

A review of two different methods for the estimation of water footprint of crops

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Abstract: The rapid increase in world population has increased the demand of food and biofuels leading to stress on water resources and increase in competition between different sectors around the globe. Under the combined impacts of climate change, population growth, urbanization and economic development, the pressure on the water resources is continually increasing. Therefore, an appropriate approach is required for effective water accounting. Water footprint concept has been introduced to indicate the water use and impact of production systems on water resources. In this study, two different approaches for the estimation of water footprint of crops have been reviewed, i.e. the Water Footprint Network (WFN) approach and Life Cycle Assessment (LCA). These approaches are used in many countries and numerical models have been developed to facilitate the calculations. By clarifying the concerns about water accounting, we identify that the main differing perspective between the WFN and LCA approaches is that LCA aims to account for the environmental impacts related to water resources, while WFN aims to account for water productivity of global fresh water as a limited resource. We conclude that the WFN approach could benefit from considering the impact assessment methodologies evolving within the LCA community and joint efforts could lead to some consensual metrics to better assess the sustainability of freshwater use.

Keywords: Water footprint, life cycle assessment, water footprint network, water scarcity, environmental impacts

INTRODUCTION

Due to the population growth, the production demand for the goods is continuously increasing (Rockstrom *et al.*, 2013). The population of the world could reach about 9.3 billion in 2050 according to an estimate of the United Nations (United Nations, 2011). Today, the water crisis is one of the top-ranking environmental risks due to the failure in mitigating and adapting to climate change. Climate change can contribute to creating disturbance in the hydrological cycle, thereby causing an increase in the frequency of floods and droughts which can ultimately be a source of water stress (World Economic Forum, 2017). Agriculture is one of the most important sectors consuming around 70% of the total freshwater in the world. The meteorological effects due to the changing climate can lead to an increase in the irrigation water demand causing an increasing pressure on the freshwater resources (Bocchiola, 2015; Gheewala *et al.*, 2014).

Adequate quantity of freshwater with sufficient quality is a fundamental resource for all ecological and societal activities including food production, industrial activities and human sanitary conditions (Bayart *et al.*, 2010). The growing body of research on water use, scarcity and pollution in relation to consumption, production and trade has led to the emergence of the field of water assessment (Su *et al.*, 2015). Currently, about one third of the world's

population is threatened by the lack of freshwater to meet their daily needs; and furthermore, increased water scarcity is expected in the future in many regions due to a variety of factors such as the population growth, climate change, urbanization, and changing lifestyles. It is anticipated that water withdrawal, especially for agriculture, will increase by 50% in developing countries by 2025, and 18% in developed countries (Gheewala *et al.*, 2013).

According to the Intergovernmental Panel on Climate Change (IPCC), an increasing trend is revealed in the average annual temperature i.e. between 0.6-1.1°C, as well as a decrease in the average annual rainfall volume by 4% in 2020 compared to 2000 levels. In future, the changing climatic pattern i.e. increase in temperature and less rainfall, is predicted to accelerate the global hydrological cycle, a change in the intensity and the frequency of rainfall and evapotranspiration rates. Consequently, it may increase the intensity of floods and droughts with substantial impact on water resources at the local and regional levels (Roachdane *et al.*, 2012). According to IPCC, water availability and quality will be the main issues for societies and the environment under the climate change impact. Due to climate change, the water shortage will increase in future, the natural water storage capacity will decrease due to glacier melts and the vulnerability of ecosystems will increase because of rise in temperature and change in precipitation patterns.

Also, the water demand in agriculture will increase for irrigation purposes due to prolonged dry periods and severe droughts (United Nations, 2009). So, it is necessary to find an appropriate approach for water accounting to assess the water use by the crops and its impacts on the environment.

There are basically two approaches of evaluating water footprint. The first approach was proposed by the water footprint network (WFN) and the other one is based on the approach of life cycle assessment (LCA). Water footprint (WF), as defined by WFN, “is an indicator of water use efficiency which refers to the volume of freshwater requirement for all production processes”. The WF approach of the WFN will be henceforth referred to in this article as WF-WFN. WF-WFN divides the water into three components, viz., green (the volume of rainwater consumed during production processes), blue (the volume of surface and ground water consumed during production processes), grey (the volume of freshwater required to assimilate the load of pollutants) (Marrison & Schulte, 2010).

Research and resulting scientific literature on the water footprint concept has been growing very fast during the last few years (Marrison & Schulte, 2010). Focusing on the volumetric WF indicator, as outlined above, does not directly provide information about the actual water use and its impacts. In parallel to WFN, the life cycle assessment (LCA) community has proposed their approach on assessing the water footprint. LCA is a decision-support approach that has primarily been used for three kinds of decisions: Engineering decisions for product and process improvement, policy decisions at the company and government level, environmental purchase and sales decisions (Boulay et al., 2013). The developments of the main concepts on water assessment in LCA have been framed in the international standard on water footprint (ISO 14046). LCA studies report the total amount of water used by the production system, from cradle (raw material acquisition) to grave (waste management) as the water inventory. In the LCA approach, water footprint is “the quantification of the environmental impacts related to water” and therefore does not primarily report the volume of water used, but the potential impacts caused thereof (Pfister et al., 2017). The WF approach of LCA will be henceforth referred to in this article as WF-LCA.

There have been many studies conducted on water accounting according to the WFN as well as LCA approach. Chapagain et al. (2006) conducted a study on the WF-WFN assessment of cotton. The results showed that cotton is responsible for about 2.5% of the total water use worldwide and about 80% of total water footprint of cotton production in Europe results in major impacts in India and Uzbekistan (Chapagain et al., 2006). Mekonnen & Hoekstra (2011) conducted a study to assess the WF-WFN of agricultural crops, and the largest blue water footprint was found for rice and wheat contributing around 45% of the total water consumed in the world (Mekonnen & Hoekstra, 2011). Mekonnen & Hoekstra (2012) conducted another study to

assess the WF-WFN of farm animal products and found that the animal products (milk, eggs and meat) have a larger blue and grey water footprint than crop products having equivalent nutritional value. Page et al. (2011) performed a study to assess the water scarcity caused by tomato production in the Sydney market and found that the water scarcity is more in Sydney than other areas of its production i.e. Queensland and New South Wales tableland. A life cycle assessment-based study was conducted by Cha et al. (2017) to assess the WF-LCA of white radish for the spring and autumn cultivation in Korea. The results showed that the autumn cultivation is better than other cultivation types due to its lower water use impacts. Many other similar studies were conducted for the impact assessment of water use. Hess et al. (2014) conducted a study on potato production to assess the water scarcity in Great Britain. The results showed higher values of water scarcity index in the East of England as compared to other regions of Great Britain e.g. Scotland, because most of the water requirements in Scotland are met by rainfall. The East of England is found to contribute the largest share to the national blue water consumption, and 62% of water consumed from water resources which are over-abstracted. A study focusing on freshwater use impacts from oil palm-based biodiesel production, based on LCA approach, in different regions of Thailand was conducted by Nilsalab et al., 2016. The results showed that more water was extracted in the central region than the southern and eastern regions to fulfill the crop water requirement due to which the deprivation potential of water found to be higher in the central regions of Thailand.

The aim of this study is to compare the two major approaches of water footprint assessment to better understand and estimate the water accounting in a production process.

METHODOLOGY

Water footprint was originally developed as an approach for water resource management and is currently well-established as a leading methodology in this field (Marrison & Schulte, 2010). Different researchers used different methods for the estimation of water footprints of crops. The current methods for the estimation of water footprint have different histories, intended objectives and outputs (Berger & Finkbeiner, 2010). WF-WFN is the volumetric measure of water appropriation by capturing the volume, location and timing of water uses and discharges. WF-WFN assessment is divided into four stages as follows:

- 1) Setting goals and scope (setting the boundaries of assessment)
- 2) WF-WFN accounting (water uses are measured by volume)
- 3) WF-WFN sustainability assessment (impact assessment to compare water use with local water availability data)
- 4) WF-WFN response formulation (response options such as strategies, targets, or policies are formulated).

According to the framework of WFN approach, the total water consumed by a certain product is assessed by Equation 1.

$$WF_{total} = WF_{blue} + WF_{green} + WF_{grey} \quad (1)$$

Where, WF_{total} is the total amount of water consumed, WF_{blue} (blue WF) is the amount of surface and ground water used, WF_{green} (green WF) is the amount of rain water used and WF_{grey} (grey WF) is the amount of water to assimilate the loads of pollutants to produce one unit of a certain product (Mohlotsane *et al.*, 2018; Hoekstra *et al.*, 2011; Chapagain & Orr, 2009; Ababaei & Etedali, 2014). The blue, green and grey WF-WFN can be calculated by using Equations 2, 3 and 4 respectively.

$$WF_{blue} = \frac{WU_{blue}}{Y} \quad (2)$$

$$WF_{green} = \frac{WU_{green}}{Y} \quad (3)$$

$$WF_{grey} = \frac{(\alpha \times AR)}{Y} / \frac{(C_{max} - C_{nat})}{Y} \quad (4)$$

Where, WU_{blue} is the sum of surface and ground water used (m^3), WU_{green} is the total rain water used (m^3), Y is the yield of the product (tonnes), α is the leaching runoff fraction of a chemical, AR is the application rate of a chemical to the field (kg/ha), c_{max} and c_{nat} is the maximum acceptable and natural concentration (kg/m^3) of the pollutant, respectively, whose assimilation is required (Hoekstra *et al.*, 2011).

Rather than considering a single environmental resource (i.e., water) as focused in the WFN approach, the LCA approach considers the environmental load related to the water use and the impacts of water use due to emissions causing the resource pollution. LCA is also typically comprised of four basic stages and it deals with a more comprehensive process than the strict water related measurements as considered in water footprinting. The four stages are as follows:

- 1) Goal and scope (establishment of system boundaries to be assessed i.e., the determination of what is being measured and a measure of the product or service being assessed)
- 2) Life cycle inventory (the measurement of environmental inputs and outputs e.g., the volume or mass of the contaminants released to the waterways are captured)
- 3) Life cycle impact assessment (to transform the environmental inputs and outputs into the potential environmental impacts e.g., contribution to global warming, fresh water depletion, human health concerns, etc.)
- 4) Interpretation (to translate the environmental impacts which are determined in the life cycle impact assessment into meaningful conclusions and recommendations to improve the environmental performance of the product or service) (Kloppfer & Grahl, 2014).

In the LCA approach, the irrigation water used to produce a specific product and the water stress index (WSI) of the watershed from where the irrigation water is withdrawn are used to assess the water use impact i.e. deprivation potential (Silertruksa *et al.*, 2017; Pfister *et al.*, 2009). WSI is the ratio of the freshwater withdrawal on an annual basis to its availability within the basin (Pfister *et al.*, 2009). The water stress index can be determined based on Equation 5.

$$WSI = \frac{1}{(1+e^{-6.4 \cdot WTA^*}) (1/0.01-1)} \quad (5)$$

Where; WSI is the water stress index, WTA^* is the modified hydrological withdrawal to availability ratio of a specific basin (Pfister *et al.*, 2009; Gheewala *et al.*, 2017).

The deprivation potential of water (water scarcity footprint) comes under the impact assessment phase of LCA and is measured in $m^3H_2O_{eq}$; it describes the deficiency of water at downstream level of a basin, not available for human consumption and the ecosystem. The deprivation potential of water is an important tool to assess the water use impacts on human beings and ecosystems. The related water use impact is less with a lower value of water scarcity footprint and vice versa (Silertruksa *et al.*, 2017; Gheewala *et al.*, 2017). The deprivation potential of water can be determined by using the Equation 6.

$$\text{Water deprivation potential} = WSI \times \text{Irrigation water use} \quad (6)$$

$(m^3H_2O_{eq})$

RESULTS AND DISCUSSION

The review of the two methodologies, WF-WFN and WF-LCA, helped in better understanding about the concept of water footprint. Nowadays many researchers use the LCA approach for the estimation of water footprint due to its wide applications and characterization of the impact of water use. The decision about the estimation method also depends upon the study objectives.

According to the WFN approach, the water accounting is done in terms of volume. This approach can be helpful to assess the amount of water used during the production process of a product where the water is used, and what type of water is used. But this approach does not give information about the stress level of a water body due to the water use. On the other hand, the LCA approach to water accounting gives an estimation of water scarcity occurring during the time of its use in a certain watershed as well as includes other impacts related to the deterioration of water quality. The LCA approach gives an estimation of the water stress level in a water body on a seasonal basis as the availability of water may change with the variation in the rainfall with the changing seasons. So, the LCA approach provides information about the regional hydrologic

Table 1: Summary of scope and structure of LCA and WFN (Marrison & Schulte, 2010).

Criteria	Water Footprint Network	Life Cycle Assessment
Definition	<ul style="list-style-type: none"> Measures the total volume of freshwater used to produce the products 	<ul style="list-style-type: none"> LCA quantifies the environmental impacts related to the water use of a given product from the cradle to grave
Scope	<ul style="list-style-type: none"> Measurement of corporate water use Measures the consumptive use of water (evaporated water) 	<ul style="list-style-type: none"> Evaluates the environmental resource uses and emissions, not only limited to water Measures both consumptive and non-consumptive uses of water
Structure and Output	<ul style="list-style-type: none"> The results are provided in actual volumes 	<ul style="list-style-type: none"> The results can be shown in different impact categories
Origins	<ul style="list-style-type: none"> Corporate water accounting calculations and impact assessment methods 	<ul style="list-style-type: none"> A well-recognized broad method for environmental assessment of product and regional systems

condition of a watershed based on the difference in the seasonal precipitation (Sala *et al.*, 2013).

The scope and the structure of both WF-WFN and WF-LCA are explained in Table 1. According to Hoekstra (2016), the main goal of WF-WFN is to account for global water use as if the global resources are limited although there is no global freshwater shortage. WF-LCA on the other hand, produces a single number for each impact category which seeks to describe the potential impact (e.g. on water scarcity) across the life cycle. Most LCA methods address water scarcity and some model potential impacts on human health or biodiversity. While water flows, in principle, can be determined by physical measurement, impacts are complex and cannot directly be measured (Pfister *et al.*, 2017).

About data availability, the WF-LCA offers a systematic approach to calculate water requirements by crops, which could be used by LCA practitioners. Beyond the farm boundaries, however, there is a general lack of data on water consumed by products and services. In this context, the LCA databases can be used which focus on water abstraction though lacking details required to assess impacts on water resources. The growing interest in water by the LCA community is, however, driving the improvement of existing inventory databases (Jefferies *et al.*, 2012). The two methods which are discussed in this paper show different scopes regarding type of water and water use accounted for, as well as inclusion of spatial and quality information.

CONCLUSION AND RECOMMENDATIONS

Water is an essential resource of nature and its demand is increasing with the population growth, urbanization and economic development. Many studies have been performed in the past for water accounting. This study was performed to compare the two methods of water accounting i.e. Water Footprint Network (WFN) approach and Life Cycle Assessment (LCA) approach. The study will help decision

makers to understand the LCA and WFN approaches for calculations of volumetric freshwater use, water stress index, and water scarcity footprint as a tool for enhancing sustainable cultivation of crops in different regions in view of water sustainability. WFN could benefit from considering the impact assessment methodologies evolving within the LCA community and joint efforts could lead to some consensual metrics to better assess the sustainability of freshwater use. The review of both methodologies helped in better understanding the concept of water footprint. Spatial and temporal resolutions depend upon availability of data and software modeling capabilities. The three areas of protection in LCA i.e. human health, ecosystem quality and available resources, are affected much by freshwater consumption. So, the calculations of freshwater consumption must consider both freshwater withdrawal and freshwater release after it is used. Both LCA and WFN have their own advantages and disadvantages, but selection should be done based on previous studies, available data and purpose of the study and desired output from the study.

The estimation of water scarcity in LCA could be improved if we would account for the effect of dams and interbasin water transfers. In cases where dams smoothen surface and ground water availability, we may have overestimated blue water scarcity in the dry months to which water is carried over from previous wetter months. In cases where inter-basin water transfers are very substantial, we may have underestimated the water scarcity in the basins from which the water is taken and overestimated it in the basins where it is going to.

It is recommended to use the life cycle assessment approach to water accounting as it provides potential impacts related to the water at the time of its use. It can address the regional and seasonal scarcity of water in the watershed and evaluates the environmental impacts related to indirect use of water to address the resource quality in terms of different impact categories (eutrophication, acidification, etc.).

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