COMPARING THE USEFULNESS AND APPLICABILITY OF DIFFERENT WATER FOOTPRINT METHODOLOGIES FOR SUSTAINABLE WATER MANAGEMENT IN AGRICULTURE†

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ABSTRACT

The lack of sustainability of our water resources threatens food security in many places worldwide. Different water footprint (WF) methodologies were investigated for their ability to improve water management at various scales. Methodology according to the Water Footprint Network (WFN), Life Cycle Assessment (LCA) and hydrological-based approaches were assessed, and a working example is given for apples produced in South Africa. A fundamental viewpoint was defined and the knowledge hierarchy applied to investigate the approaches and information generated. WFs reported simply as a volume of water used per mass of crop produced cannot indicate the sustainability of the water use unless interpreted within the local hydrological and environmental context. The WFN methodology appears most useful to resource managers due to its quantitative nature and ability to compare blue and green water consumption versus water availability. The LCA approach may be best for comparisons of the impact of different products. None of the methodologies provide a single metric that can be used to inform wise consumer choices as it is not possible to incorporate all the complexities associated with water use into a single number that can be used to inform sustainable water use.

KEY WORDS: sustainable water use; knowledge hierarchy; Water Footprint Network; Life Cycle Assessment; consumer awareness.

† Comparaison de l'utilité et de l'applicabilité de différentes méthodes d'empreinte de l'eau pour une gestion durable de l'eau en agriculture

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RÉSUMÉ

Le manque de durabilité de nos ressources en eau menace la sécurité alimentaire dans de nombreux endroits du monde. Différentes méthodologies de l'empreinte d'eau ont été étudiées pour leur capacité à améliorer la gestion de l'eau à différentes échelles. La méthodologie selon le Water Footprint Network (WFN), l'analyse du cycle de vie (ACV) et les approches hydrologiques ont été évaluées, et un exemple pratique est donné pour les pommes produites en Afrique du Sud. Un point de vue fondamental a été défini et la hiérarchie des connaissances a été appliquée pour étudier les approches et les informations générées. Les WF déclarés simplement comme un volume d'eau utilisé par masse de culture produite ne peuvent pas indiquer la durabilité de l'utilisation de l'eau à moins d'être interprétés dans le contexte local hydrologique et environnemental. La méthodologie WFN semble la plus utile aux gestionnaires de ressources en raison de sa nature quantitative et de sa capacité à comparer la consommation d'eau bleue et verte par rapport à la disponibilité de l'eau. L'approche ACV peut être la meilleure pour comparer l'impact de différents produits. Aucune des méthodologies ne fournit une seule mesure qui peut être utilisée pour éclairer les choix judicieux des consommateurs, car il n'est pas possible d'incorporer toutes les complexités associées à l'utilisation de l'eau dans un seul chiffre qui peut être utilisé pour une utilisation durable de l'eau.

MOTS CLÉS: utilisation durable de l'eau; hiérarchie des connaissances; Water Footprint Network; évaluation du cycle de vie; sensibilisation des consommateurs.

INTRODUCTION

Water scarcity is increasing in many places around the world. Climate change, population growth and improved standards of living will exacerbate this even further in the future. Future water scarcities will present many challenges, of which global food production is of specific concern. The water footprint (WF) concept was developed to help address these challenges.

In 2009 the Water Footprint Network (WFN) (now operating as the Water Footprint Research Alliance) published the first WF assessment manual (Hoekstra *et al*., 2009), which was followed by a more comprehensive manual in 2011 containing prescribed methodology to determine the impact on water resources by individuals, communities, businesses as well as during production processes (Hoekstra *et al*., 2011). Hoekstra *et al*. (2011) distinguish between blue, green and grey WFs. Surface water and groundwater resources, which are available to multiple users, are defined as blue water. In a crop production context, the blue WF consists predominantly of the irrigation water consumed. Green water is water originating from rainfall that is stored in the soil and available for vegetation growth only. Hoekstra *et al*. (2011) proposed the concept of a grey WF, which is the volume of water required to dilute pollutants to ambient levels. Expressing water pollution impact in this way enables the reporting of a total (blue + green + grey) WF as a volume which includes water quality and quantity impacts.

Modified WF methodologies have been proposed in an attempt to overcome some of the weaknesses of the WFN approach, most notably the Life Cycle Assessment (LCA) (i Canals *et al*., 2009; Pfister *et al*., 2009), and the hydrological-based methodologies (Deurer *et al*., 2011). In 2014, the first International Standards Organisation WF standard was released (ISO 14046 2014), which, while somewhat vague in its prescription on how to calculate a WF, aligns most closely with the LCA approach. Both before and preceding this publication, there has been scientific debate between proponents supporting and opposing WF methodologies, including in the form of letters to the editors of journals (Hoekstra 2016, Hoekstra *et al*., 2009, Pfister *et al*., 2017, Pfister and Hellweg 2009). Several authors criticized the WFN approach for producing information that is misleading, because without the sustainability assessment these authors claim the WFs don't reflect the local environmental and hydrological conditions where the water is used (Perry, 2014, Wichelns, 2011, Wichelns, 2011).

The International Commission on Irrigation and Drainage (ICID) has been assisting the international irrigation community with definitions and applications of the concepts of water use efficiency and water productivity. Further clarity is now required to understand the definitions and applications of WFs. The WFN, LCA and hydrological-based methodologies are described and evaluated in a simple case study for apples (*Malus pumila*) grown in the Kouebokkeveld, South Africa. To better understand the different approaches and the information generated, a fundamental viewpoint was defined and the knowledge hierarchy applied. Strengths and weaknesses for each approach are discussed in an attempt to identify the most appropriate methodology for a specific application as well as intended usefulness of the information. Through this analysis, we hope to improve communication and understanding between scientists that are involved in the WF debate.

MATERIALS AND METHODS

Water Footprint Network (WFN) Methodology

The WFN proposes two phases, firstly a WF accounting phase and secondly a sustainability assessment of the WF. During the accounting phase, a volume of water used per product yield is determined. During the sustainability assessment phase, the water use is compared to water availability to reflect the local impact of the WF (Hoekstra *et al*., 2011).

The equations for blue and green WFs (Equation 1 and 2) were taken from the WFN manual. According to Equation 1 and 2, the blue plus green WFs include water evapotranspired by the crops during cultivation taking into account how much of the water was provided by irrigation.

$$Blue\ WF = \frac{minimum\ (total\ net\ irrigation, actual\ irrigation\ requirement)}{Yield} \quad (1)$$

and

$$Green\ WF = \frac{[Crop\ ET - minimum\ (total\ net\ irrigation, actual\ irrigation\ requirement)]}{Yield} \quad (2)$$

where *Crop ET* is the total crop evapotranspiration (mm). The result of the blue plus green WF is therefore equal to actual crop ET / crop yield, and is also called the volumetric WF. Another method is described in Hoekstra *et al*. (2011), which makes use of crop ET and effective rainfall to calculate the blue and green WFs.   shows the formula that is used to calculate the grey WF (Hoekstra *et al*., 2011).

$$\text{Grey WF} = \frac{L}{C_{max} - C_{nat}} \quad (3)$$

where L (kg ha^{-1}) is the load of pollutant released into a water body, C_{max} (kg m^{-3}) is the maximum concentration of pollutant at ambient water quality standards, and C_{nat} (kg m^{-3}) is the natural concentration of the pollutant in the receiving water. The natural concentration of the pollutant in the receiving water and the ambient water quality standards differ from one country to the next according to their individual guidelines. Therefore, the same pollutant load can have different grey WFs depending on the natural background concentration and the user-selected water quality standards (Hoekstra *et al*., 2011). The blue, green and grey volumetric WF is divided by crop yield (tonnes ha^{-1}) to give units in volume of water per mass of crop yield (Hoekstra *et al*., 2011).

Life Cycle Assessment Methodology

The LCA community suggested that crop WFs according to the WFN (a volume of water used per yield of crop) can be misleading if communicated outside the context of the local circumstances and without some type of sustainability assessment. This community also felt they had better assessments for the impact on water quality than the grey WF concept. Pfister *et al*.

(2009) suggested a WF method based on the LCA approach, in which a regional Water Stress Index (WSI) is calculated to characterise local water use impacts, which follows a logistic function from 0.01 to 1, with a withdrawal-to-availability ratio of 0.4 (often referred to as the threshold between moderate and severe water stress) resulting in a WSI of 0.5. The LCA method attempts to address temporal variation by including a variation factor into the WSI as a measure of variation in climatic conditions. Variation in water availability will result in a higher variation factor and a higher WSI which will in turn increase WFs. The LCA water scarcity-weighted WF is calculated using Equation 4:

$$Blue\ WF = Water\ Consumption\ (m^3 Functional\ Unit^{-1})\ \times WSI \qquad (4)$$

The results are a stress-weighted index reported as 'water equivalents' (H_2O-e) which gives an indication of a product or activities' impact on water resources (Ridoutt and Pfister, 2010). For this approach, green water use is not considered because it is accounted for in other LCA metrics, such as land use, and because natural vegetation would have used green water anyway. An alternative to the grey WF method is proposed by Ridoutt and Pfister (2013), which makes use of advanced LCA modelling using eutrophication, freshwater eco-toxicity and human health impacts as impact indicators (Ridoutt and Pfister 2013).

The International Standards Organization (ISO) published a 'Global WF Standard' in August 2014 (ISO 14046 2014), which is closely related to the LCA method proposed by Pfister *et al.* (2009). The standard gives broad and flexible guidelines and includes a few important principles. Water footprints, according to the standard, must consider the full life cycle of a product, must include an environmental impact assessment and must preferably be based on scientific evidence. The standard also has specifications on how WFs are reported, in order to ensure transparency, but does not include a way to report the results as product labels. Similar to the LCA methodology of Pfister *et al*. (2009), it is suggested that results be reported as 'water equivalents' (H_2O-e). The Standard also proposes the use of other mid-point indicators firmly established in LCA methodology, such as estimating eutrophication potential in 'phosphate-equivalents' in the case of nitrogen and phosphorus pollution from agriculture.

Hydrological-based methodology

Deurer, Green, Clothier and Mowat (2011) introduced a WF method based on hydrology, aiming at considering all components of the water balance and not just water consumption. The calculation of the blue WF is based on Equation 5:

$$\Delta\, Blue\ Water = D^r + D^{ir} + R^r + R^{ir} - IR \tag{5}$$

where D^r is drainage under rainfed conditions, D^{ir} is the difference between drainage under rainfed and irrigated conditions, R^r is runoff under rain fed conditions and R^{ir} is the difference between runoff under rainfed and irrigated conditions. Drainage and runoff collectively forms the inflow into the blue water resource. IR is the amount of water abstracted from the blue water resource for irrigation and represents the outflow from the blue water resource. The calculation of the green WF is based on Equation 6.

$$\Delta\, Green\ water = D^r + ET^r + R^r - RF \tag{6}$$

where ET^r is the ET under rainfed conditions and RF is the effective rainfall, excluding any water that is intercepted by the plant cover. Collectively D^r, ET^r and R^r forms the outflows from the green water resource and RF is the inflow into the green water resource.

According to this method, a negative WF is possible if the recharge of the blue water resource through return flows and precipitation exceeds the volumes abstracted. A negative blue WF is therefore required for a catchment or aquifer to sustain ecosystems downstream. A positive WF indicates water abstraction exceeds recharge through return flows and precipitation (Deurer *et al*., 2011). A zero WF is possible if return flows and precipitation are equal to abstraction volumes. Data used to calculate hydrological-based WFs are obtained on a local scale and over an annual water cycle (Herath *et al*., 2013a). Blue and green water use are divided by yield to obtain the WFs. Grey WFs are calculated in the same way as proposed by Hoekstra *et al*. (2011).

Case study - the water footprint of apples according to different methodologies

The Olifants-Doorn Water Management Area (WMA), located in the Western Cape Province of South Africa, is a region experiencing extreme water scarcity. Climatic conditions vary considerably across the Olifants-Doorn WMA as a result of the variation in topography. The mean annual precipitation (MAP) ranges from approximately 1 500 mm in the south-west to less than 100 mm in the far north (DEA&DP 2011). With the MAP over much of the WMA being less than 200 mm, the result is that, except in the wetter south-west, the climate is not suitable for dryland farming on a large scale. Irrigation in the WMA depends heavily on surface water (76%) and groundwater (16%) as sources of supply. The deciduous and citrus fruit industries are particularly at risk as they utilize large volumes of water per unit weight of fruit produced (Dzikiti and Schachtschneider 2015). Consequently, more than 90% of the land in the Olifants-Doorn WMA is used as grazing for livestock, predominantly for sheep and goats. However, the principal economic activity in the WMA is irrigated agriculture, and 87% of total water use is for irrigation (DEA&DP, 2011). A recent estimate (Bailey and Pitman 2015) puts the total area under irrigation in this WMA at 730 km². Water footprint methodologies were applied to apple production in the Olifants-Doorn WMA to assess their ability to improve water resource management of agriculture in this water scarce region (Van der Laan, 2017).

Fundamental viewpoint

The fundamental viewpoint is that WF assessments or metrics must primarily promote sustainable water use (Figure 1: Level A). Each WF method was evaluated according to this viewpoint. Sustainable water use is determined by several variables (Figure 1: Level B), including:

- variables in the hydrological system that determines water availability. Such variables include climatic/weather conditions, soil types, topography, landscape characteristics and land-use;
- variables that define the systems that determine water demands and receive impacts from water use. Such variables include the ecological, social and economic systems (including agriculture);
- variables related to water use, including water use management (catchment and national level), water use efficiency and water productivity (field and consumer level).

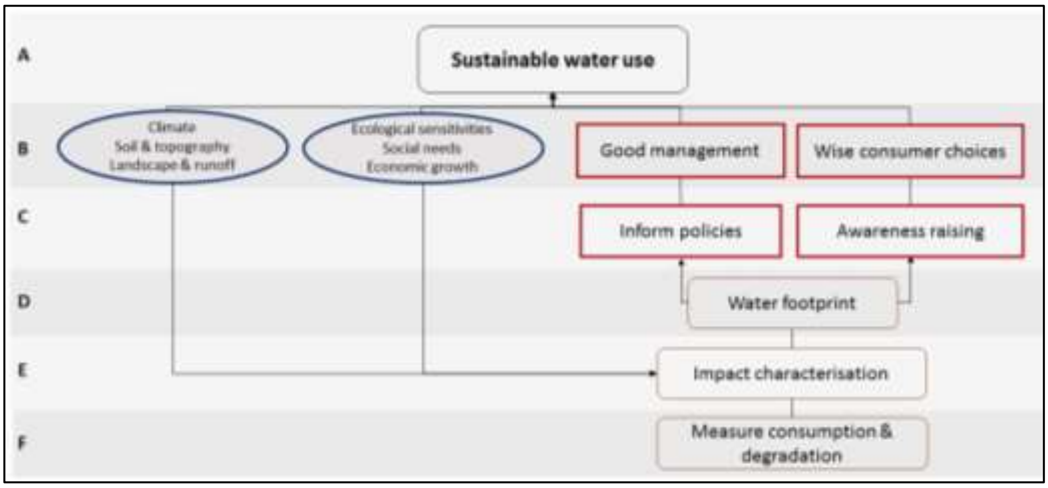

Figure 1: Schematic representation of the role of water footprint assessments towards the goal of sustainable water use. Blue circular ovals are variables that impact on sustainable water use, but are difficult or impossible to manipulate. Red square boxes indicate variables that impact sustainable water use the process through which these impacts can be managed through water footprint assessments.

Most of these variables are difficult or impossible to manipulate, but more efficient water use management can be enforced through policies and regulation, and water use efficiency can be achieved through increasing public and commercial enterprise awareness (Figure 1: Level C). In order to manage and increase the efficiency of water use, the volumes of water consumed and polluted must be measured and characterised according to local water resource availability and sensitivity (Figure 1 Levels E & F). Impact characterisation should be informed by both the hydrological system that influences water availability, as well as the environmental setting where water is required. Current and future water demands and management practices should also be considered as part of the environmental assessment and sustainability (Figure 1: Level B).

Through a literature review the fundamental viewpoints of the three WF methods were compared with the fundamental viewpoint defined for this review as illustrated in Figure 1 and discussed below. It must be noted that the similarities investigated here are only a reflection of the aspects that are considered by the various methods and not an indication of how successfully these aspects are measured.

RESULTS

Case Study - The water footprint of apples according to different methodologies

For the 12 year old apple orchard-scale WF, taking into account all water uses and a fruit yield of 61.5 t ha^{-1}, according to the WFN approach we estimated a blue WF of 133 m^3 t^{-1} and a green WF of 32 m^3 t^{-1}. To estimate the blue WF according to the LCA method, the blue WF was multiplied by the WSI for the region (0.78) to get a value of 104 H_2O-e $tonne^{-1}$. For the hydrological-based approach, the blue WF was estimated to be -41 m^3 $tonne^{-1}$. It was, however, not possible to calculate green WFs according to the hydrological approach in the same way as the published methodology prescribes, because modelling under rainfed-only conditions is required, and as this crop grows in summer in a region with a winter rainfall, a marketable yield will not be achieved with which to calculate the green WF. A similar situation developed when trying to estimate green WFs of vegetable crops grown in winter in a summer rainfall region (Van der Laan, 2017). As pointed out by a reviewer, it is difficult to learn from numbers that are completely different; not even the signs are the same.

Analysis in terms of the fundamental viewpoint

The WFN proposed a useful way to measure water consumption and pollution. The method differs from the fundamental viewpoint in that the WF is calculated before the sustainability assessment, and is therefore not a sustainability indicator in itself (note the inverse in Levels D and E for Figure 1). Ecological impacts are accounted for by considering water quality impacts through grey WFs and impacts due to consumption by including ecological flow requirements.

The method mentions the need to reserve flow for basic human and ecological needs, but has not yet been developed to quantify these needs. Soil type is captured by the green WF, more green water will be available for soils with a higher water holding capacity. If all relevant information, such as landscape and land use effects on runoff is included in the calculation of water availability, all aspects of the hydrological cycle will be included. The method proposes the concept of virtual water, which can inform policies by providing a simple universal way to estimate consumptive use per yield of product, and can assist catchment management practices. The WFN has been successful in raising awareness of water use impacts as a result of water consumed to make and distribute products. Whether the WFs that are communicated to consumers will enable them to make wise decisions that will lead to more sustainable water use is uncertain, especially if they are used outside the local context or without the sustainability assessment (Figure 1).

Compared to the fundamental viewpoint in Figure 1, the LCA approach includes some aspects of the hydrology. Water availability is determined using monthly and annual rainfall data. Landscape characteristics are considered in terms of stream flow regulation in the particular catchment. Green water is excluded, because it can only be accessed through occupation of land. Therefore, the effects of soil types and topography are not addressed. This indicator includes many aspects of the environment and people, by determining impacts on human health (social need), ecosystem quality (ecological sustainability) and resource depletion (economic requirements). However, ecological, social and economic systems are extremely complex and measurements of these endpoint indicators are mostly calculated with many uncertainties (Goedkoop *et al*., 2013). The WSI generated by this method can theoretically be used on product labels for awareness raising, but it cannot really contain all the information needed by consumers to make wise decisions that will lead to sustainable water use with all the complexities this involves (Figure 2).

Compared to the fundamental viewpoint in Figure 1, the hydrological approach provides information on the local climate and geographical features that determine water inputs, outputs and changes in water storage to produce a sustainability indicator that includes all components of the hydrological cycle. The sustainability indicator of this approach does not address social needs and economic requirements. Ecological impacts due to pollution are taken into account through the grey WF, but the impacts on ecosystems sustainability due to a reduction in water availability and changes in river flows are not yet considered. It also does not consider current and future water use and environmental management practices and the effectiveness of the approach to inform consumers to make wise decisions on their water uses is not clear (Figure 3).

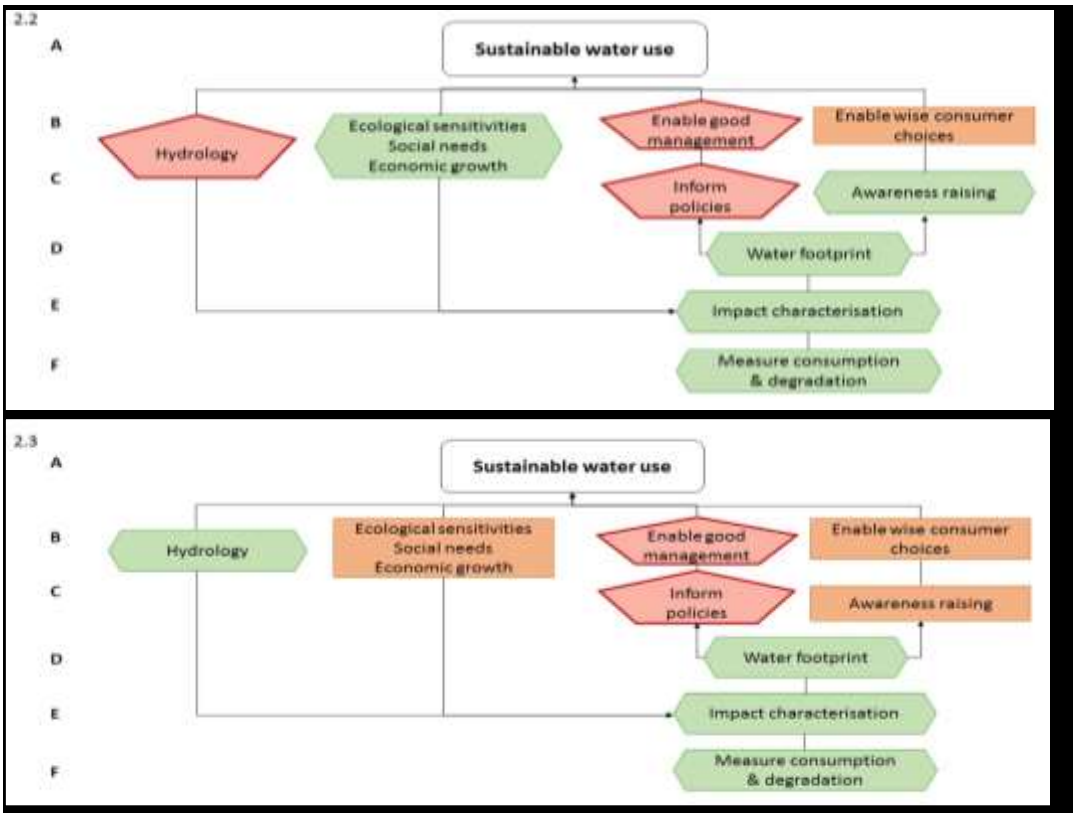

Figure 2: Similarities between the fundamental viewpoints of the WFN (2.1), LCA (2.2) and hydrological (2.3) methodologies and the fundamental viewpoint proposed in Figure 1. Hexagon shapes (green) indicate similarities in the viewpoints, pentagon shapes (red) indicate aspects partly included, and square shapes (orange) indicate aspects lacking, in each methodology.

Although the volumetric WF according to the WFN, which is a volume of water used by the crop (ET) / mass of produce, does not indicate the sustainability of the water use unless it is interpreted within the local hydrological and environmental context, for example by simply stating that it takes 162 m^3 blue plus green water to produce 1 tonne of carrots in winter, it was considered to be the most useful methodology to be used for catchment management and decision-making. Reasons for this include:

- the methodology is well-developed, WFs are relatively simple to calculate and understand and can be included in a water balance for further interpretation on the sustainability of water use;
- the quantitative nature of these WFs can potentially be used in different information systems, such as water allocation and water use licensing services, given that it is first interpreted in terms of the local environmental and hydrological environment;
- by altering the functional units, these metrics can be used for applications such as understanding WFs per nutritional unit produced or economic gain;
- these WFs can reveal impacts on water resources in different seasons of a hydrological or calendar year;

- it can indicate high WFs of certain crop species, or certain growing regions, such as those which experience relatively high vapour pressure deficits or with poor soils;
- it allows for local contextualisation if there is suitable information to conduct the sustainability assessment.

The LCA methodology has some important strengths, most notably the more advanced calculation of water quality impacts in terms of eutrophication, freshwater ecotoxicity and human health (Pfister *et al*., 2009). The method takes multiple environmental impacts into account simultaneously, including water consumption and carbon footprints. Considering the unique geohydrological characteristics and water issues that often exist, for example, in the Olifants-Doorn WMA case study, more detailed local WS Indices are required. Although spatial variations may impact the WSI, it most likely will also be sensitive to temporal variations within a year and over longer periods. A WSI may need modification when, for example, commercial agriculture expands. The variation factor is lower for catchments with dams or aquifers that regulate flows and reduce variations in water availability (Pfister *et al*., 2009). Groundwater availability will reduce variations in overall water availability, which will reduce the WSI.

To calculate blue and green WFs, the hydrological-based method takes all water flows into account, as opposed to the WFN, which considers crop ET only. Although the hydrological-based method seems more biophysically comprehensive than the WFN method, the following issues were encountered in the assessment of the method:

- according to the hydrological-based methodology, blue WFs are the difference between volumes abstracted through irrigation and volumes recharged due to deep drainage and runoff. In the original method by Deurer *et al*. (2011), runoff was considered to re-enter the blue water source, which was groundwater in their case, because of the flat topography of their study area. However, in different circumstances runoff may flow out from a catchment and not replenish the local aquifer. In this case the original method will overestimate aquifer replenishment and underestimate blue WFs. A carefully calculated water balance is important to understand the sustainability of a water use, but the issue on including or excluding runoff illustrates how difficult it is to standardise a water balance calculation. We therefore recommend that water use data, as calculated by the WFN method, be used in a site-specific water balance, as illustrated by le Roux *et al*. (2017);
- green WF calculations are complex to make and may require sophisticated modelling to estimate what the yield would be under rainfed conditions;
- WFs according to the hydrological-based approach are calculated over a year. To determine WFs for short season vegetable crops, for example, crop sequences need to be used for a

year. This may conceal the high WFs of certain crops in the sequence, and the impact on water resources in dry seasons. The method is therefore more suitable to perennial crops;

- the WF according to the hydrological-based approach may provide valuable information to a water resources manager, but care is needed as the result may be counterintuitive. For example, if water used by agriculture in a catchment was exactly the same as the volume of water received, the collective WF will be zero, but if all the available water is used there will be no discharge from the catchment, which will affect the downstream users and aquatic ecosystems. If a product is labelled with a zero WF, it would seem that its production was done sustainably. However, in this case a zero WF does not indicate sustainable water use during production. One instead needs a negative WF to be sustainable, but how negative should your WF be? This will be different for each catchment and the method does not include guidelines on how to include the water requirements of downstream users or specify the volumes of water that is required to flow from a particular catchment. You could argue that an activity that supplies fresh water to a catchment, like a desalination plant or waste water treatment plant will have a negative water footprint. But, if agriculture in a catchment uses less than the available rainfall, they are not actually supplying water to the aquifer, and should therefore not have a negative water footprint;
- using the hydrological-based method for crops for which drainage plus runoff is higher than irrigation, will likely produce a negative blue WF. It is confusing to obtain a negative blue WF for a crop that is heavily reliant on irrigation, even if deep drainage plus runoff is greater than the total amount irrigated. This was the case for our study in the Olifants-Doorn WMA because irrigation is applied during the dry summer season, while rainfall during the wet winter months (when the orchard is dormant) results in recharge and runoff.

Analysis in terms of the knowledge hierarchy

The aim of any method to improve water management practices should be to encourage sustainable water use. This must be done at national, regional and local levels to address water resources management and/or to change the behaviour of consumers. The so-called knowledge hierarchy (Ackoff 1989) provides a useful way to better understand the difference between WF methodologies and the complexities involved in developing and using them (Figure 3).

Figure 3: The knowledge hierarchy (Rowley 2007)

According to Chaffey and Wood (2005) as cited by Rowley (2007), higher orders of the hierarchy has more meaning than lower orders. As indicated in Figure 3, data which is meaningless in itself, is at the bottom of the knowledge hierarchy. Data that is interpreted becomes information, knowledge is the know-how or experience of what to do with information, and wisdom is the judgement of whether our actions are right or wrong. In a water management context, the volume of water that is used to produce a product is data. This data only becomes informative when interpreted in a local context of water availability and environmental sustainability. Somehow the information should be communicated to consumers, producers and water resource managers so they make wise decisions that will lead to the sustainability of the water used to produce a product. Awad and Ghaziri (2004) as cited by Rowley (2007), said that data can be programmed, while wisdom cannot be programmed or generated by a computer (Figure 3). For these reasons it is not possible to develop a WF method of which the outcome is an undisputed number that can be used on product labels and will indicate 'right' or 'wrong' to a consumer. There is probably no 'right' or 'wrong' answer and it might be more important to indicate if one is moving towards sustainability or away from sustainability.

Volumetric WFs according to the WFN methodology are at the level of data, defining the WF as a volume of water used to produce a product or provide a service. Data is often most valuable, because a water resource manager can interpret it within his specific location to get the necessary information for decision making. However, care must be taken not to communicate a WF defined as a volume of water used, which is mere data, as information or wisdom implying that a volume used is 'good' or 'bad', 'high' or 'low'. Using hypothetical examples, Wichelns (2017) took WFs according to the WFN approach (i.e. data) and rightfully interpreted them together with socio-economic impacts, such as employment opportunities and use of energy (i.e. produced information). Similarly, Ridoutt and Pfister (2010) interpreted data on water use in terms of water availability, which provided important information. The above examples demonstrate how a water resource manager should apply water use data in the decision-making process. It is, however, also important to note that these kinds of assessments would not be possible without the data on water use (such as the WFs calculated according to the WFN approach). For this reason, the LCA and hydrological-based communities developed modified methodologies seeking to interpret the data to obtain information (a better understanding of the water use in terms of water availability and the hydrology) and wisdom (the LCA methodology potentially providing consumers with a label that will indicate the degree of impact).

Although it is very important to get from data to wisdom, there are many complexities involved in standardising a method on these higher levels of the knowledge hierarchy. Figure 3 also indicates this, by showing that the higher levels of the knowledge hierarchy cannot be programmed and calculated by computers. For example, the WSI calculated for the LCA methodology considers the availability of water within a certain area. The WSI, is based on the withdrawal to availability ratio (WTA) of which 0.4 is assumed to be the threshold indicating severe water stress. However, this WTA of 0.4 is a fixed number, which does not apply to all catchments at all times. For example, the Ganges River is characterised by severe flood and drought cycles (Sharma *et al*., 2010), and different WTA ratio would be needed to represent the threshold indicating severe water stress in these different cycles. Although it is important to consider water availability in relation to water use, it is not the only consideration in terms of sustainability. Water requirements of the ecosystem, people and economy must all be considered. This can become very complex, taking ecological water requirements as an example. It is commonly recognised that flow reductions in rivers are not desirable (Lake, 2003) and that floods are important ecological events that flush the river from alien vegetation and sediments (Rountree 2014). However, changes in the seasonality of flows such as increasing dry season flows and decreasing wet season flows, which is common in irrigation schemes, also have an impact on river ecosystems (Lake 2003, Pattie *et al*., 1985, Rountree 2014). Aquatic species are adapted to certain flow regimes, which support connectivity in the aquatic ecosystem and habitats (Bunn and Arthington 2002). Changes to geohydrological characteristics, such as groundwater converted to surface water are undesirable (Rountree 2014). Maintaining natural flows of rivers are more important if the aquatic and riparian biodiversity is sensitive with, for example, red data species (Rountree 2014). Often a water resource manager has to decide whether to allocate water to people or ecosystems, which involves trade-offs of various impacts. These are only some of the complexities associated with the water requirement of an ecosystem, and the LCA methodology does not address this.

CONCLUSIONS

One of the drawbacks of water becoming a global resource is that water users become disconnected from and unaware of the impacts of their water uses. It is therefore important to consider ways of providing quantitative information on water use and/or impact and to influence consumer behaviour towards sustainability. How this should be done has been debated by scientists that are involved in WF assessments. The volumetric WF of the WFN, even with the sustainability assessment, is not a suitable metric for communication to consumers and for product labelling, because it does not fully describe the context of the water use, including socio-economic factors. The other methods have attempted to interpret and modify the WFN metric, most notably the LCA method that aimed to produce product labels. As the ISO Standard (ISO 14046 2014) does not specify ways of reporting WFs to consumers for awareness raising, this indicates that they too struggled with the complexity of standardising such a method.

This study on WFs has indicated that calculating WF labels still requires much refinement and debate, and at best may result in a symbol indicating responsible water use or stewardship, as opposed to a quantitative or even water scarcity-weighted volumetric WF label. Consumers need all levels of the knowledge hierarchy (data, information, knowledge and wisdom) to make wise decisions about the products they buy. However, influencing consumers through education may have unpredictable outcomes. Some consumers may choose products based on potential impacts on people, while others could make decisions based on ecological sustainability. Advertisement and marketing also influences market demands and the interpretation of information. Future studies must pay attention to the various ways in which consumer behaviour can be influenced to change market demands. Personal experience has shown that second year biological sciences undergraduate students at the University of Pretoria relate better to the concept of a WF than to water use efficiency or water productivity.

Ultimately it may be that natural scientists prefer the WFN approach due to its volumetric nature, which means it is quantitative and can be applied to identify hotspots at larger spatial scales (Multsch *et al*., 2016), or be used in catchment to basin water management (le Roux *et al*., 2017). Engineers may prefer the LCA approach due to its compatibility with determining other potential impacts simultaneously, and being able to link it to a functional unit allowing product cross-comparisons. From this study, it can be concluded that the choice of method depends on the objective(s) that it is used for, and it is hoped that this review will contribute to further discussion and evolution towards a practical and useful WF methodology.

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