EPA Public Access

Author manuscript

Ecol Indic. Author manuscript; available in PMC 2018 October 17.

About author manuscripts

Submit a manuscript

Published in final edited form as:

Ecol Indic. 2017 January ; 72: 352–359. doi:10.1016/j.ecolind.2016.07.051.

Understanding the LCA and ISO water footprint: A response to Hoekstra (2016) “A critique on the water-scarcity weighted water footprint in LCA”

Stephan Pfister¹, Anne-Marie Boulay², Markus Berger³, Michalis Hadjikakou⁴, Masaharu Motoshita⁵, Tim Hess⁶, Brad Ridoutt⁷, Jan Weinzettel⁸, Laura Scherer⁹, Petra Döll¹⁰, Alessandro Manzardo¹¹, Montserrat Núñez¹², Francesca Veronesi¹³, Sebastien Humbert¹⁴, Kurt Buxmann¹⁵, Kevin Harding¹⁶, Lorenzo Benini¹⁷, Taikan Oki¹⁸, Matthias Finkbeiner³, and Andrew Henderson¹⁹

¹Institute of Environmental Engineering, Chair of Ecological System Design, ETH Zurich, 8039 Zurich, Switzerland ²CIRAIG, Sherbrooke University, Sherbrooke (QC), Canada ³Technische Universität Berlin, Chair of Sustainable Engineering, Office Z1, Straße des 17. Juni 135, 10623 Berlin, Germany ⁴Water Research Centre, School of Civil and Environmental Engineering, UNSW Australia, Sydney, NSW, 2052, Australia ⁵Research Institute of Science for Safety and Sustainability, National Institute of Advanced Industrial Science and Technology, 16-1 Onogawa, Tsukuba, Japan; m-motoshita@aist.go.jp ⁶Cranfield Water Science Institute, Cranfield University, Cranfield, Bedford, MK43 0AL, UK. t.hess@cranfield.ac.uk ⁷Commonwealth Scientific and Industrial Research Organisation (CSIRO) Agriculture, Private Bag 10, Clayton South, Victoria 3169, Australia; and University of the Free State, Department of Agricultural Economics, Bloemfontein 9300, South Africa; Brad.Ridoutt@csiro.au ⁸Charles University in Prague, Environment Center, José Martího 2, 162 00 Praha 6, Czech Republic and Czech Technical University in Prague, Faculty of Electrical Engineering, Department of Electrotechnology, Technická 2, 166 27 Praha 6, Czech Republic; phone: 00420 220 199 476, e-mail: weinzettel@seznam.cz ⁹Faculty of Earth and Life Sciences, VU University Amsterdam, The Netherlands ¹⁰Institute of Physical Geography, Goethe University Frankfurt, Altenhöferallee 1, 60438 Frankfurt, Germany; p.doell@em.uni-frankfurt.de ¹¹CESQA, Department of Industrial Engineering, University of Padova ¹²Irstea, UMR ITAP, ELSA Research Group & ELSA-PACT Industrial Chair for Environmental and Social Sustainability Assessment, 34196 Montpellier, France ¹³Department of Energy and Process Engineering, Industrial Ecology Programme, NTNU Trondheim ¹⁴Quantis, PSE D, EPFL, 1015 Lausanne, Switzerland, 0041 79 754 75 66, sebastien.humbert@quantis-intl.com ¹⁵Route de Sion 28, CH-3960 Sierre, Switzerland ¹⁶Industrial and Mining Water Research Unit (IMWaRU), School of Chemical and Metallurgical Engineering, university of the Witwatersrand, Johannesburg, Private Bag 3, WITS, 2050, South Africa, e-mail : kevin.harding@wits.ac.za ¹⁷European Commission, Joint Research Centre, Directorate of Sustainable Resources, via Enrico Fermi 2749 T.P. 270, 21027 Ispra, VA, Italy ¹⁸Institute of Industrial Science, The University of Tokyo, 1-4-6 Komaba, Meguro-ku, Tokyo 153-8505, Japan ¹⁹United States Environmental Protection Agency, Sustainable Technology

Division, Systems Analysis Branch, National Risk Management Research Laboratory, Cincinnati, OH 45268, USA

Abstract

Water footprinting has emerged as an important approach to assess water use related effects from consumption of goods and services. Assessment methods are proposed by two different communities, the Water Footprint Network (WFN) and the Life Cycle Assessment (LCA) community. The proposed methods are broadly similar and encompass both the computation of water use and its impacts, but differ in communication of a water footprint result. In this paper, we explain the role and goal of LCA and ISO-compatible water footprinting and resolve the six issues raised by Hoekstra (2016) in “A critique on the water-scarcity weighted water footprint in LCA”. By clarifying the concerns, we identify both the overlapping goals in the WFN and LCA water footprint assessments and discrepancies between them. The main differing perspective between the WFN and LCA-based approach seems to relate to the fact that LCA aims to account for environmental impacts, while the WFN aims to account for water productivity of global fresh water as a limited resource. We conclude that there is potential to use synergies in research for the two approaches and highlight the need for proper declaration of the methods applied.

Keywords

Water footprint; Life cycle assessment; Environmental product declaration; Virtual water; Green water; Blue water; Grey water

1. Introduction

The concept of water footprinting has emerged relatively recently, introduced under the terminology of virtual water (Allan, 1997) and coined as water footprint by Hoekstra and Hung (2002). It was adopted and further developed in a methodology guide (Hoekstra et al., 2011) by an NGO called the Water Footprint Network (WFN). They consider water footprint as a volumetric approach, focusing on water productivity: “The water footprint of an individual, community or business is defined as the total volume of freshwater used to produce the goods and services consumed by the individual or community or produced by the business”. In parallel, the Life Cycle Assessment (LCA) community’s vision on water resources quickly matured to integrate water use into LCA (Bayart et al., 2010), by expanding the coverage of environmental exchanges covered in LCA to include water resources. These developments in LCA have framed the main concepts in the international standard on water footprint (ISO 14046). There, the water footprint is defined as “metric(s) that quantifies the potential environmental impacts related to water” and therefore does not primarily report the volume of water used, but the potential impacts caused. Moreover, an international working group, founded under the UNEP/SETAC Life Cycle Initiative, has been fostering a methodological development to address Water Use in LCA (WULCA) and has recently achieved international consensus on a water scarcity index for use in water footprinting (Boulay et al., 2015, Boulay et al., 2016).

The fact that the two aforementioned groups use the same name to describe a slightly different water accounting approach has created debate over their relative merits and limitations. Nonetheless, a major difference is in the terminology used and communication made rather than on the fundamental principles. Ridoutt et al. (2015) recently outlined general principles for LCA-based footprints, emphasizing the importance of aggregating data only when there is environmental equivalence. Similarities, complementarities and more importantly, the difference in the metric called “Water footprint” in WFA (Water Footprint Accounting, as proposed by the WFN) and in LCA (the impact assessment metric) have already been identified in a joint publication between the two approaches (Boulay et al., 2013). Challenges in the application of these complementarities were further identified in a reply (Pfister and Ridoutt, 2013). Now, three years later, the article “A critique on the water-scarcity weighted water footprint in LCA” was published by Hoekstra (2016), the initiator and co-founder of the WFN, and current chair of the WFN Supervisory Council. Since the article contains some misinterpretation of research in the water footprint field outside of the studies affiliated with the WFN, there is an urgent need to inform readers about these issues and present a more comprehensive picture.

We therefore aim to (1) clarify any misconceptions, (2) highlight differences among the approaches and (3) provide a conclusion fostering a healthy discussion with regards to which approach provides a best fit for answering different questions.

2. What is LCA and ISO-compliant water footprint?

LCA has a long history in science as well as in practical application, which is reflected by ISO standards (ISO 14040/14044) initially published in the 1990s. It consists of four main phases: (1) Goal and Scope Definition, which includes system description and methods chosen, (2) Inventory Analysis (LCI), which accounts for all environmental exchanges, such as water use, in the product system, (3) Impact Assessment (LCIA), which assesses the potential impacts of LCI results on the environment, and (4) interpretation (Fig. 1). It is an iterative approach, where interpretation of LCI and LCIA results might lead to changes in Goal and Scope Definition, inventory results and impact assessment. The ISO water footprint (ISO 14046), which builds upon LCA principles, contains the same elements and principles, but is focused on water availability and degradation. It is important to note that there are generally two levels of impact assessment in LCA: “midpoint metrics”, which describe a potential impact in the middle of the cause effect chain (e.g. water scarcity) and “endpoint metrics”, which denote a damage occurring at the end of a cause effect chain (e.g. health or ecosystem damages resulting from water consumption). The latter obviously involves more parameter and model uncertainties, but reports more tangible results and allows for comparing and aggregating damages resulting from different environmental interventions, such as water consumption, water pollution, or greenhouse gas emissions.

In LCA, the focus is on interpreting the assessment at different levels, where accounting for water flows and related impacts are complementary steps. Assessing potential environmental impacts helps to aggregate the effects on a basis that ensures a degree of comparability across locations. Even if water consumption (LCI) and related impacts (LCIA) are sometimes correlated, this step adds to the interpretation of environmental impacts and helps

to identify major contributors to water consumption and potential impacts in a very complex product system. Thus, both steps of LCI and LCIA are important for identifying hotspots regarding environmental consequences of human use of water resources. Therefore, the statement that LCA and LCA-based water footprints chose not to assess water use itself is incorrect (Hoekstra, Section 2.2), as life cycle water use is assessed in the LCI phase.

2.1. Why account for water use: global vs. local perspective

If any type of impact assessment is applied in LCA, an impact pathway is followed by tracing the resource consumption and emission in a product system and accounting for its effects in the environment. Resources and emissions are aggregated based on similarity in the impact mechanism they cause. For example, emissions causing radiative forcing are typically aggregated based on their potential to contribute to the greenhouse effect, as it drives global climate change. In the case of a water shortage, potential damages to ecosystems and the population result, and the shortage is therefore a local problem, which is why water consumption is important in LCA. On the other hand, the argumentation by Hoekstra (2016) implies that the main goal of the WFN approach is to account for global water use as if the global water resources are limited – although there is no global fresh water shortage.

Hoekstra (2016) repeatedly states that water is a global resource because it is virtually traded via products – including between water abundant and water scarce regions. Due to this global dimension, the volumetric footprint, which expresses the global freshwater appropriation of a product, would thus represent the most meaningful indicator for decision making. Yet, this implies that, for example, the evapotranspiration of 2 m³ of soil moisture (green water) in Canada is “worse” than the consumption of 1 m³ of groundwater (blue water) used for irrigation in Morocco – regardless of local scarcity and impacts (Berger and Finkbeiner, 2013). Even though this may be correct when water is considered from a purely global perspective, this example highlights the need for additional interpretation of volumetric consumption figures – which is also acknowledged by Hoekstra on p. 571. Hence, both volumetric and impact-based footprints provide specific information that complement each other. The concepts should thus be seen as complementary rather than competing, as in the case of inventory and impact assessment in LCA of ISO-based water footprints.

Following the logic of global virtual water trade, Hoekstra (2016) recommends that water intensive goods should be produced in water abundant regions and then exported to water scarce regions. It is also argued that water-inefficient production in water rich regions, which is usually considered unproblematic in impact based water footprints, are very problematic in reality. If higher water efficiency could be achieved, this would lead to higher production yields. Since this gain in production could be exported, the need for production (and related water consumption) in water scarce countries could then be reduced. In addition to the fact that this would only be valid if water was the limiting production factor, which it is not in many cases (Nemani et al., 2003), we have some doubts on the robustness of the argumentation for global water management. It requires the assumption that either water can be efficiently redistributed from water rich to water scarce regions (such as oil or other

resources) or that trade decisions are made solely on the basis of water consumption and availability. In reality, water is principally a non-tradeable good, since its specific value is too low for long-distance transport. Additionally, factors such as land availability, food security, export income, local demand and other politically-driven decisions are often more influential on the decision of growing a crop rather than solely its water requirements, and therefore trade depends mainly on other factors (Wichelns, 2010). Some economists warn about implementing political strategies solely on the basis of virtual water trade as this may cause economically harmful decisions. In addition, developing countries should consider a variety of different aspects in addition to water when selecting paths of economic development (Wichelns, 2015). For that reason, Gawel and Bernsen (2013) go as far as to consider the concept of virtual water trade as “unspecific and inconsistent, implying governance schemes which will neither improve efficiency nor sustainability in today’s trade patterns”.

Therefore, the LCA method focuses on environmental impacts rather than on global water use. The question emerges whether or not it is possible to compare the consequences of water use in water rich and water poor regions. The answer given by the LCA community is ‘yes’, and scarcity weighted water use is such a metric. However, while this approach is very relevant when the goal is assessing potential impacts in a complex supply chain, it is definitely less robust from an epistemic viewpoint than simple accounting for water consumption, as the latter doesn’t imply a number of value choices which are instead inherently defined in non-physical metrics such as scarcity equivalents. This is a common problem of footprint metrics.

2.2. Consistency with other footprints (carbon and ecological), which include impact assessment

The comparison of LCA, WFA, and other footprints such as carbon and ecological footprint have been discussed previously (Pfister and Hellweg, 2009, Hoekstra et al., 2009, Berger and Finkbeiner, 2013, Chenoweth et al., 2014). There are several misunderstandings that need to be clarified. First, Hoekstra (2016) claims that other footprints report volumes of resource use or emissions instead of impacts. However, both the carbon footprint and the ecological footprint undergo a necessary step to make the numbers meaningful and portray a sense of harmonized impact. The carbon footprint reports not a “volume emitted” but a “mass-equivalent” in terms of cumulative radiative forcing, typically integrated over a 100 year time frame (IPCC 2013). It therefore already addresses the environmental fate of the emission as well as the impact on radiative forcing, which varies from substance to substance. The ecological footprint reports global hectares (“gha”) – a virtual land use, which is reported as a productivity-weighted land use required to assimilate the human interventions, i.e. the appropriation of “bio-capacity”. This can happen through sequestration of CO₂ emissions or actual land use of various different types, and therefore has a hypothetical (Lin et al., 2015) and normative character (Giampietro and Saltelli, 2014), indicating that we are using “1.5 Earths” to sustain our current global economy, whereas physically we only have one Earth.

Therefore, impact assessment as done in LCA is clearly related to the approaches of the carbon and ecological footprint. The reported land use or emission equivalents are not actual physical units, but impact equivalents (CO₂-eq in the case of the carbon footprint and “gha” in the case of the ecological footprint). Accordingly, the ISO water footprint standard suggests impact equivalents that reflect the pressure exerted by the water consumption on the water resources translated into a relative impact. Finally, this is in line with the general ISO definition of footprints as “metric(s) used to report life cycle assessment results addressing an environmental area of concern” (ISO 14026). Such LCA results include indicators calculated in the impact assessment phase of the LCA study, which can occur both at midpoint or endpoint level (carbon and ecological footprints are midpoint metrics). Hence, Hoekstra’s statement that other footprints are calculated on the inventory level reveals a misunderstanding of midpoint impact assessment rather than an inconsistency between carbon, ecological and ISO-compliant water footprints.

2.3. Marginal vs. non-marginal assessments and water productivity

Water footprints can be applied to a single product (or to any other points in the supply chain), an organization or total consumption of a political unit. One of the fundamental concepts of LCA is that it typically assumes a marginal change to the environment in comparison to the background situation, as it was originally designed to be product-focused. This means the underlying assumption is that a product system does not change the environmental situation significantly and therefore effects can be considered to be linear. Hence, many models in LCIA are developed based on this underlying concept and should be used as such. More recently, the desire to apply impact assessment models at a larger scale, i.e. for non-marginal changes, has emerged and has led to the adaptation of models to reflect such applications (Pfister and Bayer, 2014, Benini et al., 2015). The main difference lies in the understanding of impact assessment: when assessing a marginal contribution, the impact is assessed based on the current background situation and its current level of vulnerability to impacts. However, if a large fraction of already occurring impacts is to be assessed, such as the consumption of an entire nation, then impacts should be integrated over the entire water consumption (Pfister and Bayer, 2014). This basically accounts for the changing background situation as a function of large changes in water consumption. All of the examples given in Hoekstra (2016) actually relate to non-marginal interventions ambiguously combined with marginal characterization factors. This is not a correct application of LCA and therefore not a valid criticism because the scope of the assessment in the examples varies from the principle of LCA. Another misinterpretation in Hoekstra (2016) is the statement that water productivity is not accounted for in LCA or ISO water footprints. Productivity is inherently part of the LCI and therefore productivity is higher if the water consumption per product is lower. The example shown in Table 1 by Hoekstra (2016) assumes that all farmers in a water basin would double irrigation water productivity. Assuming this is possible, it would, as discussed above, lead to a non-marginal change and would thus need to be assessed using non-marginal characterization factors. The resulting situation would therefore also suggest that basin A has a similar footprint per unit of product as basin B in the possible solution. However, in the current situation, it already becomes obvious that basin B does not necessarily have a higher WF per product since water scarcity is higher in basin A. The

example in Table 1 by Hoekstra (2016) therefore supports the use of characterization factors (scarcity weighting).

2.4. "Squaring the footprint and being charged by the footprint of others"

In LCA impact assessment of water use, characterization factors generally do not set total water consumption in the life cycle inventory as current demand in a catchment, such as mentioned in the examples in Hoekstra (2016) – unless the whole system is analyzed under the conditions of non-marginal use which therefore requires special attention, as discussed above. Thus, no squaring of the footprint would happen in the application of LCIA methods to water footprinting. However, it is true that the water footprints of a company may increase because of suppliers' increasing water footprints, despite the company's reduced water consumption due to their own activity. This is the same for WFA because it also accounts for the whole volumetric water amounts over the life cycle in addition to the water volume directly used in a company. Therefore, a producer is charged for the footprint of others in his supply chain, which makes sense and is also the purpose of LCA. However, this does not render the WF of a company useless. The increase of the water footprints of a company regardless of their reduction achievement indicates that a company should also recognize the significance of its suppliers' activity on water consumption in terms of the responsibility as a stakeholder in the supply chain. This finding provides an opportunity to communicate with suppliers and commit to the reduction of the whole water footprint in the life cycle with cooperation between stakeholders. This is one of the most essential features of these assessments.

Furthermore, no one is "charged by the footprint of others" outside the production system, but the impacts might be higher if the production takes place in a water scarce region. In this context, there is no inconsistency between LCA and WFA approaches for the purpose of reducing pressure on water resources.

2.5. "Green" water

The concept of "green water" originates from Falkenmark (1995) and was used to partition the water used for plant growth between naturally available water from precipitation (green water) and irrigation water withdrawn from rivers and aquifers (blue water). It is typically defined as soil water that is later consumed by plant growth. One of the confusing messages in Hoekstra (2016) is that he criticizes LCA for neglecting green water use (abstract and p. 567) while later (page 571) stating that he agrees that in LCA green water impacts are best considered in the context of the land use impact category. LCA and ISO compliant water footprints do not neglect green water, as all inputs and outputs of the system being studied are explicitly included in the water footprint inventory analysis (ISO 14046; Pfister et al., 2015) and green water use and its effects have been explicitly addressed in LCA literature (e.g. Núñez et al., 2013, Quinteiro et al., 2015), as well as in case study applications (e.g. Mila' i Canals et al., 2009, Ridoutt et al., 2010, Ridoutt et al., 2012). However, in the absence of human interventions, natural vegetation would have also consumed green water. Indeed, it has been shown that land, and thereby green water, use by humans has led to reduced green water consumption compared to natural vegetation (Rost et al., 2008, Gordon et al., 2005). Although green water might be depleted by human intervention, it is only the

net change compared to a baseline condition that can be compared to blue water consumption.

Accounting for total green water consumption might lead to double-counting of impacts with land use impacts in LCA or with the ecological footprint, which should be avoided for transparent information to stakeholders. The inclusion of the net change in green water consumption compared to natural vegetation is nevertheless meaningful and part of LCA and ISO water footprint (Núñez et al., 2013, Pfister et al., 2015; ISO/AWI TR 14073). In this way the relevance of efficient green water use and management (Rockström 2009), which can reduce blue water consumption and resulting impacts, is considered in ISO based water footprints.

2.6. Assessing potential impacts based on availability

Another major difference in reasoning between the two methods is that Hoekstra (2016) assumes one's water footprint is independent of what others do in a region, whereas in LCA impact assessment the local context, and hence the intensity of the demand from other human and ecosystem users, is highly relevant. The method proposed by Hoekstra in section 3.4 in fact supports the new AWARE method proposed by the WULCA group (Boulay et al., 2015): an indicator based on the relative availability of water in a region compared to a reference region. However, in AWARE the availability is actually the remaining availability, once demand has been met, in order to account for the intensity of the current local demand (level of competition). The discrepancy between the two methods in this case lies in the indicator of local demand intensity (whether total or remaining) giving rise to subtly different water use impact implications, both of which potentially offer useful insights to account for water scarcity problems.

3. Where are the differences to the WFN approach?

Both methods follow a life cycle approach and the WFN handbook includes principally the same steps as LCA (although named differently). The difference is therefore in the application, communication and in the method development, not in the data collection. While ISO 14046 can be considered a fixed standard, it allows a considerable degree of freedom in terms of how the impact assessment is performed. The WFN has sole control of its own approach and therefore controls development of its methods. LCIA methods are largely independent from standardization and thus benefit from regular updates based on state-of-the-art knowledge. This is clearly advantageous from a scientific point of view; while LCA practitioners might prefer more lasting standardized LCIA methods for the sake of LCA's comparison, even standardization may imply a lag between state of-the-art LCIA methods and recommended ones. To this aim, the European Union (JRC, 2011, Sala et al., 2016) provides a periodic update of recommended LCIA indicators.

Another major difference between LCA and WFN water use accounting is in the communication of the results. While the WFN has often reported the water footprint as a standalone single score indicator, LCA reports a set of indicators as a result. As other environmental problems are better addressed by more specific indicators in LCA, environmental problems directly related to water use are aimed to be quantified by water use

impact assessment in LCA. This is an important difference, as it directs the discussion whether green water (evapotranspiration from soil moisture) and grey water (water quality impairment) should be part of the water footprint metric. We argue that they should not be accounted for in water footprint LCA-based metric as equal volumes, as there are other more specialized indicators such as land use, toxicity or eutrophication impacts, which cover environmental impacts associated with green and grey water. Presenting green and grey water next to these indicators would thus give rise to double-counting of impacts. We therefore suggest that they are not explicitly considered in LCA or other studies where specific indicators accounting for impacts on land, soils and water quality have been considered.

For reporting, it is most important to clarify exactly what has been done and what has not been done if a specific approach is chosen, and to provide the underlying data source in order to allow critical reviews. A public, comparative LCA report based on ISO needs an independent critical review to ensure data quality and helps to highlight important assumptions.

4. Common limitations

Water footprint or accounting methods are not meant to be used to replace water management. There exist other more holistic and comprehensive methods that are used, such as those in the research field of integrated water resource management(IWRM). LCA and WFA can be an additional piece of information or an invaluable tool (e.g. Bayer et al., 2009), but are mainly useful for hotspot assessments in broader, more complex systems, such as supply chains of products. These approaches rely on highly uncertain model outputs concerning water use and availability, and LCA involves additional uncertainty in the impact assessment phase. Improved data quality and frameworks to quantitatively account for uncertainty in a more rigorous manner is certainly an area where both approaches could benefit from.

5. Physical interpretation of water stress index and other characterization factors

Hoekstra (2016) stated that the water stress indicators by Pfister et al. (2009) and Ridoutt and Pfister (2013) lack a physical interpretation. In fact, the result of characterization in LCA is not a physical unit, but aims at quantifying a potential impact. The final result of LCA and ISO compliant water footprint includes some characterization to be applied to water use. Water consumption is included in all water footprint frameworks as an inventory (or accounting) result. These results represent physical flows, but are in most cases results of simplified global modelling. This is true for all comprehensive water consumption databases available (Mekonnen and Hoekstra, 2011, Pfister et al., 2011, Vionnet et al., 2012, Pfister et al., 2015) and therefore accounting data do not represent measured values. The impact assessment aspect attempts to relate a physical intervention (resource use or emission) to a potential environmental impact. It accounts for a common unit by which this impact can be measured. In carbon footprinting it is based on radiative forcing, in ecological footprinting

as appropriation of bio-capacity and in water footprinting different approaches have been suggested (e.g. Kounina et al., 2013).

Most LCA methods address water scarcity (midpoint), and some model potential impacts on human health or biodiversity (endpoint). While water flows can in principle be determined by physical measurement (e.g. m³ water), impacts are complex and cannot directly be measured. Therefore the main critique on the water stress index (WSI) by Pfister et al. (2009) in section 3.6 of Hoekstra (2016) is not relevant, since water scarcity cannot be “empirically tested”. In LCA, characterization factors are used to quantify potential impacts and not actual impacts in a simplified global model. Likewise, Carbon footprinting is based on a large body of research (IPCC), although results still cannot be measured or verified, since it predicts impacts on radiation over the next 100 years. The meaningful interpretation of WSI and other scarcity indicators is quite straightforward considering it is a conceptual way of addressing water scarcity. WSI is clearly described as m³ water deprivation per m³ water consumption (Pfister et al., 2009). Obviously this is not measured, as the environmental flow requirements suggested by Hoekstra et al. (2011), Hoekstra (2016) are neither: the definition of a reserve for environmental flow is a similar concept, which is actually represented by the logistic function (S-curve) of the WSI.

The main goal of characterization is to transform different inventory flows (e.g. water consumption in different locations) into environmentally equivalent flows. The new method developed by WULCA follows a similar but yet subtly different concept (Boulay et al., 2015), and applying different LCIA methods is always suggested to test robustness (the same is true for inventory/accounting results). Characterization is also required to aggregate these flows into a single number based on the ISO norm on communication of footprint information (ISO/CD 14026:2016). If no characterization factor is applied for reporting footprint results, it could be interpreted that the impact is the same everywhere and consequently the characterization factor is just one throughout. Hoekstra’s (2016) suggestion (in section 3.4 and Table 2) to consider a water footprint weighted in relation to water availability as opposed to water scarcity is, in all respects and purposes, still essentially a form of characterization to ensure comparability of the relative water use impacts in different locations.

Finally, impact assessment follows a line of argumentation with an underlying quantitative model, which is accepted standard in LCA (Hellweg and Milà i Canals, 2014), and required for any quantitative impact assessment. It is therefore not “madness” if research results provide an impact assessment method to relate water consumption to malnutrition (and related DALYs). The mechanism even includes the trade effect (Motoshita et al., 2014) that Hoekstra (2016) wrongly reports as missing. Obviously, this includes many uncertainties; however it allows comparing different impacts within an LCA framework (e.g. toxic emissions to water, and the DALYs that result from these emissions). The wealth of LCA approaches in terms of characterizing results to a common unit for relative impact assessment reflects the notion that characterization should reflect the hypothesis being tested. As long as the ultimate aim of any study is to achieve improved environmental efficiency or impact minimization, characterization cannot be criticized for altering the volumetric nature of the water footprint. This is not meant to be taken as true value, but it

represents a more damage-oriented method to combine emissions and water consumption impacts than for instance the “grey water” concept (Ridoutt and Pfister, 2013). Finally, biodiversity loss is not related to WSI, but follows a different concept, assessing NPP limitation by water resource (Pfister et al., 2009), impacts of groundwater level drawdown (van Zelm et al., 2011), desiccation of wetlands (Verones et al., 2013) or reduced river flows (Tendall et al., 2014).

6. Conclusions

In this paper we have one important difference between LCA/ISO water footprint and WFN water use accounting, which appear to be at the heart of the disagreement between the two groups: While LCA aims to account for environmental damage and the deprivation caused by water use, it seems that the WFN aims to account for water productivity as global fresh water is a limited resource, and opts for a subsequent, optional sustainability assessment of the water consumed.

There is no need to argue for a right or wrong method or even madness of research output. Most importantly and the mutual scope of both approaches is to study a system and learn about its improvement potentials. Both approaches provide information to the stakeholders and decision makers. ISO water footprint and LCA allow this for a manufacturing, organizational, consumer and (with non-marginal factors) territorial focus.

In order to clarify the misunderstandings, we provide a concluding response to the six main issues raised by Hoekstra (2016):

1. “counting litres of water use differently based on the level of local water scarcity obscures the actual debate about water scarcity, which is about allocating water resources to competing uses and depletion at a global scale”

Since water is a non-tradeable good, there is no global competition for water at a specific location. This is a main difference to other resources, such as oil. If we want the water footprint to re-allocate water use away from water scarce regions, we need to reflect water scarcity within the indicator. Otherwise, it may only help to minimize total water consumption, but the environmental impacts globally might be higher than if we optimize for water scarcity or another indicator of impacts.

2. “the neglect of green water consumption ignores the fact that green water is scarce as well”

We agree that “green water” can be locally scarce too, but it should be carefully discussed, especially if the water footprint indicator is used in combination with a land use indicator which better reflects the land occupation and therefore appropriation of soil moisture. This is the case in LCA and also if WF is combined with ecological footprint, or other land footprint concept. Otherwise the land occupation is double counted. In any case it should be reported separately.

3. “since water scarcity in a catchment increases with growing overall water consumption in the catchment, multiplication of the consumptive water use of a specific process or activity with water scarcity implies that the resultant weighted

WF of a process or activity will be affected by the WFs of other processes or activities, which cannot be the purpose of an environmental performance indicator”

Since water availability is a flow (e.g. m³/year) scarcity is driven by competition for this resource. The more water is consumed, the scarcer it becomes (e.g. groundwater level drops further down and limits access to other users or plants). Therefore, using water in an already scarce situation is more damaging, since the system is in a more critical state and therefore we argue that environmental performance indicator should include the current local conditions as that is closer to reality even though they may be affected by other stakeholders.

4. “the LCA treatment of the WF is inconsistent with how other environmental footprints are defined”

Actually, the criticized definition is exactly in line with the ISO standards on the water footprint and the general communication of footprint information. Furthermore, it is compatible with the prominent carbon and ecological footprint definitions.

5. “the Water Stress Index, the most cited water scarcity metric in the LCA community, lacks meaningful physical interpretation.”

The physical interpretation is given as the amount of water downstream users are lacking as a function of water consumption. However, it is not the result of a physical model, but an empirical equation. The same is true for “gha” used in ecological footprint or the blue water scarcity index provided by the WFN. Finally, it is a weighting factor to reflect local water scarcity.

6. “It is proposed to incorporate the topic of freshwater scarcity in LCA as a ‘natural resource depletion’ category, considering depletion from a global perspective.”

LCA Literature addressed this topic in the above cited publications: there are deposits (e.g. fossil aquifers) and flow resources. Deposits are quantified by natural resource depletion such as done for oil consumption. However, ecosystem can be destroyed even without depletion of water, due to the fact that water is vital for life. Based on Steffen et al. (2015), water resources are not critical from a global perspective, but related damages on biodiversity are. Therefore, the environmental concern includes the impacts of water consumption and not just the depletion of water resource as such.

Having devoted nearly the entirety of this paper to clarifying misinterpretations, we would still like to highlight the similarities between the water footprint approaches and focus our attention on our common goal, namely to develop methods and tools to enable analysis of water use and to provide the necessary information to support stakeholders and decision makers in their fight against global water scarcity. Despite its volumetric focus, the WFN also acknowledges the need for additional interpretation of local water use pressures and provides so-called water footprint impact indexes, which are, in fact, similar to characterization models developed by LCA researchers. To illustrate compatible applications, the ISO/TR 14073 also includes an example based on the WFN approach. Since LCA, by definition, analyses environmental impacts resulting from emissions and resource consumption, it inherently focuses on the development of impact assessment

methods, allowing for a comprehensive interpretation of water consumption in addition to traditional impact categories such as global warming or toxicity. Nevertheless, there is no doubt that the volumetric water footprint inventory remains the basis of every impact assessment and an important component of the ISO based water footprint. Hence, both communities have a lot in common but maintain different viewpoints.

In closing, we therefore argue that the two communities would achieve a more tangible contribution in mitigating global water stress when working together to harness the benefits of diversity and complementarity in their respective approaches.

Acknowledgements

The views expressed in this article are those of the authors and do not necessarily represent the views or policies of the US Environmental Protection Agency. We thank Christie Walker for proof-reading the final manuscript.

References

- Allan T (1997) “Virtual water”: a long term solution for water short Middle Eastern economies?
- Bayart J-B, Margni M, Bulle C, et al. (2010) Framework for assessment of off-stream freshwater use within LCA. *Int J Life Cycle Assess* 15:439.
- Bayer P, Pfister S and Hellweg S (2009). Indirect water management: How we all can participate. IAHS-AISH Publication.
- Benini L, Boulay A-M, Sala S (2015) Cross-scale consistency in life-cycle impact assessment: the case of water scarcity. In: SETAC Europe 25th Annual meeting.
- Berger M and Finkbeiner M (2013). “Methodological challenges in volumetric and impact oriented water footprints.” *Journal of Industrial Ecology* 17(1): 79–89.
- Boulay A, Hoekstra AY, Vionnet S (2013) Complementarities of Water-Focused Life Cycle Assessment and Water Footprint Assessment. *Environ Sci Technol* 47:11926–11927. doi: 10.1021/es403928f. [PubMed: 24147821]
- Boulay A-M, Bare J, Benini L, et al. (2016) The WULCA consensus characterization model for water scarcity footprints: Assessing impacts of water consumption based on available water remaining (AWARE).
- Boulay A-M, Bare J, De Camillis C, et al. (2015) Consensus building on the development of a stress-based indicator for LCA-based impact assessment of water consumption: outcome of the expert workshops. *Int J Life Cycle Assess* 20:577–583. doi: 10.1007/s11367-015-0869-8.
- Chenoweth J, Hadjikakou M, & Zoumides C (2014). Quantifying the human impact on water resources: a critical review of the water footprint concept. *Hydrology and Earth System Sciences*, 18(6), 2325–2342.
- Deurer M, Green SR, Clothier BE, and Mowatt A (2011). Can product water footprints indicate the hydrological impact of primary production? – A case study of New Zealand kiwifruit, *J. Hydrol*, 408, 246–256.
- Falkenmark M. Land-water linkages: a synopsis. Land and water integration and river basin management; Proceedings of an informal FAO workshop; Rome. 31 January- 2 February 1993; 1995. 15–17. FAO Land and Water Bulletin 1, Rome.
- Gawel E & Bernsen K (2013) What is Wrong with Virtual Water Trading? On the Limitations of the Virtual Water Concept. *Environment and Planning C: Government and Policy* 31(1):161–188.
- Giampietro M, & Saltelli A (2014). Footprints to nowhere. *Ecological Indicators*, 46, 610–621.
- Gordon L, Steffen W, Jönsson BF, Falkenmark M and Johannessen Å. (2005). Human modification of global water vapour flows from the land surface. *Proc. Nat. Acad. Sci. of USA* 102(21) 7612–7617. [PubMed: 15890780]
- Hellweg S and Milà i Canals L (2014). “Emerging approaches, challenges and opportunities in life cycle assessment.” *Science* 344(6188): 1109–1113. [PubMed: 24904154]

- Hoekstra AY and Hung PQ, (2002). Virtual water trade: a quantification of virtual water flows between nations in relation to international crop trade. Value of Water Research Report Series No.11, IHE, the Netherlands.
- Hoekstra AY, Gerbens-Leenes W and van der Meer TH (2009). "Reply to Pfister and Hellweg: Water footprint accounting, impact assessment, and life-cycle assessment." Proceedings of the National Academy of Sciences 106(40): E114.
- Hoekstra AY, Chapagain Ashok K., Aldaya MM, Mekonnen MM (2011) The water footprint assessment manual: Setting the global standard. Earthscan.
- Hoekstra AY (2016). "A critique on the water-scarcity weighted water footprint in LCA." Ecological Indicators 66: 564–573.
- JRC (2011) European Commission-Joint Research Centre - Institute for Environment and Sustainability: International Reference Life Cycle Data System (ILCD) Handbook- Recommendations for Life Cycle Impact Assessment in the European context. First edition 11 2011 EUR 24571 EN. Luxembourg Publications Office of the European Union; 2011.
- Kounina A, Margni M, Bayart J-B, Boulay A-M, Berger M, Bulle C, Frischknecht R, Koehler A, Milà i Canals L, Motoshita M, Núñez M, Peters G, Pfister S, Ridoutt B, Zelm R, Verones F and Humbert S (2013). "Review of methods addressing freshwater use in life cycle inventory and impact assessment." The International Journal of Life Cycle Assessment 18(3): 707–721.
- Lin D, Wackernagel M, Galli A and Kelly R (2015). "Ecological Footprint: Informative and evolving – A response to van den Bergh and Grazi (2014)." Ecological Indicators 58: 464–468.
- Milà i Canals L, Chenoweth J, Chapagain A, Orr S, Antón A, Clift R, (2009). Assessing freshwater use impacts in LCA. Part 1. Inventory modelling and characterisation factors for the main impact pathways. International Journal of Life Cycle Assessment 14 (1), 28–42.
- Mekonnen MM and Hoekstra AY (2011). National water footprint accounts: the green, blue and grey water footprint of production and consumption, Value of Water Research Report Series Delft, the Netherlands, UNESCO-IHE 50.
- Motoshita M, et al., (2014). Consistent characterisation factors at midpoint and endpoint relevant to agricultural water scarcity arising from freshwater consumption. Int. J. Life Cycle Assess. In press. DOI: 10.1007/s11367-014-0811-5.
- Nemani RR, Keeling CD, Hashimoto H, Jolly WM, Piper SC, Tucker CJ, Myneni RB and Running SW (2003). "Climate-driven increases in global terrestrial net primary production from 1982 to 1999." Science 300(5625): 1560–1563. [PubMed: 12791990]
- Núñez M, Pfister S, Roux P and Antón A (2013). "Estimating Water Consumption of Potential Natural Vegetation on Global Dry Lands: Building an LCA Framework for Green Water Flows." Environmental Science & Technology 47(21): 12258–12265. [PubMed: 24094293]
- Pfister S, Koehler A and Hellweg S (2009). "Assessing the Environmental Impacts of Freshwater Consumption in LCA." Environmental Science & Technology 43(11): 4098–4104. [PubMed: 19569336]
- Pfister S, Bayer P, Koehler A and Hellweg S (2011). "Environmental Impacts of Water Use in Global Crop Production: Hotspots and Trade-Offs with Land Use." Environmental Science & Technology 45(13): 5761–5768. [PubMed: 21644578]
- Pfister S and Ridoutt BG (2013). "Water Footprint: Pitfalls on Common Ground." Environmental Science & Technology 48(1): 4–4. [PubMed: 24344838]
- Pfister S and Bayer P (2014). "Monthly water stress: spatially and temporally explicit consumptive water footprint of global crop production." Journal of Cleaner Production 73(0): 52–62.
- Pfister S, Vionnet S, Levova T and Humbert S (2015). "Ecoinvent 3: assessing water use in LCA and facilitating water footprinting." The International Journal of Life Cycle Assessment: 1–12.
- Quinteiro P, Dias AC, Silva M, Ridoutt BG and Arroja L (2015). "A contribution to the environmental impact assessment of green water flows." Journal of Cleaner Production 93: 318–329.
- Ridoutt BG, Juliano P, Sanguansri P and Sellahewa J (2010). The water footprint of food waste: case study of fresh mango in Australia. Journal of Cleaner Production 18:1714–1721.
- Ridoutt BG, Sanguansri P, Freer M, Harper GS. (2012). Water footprint of livestock: comparison of six geographically defined beef production systems. International Journal of Life Cycle Assessment 17:165–175.

- Ridoutt B and Pfister S (2013). "A new water footprint calculation method integrating consumptive and degradative water use into a single stand-alone weighted indicator." *The International Journal of Life Cycle Assessment* 18(1): 204–207.
- Ridoutt BG, Pfister S, Manzardo A, Bare J, Boulay A-M, Cherubini F, Fantke P, Frischknecht R, Hauschild M, Henderson A, Jolliet O, Levasseur A, Margni M, McKone T, Michelsen O, Milà i Canals L, Page G, Pant R, Raugei M, Sala S and Verones F (2015). "Area of concern: a new paradigm in life cycle assessment for the development of footprint metrics." *The International Journal of Life Cycle Assessment* 21(2): 276–280.
- Rost S, Gerten D, Bondeau A, Lucht W, Rohwer J and Schaphoff S (2008). "Agricultural green and blue water consumption and its influence on the global water system." *Water Resources Research* 44(9).
- Sala S, Benini L, Castellani V, Vidal-Legaz B, Pant R (2016) Environmental footprint - Update of Life Cycle Impact Assessment methods; DRAFT for TAB: resources, water, land.
- Steffen W, et al. (2015) Planetary boundaries: Guiding human development on a changing planet. *Science* 347(6223) doi:10.1126/science.1259855.
- Tendall DM, Hellweg S, Pfister S, Huijbregts MAJ and Gaillard G (2014). "Impacts of River Water Consumption on Aquatic Biodiversity in Life Cycle Assessment – a proposed method, and a case study for Europe." *Environmental Science & Technology*.
- Verones F, Saner D, Pfister S, Baisero D, Rondinini C and Hellweg S (2013). "Effects of Consumptive Water Use on Biodiversity in Wetlands of International Importance." *Environmental Science & Technology* 47(21): 12248–12257. [PubMed: 24087849]
- Vionnet S, Lessard L, Offutt A, Levova T, Humbert S (2012) Quantis water database—technical report Quantis International, Lausanne.
- Wichelns D (2010). Virtual water: A helpful perspective, but not a sufficient policy criterion. *Water Resources Management*, 24(10), 2203–2219.
- Wichelns D (2015) Virtual Water and Water Footprints: Overreaching Into the Discourse on Sustainability, Efficiency, and Equity. *Water Alternatives* 8(3):396–414.
- van Zelm R, Schipper AM, Rombouts M, Snepvangers J, Huijbregts MAJ 2011 Implementing groundwater extraction in life cycle impact assessment: characterization factors based on plant species richness. *Environmental Science and Technology*, 45: 629–635. [PubMed: 21121675]

Fig. 1.
LCA framework including the relevant steps for water footprint (based on ISO 14040).