟠 Company-based	6
🟢 Autre	0

10. Which Life Cycle Inventory (LCI) databases do you use?

ecoinvent	8
Managed LCA Content database...	2
US LCI	0
Autre	0

11. What type of water footprint do you calculate?

Complete Water footprint (quan...	1
Water scarcity footprint (AWARE)	3
Water scarcity footprint (other t...	0
Included in LCA results (ex: as p...	7
Autre	2

12. Which LCA software do you use?

Simapro (Pre)	6
LCA for experts (Sphera)	2
Brightway	0
Autre	2

13. What do you see as the biggest challenges for implementing water footprint indicators in your company?

Data collection	8
Modeling and tools	7
Interpretation of results	4
Autre	1

14. How do you treat uncertainty in your water footprint assessments?