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ORIGINAL ARTICLE

Water footprint concept and methodology for warranting sustainability in human-induced water use and governance

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Abstract Water footprint is a popular concept in research and water resource management discourse, which can be used to improve the management and sustainability of global water resources. It offers a huge potential towards water resource and impact decoupling at various levels/ scales. In this paper, we review scientific literature on the water footprint methodology with the aim of improving the understanding of the concept to various stakeholders, its applications, and significance to water use and management. We highlight the applications of the methodology and their significance. In addition, we outline the phases in water footprint assessment, the approaches used in water footprint accounting, the limitations of the methodology, usefulness, and some recent successful applications. We conclude that the water footprint methodology is a powerful policy tool that can be used worldwide to manage scarce freshwater resources and in promoting sustainability and governance in human-induced water use. More so, the concept has an important role to play in disengaging development with excessive water resource use and adverse environmental impact. Therefore, it is imperative to understand and apply the water footprint concept particularly by various stakeholders in the developing world to mitigate excessive physical and economic water resources' scarcity.

Keywords Water footprint · Water resource management · Sustainability · Resource and impact decoupling · Water use and governance

Background and introduction

Rapid population growth, urbanization, industrialization, and other facets of economic growth and development in many parts of the world exert huge pressures on scarce global fresh water resources (Donoso et al. 2015). Water shortages present critical challenges the world over for sustainable development. According to Mekonnen and Hoekstra (2011), pressures for consumptive water use may lead to depletion of ground water resources and unsustainable consumption of surface water resources that may compromise freshwater ecosystems (Mekonnen and Hoekstra 2011). In addition, water availability is often cited as one of the most common limitations for the production of food (Gerbens-Leenes and Hoekstra 2012; Gerbens-Leenes et al. 2009; Yang and Zehdner 2002), poverty alleviation (Barker et al. 1999; Bhattarai et al. 2002; Lawrence et al. 2002), and economic development (Bates et al. 2008; Sullivan 2002) signifying the importance of water as a resource. The shortage of water can have serious implications on sustainable developmental aspirations of any country especially those with naturally limited freshwater resource endowments. Consequently, fresh water is often overexploited in circumstances that require a proper use and management. This observation

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Springer

triggered the widespread prominence of studies relating to conceptualization of water footprint (WF) as a sustainability tool meter for human-induced water consumption. The WF has been applied at different scales: local, national, and international scales (Hoekstra and Hung 2002).

The concept of WF began in 2002 as a way of finding a water indicator based on consumption. The main aim was to complement the traditional water indicators which are production-sector based (Hoekstra and Hung 2002). A significant amount of water is used and polluted by human activities and a critical realization was to improve stakeholder awareness on water use and pollution nexus in the production of goods and services. Of particular concern are industries by the nature of their production and supply-chain activities covert huge volumes of water that are linked to the final consumer products for consumption and pollution (Zhang et al. 2013). WF was developed parallel to the concept of ecological footprint (EF) (Holmberg et al. 1999; Wackernagel and Rees 1996). By definition, the EF of a population is a measure of the dependence by human race demands on the earth's environment. This definition of EF signifies the space requisites of a particular population for resource production and assimilation of generated waste in a specific location on the earth's surface at a given level of living standard (Hoekstra et al. 2011). While the focus of EF is on the area required for sustaining human life, WF is a measure of the quantity of water required (Chambers et al. 1999; Wackernagel and Rees 1996). Thus, the concept of WF largely deals with water volumes associated with the production of a product or service (i.e., volume of water measured over the full supply chain). The WF concept, as mentioned earlier is applicable at different levels, i.e., at national level (national water footprint) or for a specific product, e.g., WF of a crop. When applied to a nation, it refers to the sum of freshwater quantity utilized in the production of goods and services required by that nation. When applied to a particular product, for example, a crop, WF becomes an empirical indicator that quantifies when, where, and how much fresh water is consumed in the production lifecycle of the crop (Hoekstra and Hung 2002). The WF concept as an indicator is multidimensional, showing on one hand the sources of consumption by volumes and on the other the type of pollution and volume of water polluted. All the WF components are specified relating to time (temporal) and geographical space. The concept encompasses three components, namely, blue WF (ground and surface water resource consumption along supply chain of a product), green WF (consumption of rainwater to an extent just before it becomes runoff), and grey WF (fresh water volumes necessary to neutralize load of pollutants associated with production and supply of a product given existing quality of water standards and

natural background concentrations) (Mekonnen and Hoekstra 2011). More on the three components of the WF is highlighted in later sections.

The objective of this paper was to review WF calculation methodology as applied at different scales and highlights critical issues to improve the understanding of the concept by a wider audience especially outside the scientific world. A lucid understanding of the WF concept, its calculation, and application is important especially among stakeholders including scientists, scholars, production engineers, production economists, environmentalists, policy makers, the general public and stakeholders that make use of the overexploited, and often polluted scarce resource. Improving understanding on this topic is vital for the achievement of optimum water resource management at both local, national, and regional scales. Wider acceptance and application of the concept in the developing world, for example, can significantly contribute to economic development through reducing poverty, increasing efficiency in food production, reducing food insecurity, and reducing conflicts and offer adaptation to water scarcity problems. Water scarcity problems may be a result of climate change especially in Southern Africa. The region is one of the worst affected by climate change (Archer et al. 2007), with average temperatures being on the rise. This can worsen the scarcity of freshwater resources available in the region which justifies the sustainable management and utilization of water resources. This paper gives a simplified and holistic way for discussing and understanding WF.

The organization of this paper is as follows: "Research methodology and overview" provides an overview of literature search and methodology applied in this paper, while "Review findings and discussion" summarizes and discusses the major findings. "Conclusions and implications" provides the conclusions and associated policy implications.

Research methodology and overview

The study relied on extensive literature reviews on WF methodologies, application, and evaluations. We focus much on the literature published in the 21st century to come up with the review results. To obtain the relevant literature for the review, we searched through the ever-growing Scopus literature and other authentic academic platforms, all completed between November 2015 and March 2017. The literature search used several keyword combinations and phrases to gather the relevant studies. Some of the keyword combinations and phrases are shown in Table 1.

Identification of a few initial relevant publications on water footprint methodologies was important as a guide

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Table 1 Word combinations and short phrases used in searching for the literature

Word combinations		Phrases
Water footprint and grey/blue/green water footprint	Methodology, methodologies, calculation, approaches, application, importance, of a nation/product/service	Shortfalls of water footprint methodology
		Water footprint in Agriculture
		Water footprint in industry
		Water footprint in consumption
		Water footprint application
		Water footprint application in Africa
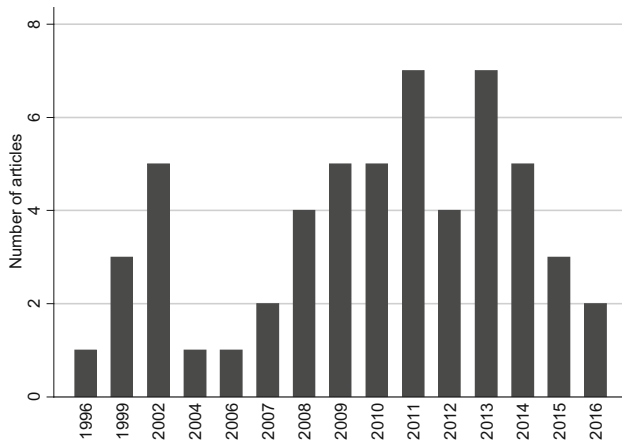
Fig. 1 Overview of articles used and cited in this paper

towards greater literature search. Moreover, references from identified publications were used to expand the literature source list. An overview of the number of articles used in the study is shown in Fig. 1.

In the end, a total of 55 articles were selected and used for the study. All the articles cited in this paper were accessed, read and used in building arguments presented in this article.

Review findings and discussion

Water footprint (WF) of a nation

From the review, it is evident that the WF calculation of a nation can be done using two methods: the bottom–up method or top–down method. In the bottom–up method, a nation's WF is obtained by the multiplication of all goods and services which are consumed by the occupants of a nation by their corresponding virtual water content (Feng et al. 2011). Here, virtual water is given by the water volume required to the production of a product or service. According to Feng et al. (2011), the term virtual water refers to water which is not entrenched in the product or service. With the top–down method, a nation's WF is calculated as total water used by a nation plus the flows that

come into the country as virtual water minus the flows that leave the country as virtual water. It, therefore, implies that with the top–down approach, the nation's WF has two components: (1) domestic (WF) and (2) external WF. Domestic WF is a measure of the volumes of water resources consumed domestically in the production of goods and services of a particular country. Precisely, it is the sum of total domestic water volume in an economy minus the volume of virtual water exported outside indirectly as exports of goods (Feng et al. 2011).

External WF on the other hand is a measure of the annual volume of water used in the production of goods and services imported into the country for consumption purposes. In other words, the external WF is the virtual water import into the country of concern minus the volume of virtual water exported to other countries as a result of the re-export of imported products (Feng et al. 2011; Ridoutt and Pfister 2010). According to Feng et al. (2011), virtual water flows measured in m^3/year are assessed by the multiplication of flows of commodity trade measured in tons per year (ton/year) by accompanying virtual water content (m^3/ton).

Hoekstra and Chapagain (2008a) were the first to apply a nation's WF based on the bottom–up approach from 1997 to 2001. The approach was revised by Hoekstra et al. (2009) and applied after revision by Mekonnen and Hoekstra (2011) to calculate water footprints of nations, separating green, blue, and grey water footprints. To date, several studies have significantly applied the methodology (de Miguel et al. 2015; Donoso et al. 2015; Gu et al. 2015). We explain our understanding of green, blue, and grey water in the succeeding section.

Water footprint of a product or service and its components

The WF concept as mentioned earlier can be applied to a specific product or service. A product or service's WF is composed of three components: (1) blue WF which is the volume of blue water resources (surface plus ground water) along a product supply chain; (2) green WF which is the volume of water evaporated from the global water

resources (rainwater stored in the soil as soil moisture); and (3) the grey WF which refers to the volume of polluted water associated with the production of goods and services. Precisely, the grey WF is the volume of freshwater required to dilute or assimilate the load of pollutants produced during the production of goods and services given natural background concentrations and ambient quality of water. In simple terms, it is the volume of water needed to dilute pollutants to a standard which is at or above the prescribed quality of safe water.

The three components following Hoekstra et al. (2009) can be calculated as follows.

Blue water footprint (WF$_{blue}$)

The blue water footprint is a consumptive use indicator of blue water. The term consumptive according to (Hoekstra et al. 2009) is used to refer to one of the following: (a) water vaporizes; (b) water is assimilated into the product; (c) water does not return to a similar catchment zone; for instance, it is returned to a different catchment zone or the sea; or (d) water does not return in the same period; for instance, it is withdrawn in a dry period and reimbursed in a wet period.

Evaporation is the most significant component among the four scenarios. It consequently implies that in most cases, the consumptive use is often equated with evaporation. However, the remaining three components can be considered depending on the situation at hand. Component (d) refers to the part of the return flow which is inaccessible for reuse within the same catchment and time period of withdrawal (Hoekstra et al. 2009).

Equation (1) illustrates how blue WF is calculated:

$$\text{WF}_{\text{blue}} = \text{Blue water evaporation} \\ + \text{Blue water incorporation} \\ + \text{lost return flow (volume/time).} \tag{1}$$

Green water footprint (WF$_{green}$)

Green water denotes water on land not running off or recharges the ground, but is kept in the soil or momentarily stays on top of vegetation or the soil. The green water footprint is an indicator of the so-called green water. Precisely, green water footprint is the volume of rainwater used during the process of production. It is, therefore, very relevant to the agricultural and forestry sector products. In such products (crops or wood), green water footprint refers to total rain water evapotranspired (from plantations and field) plus the water incorporated into the harvested product (Hoekstra et al. 2009). More so, the green WF in forestry or agriculture sector can be estimated using crop models or empirical formulas appropriate in estimations of

evapotranspiration based on crop characteristics, climate, and soil data (Hoekstra and Chapagain 2008c).

Equation (2) illustrates how the green WF is calculated:

$$\text{WF}_{\text{green}} = \text{Green water evaporation} \\ + \text{Green water incorporation (volume/time).} \tag{2}$$

According to Falkenmark and Rockstrom (2004) and Hoekstra and Chapagain (2008b), distinction concerning green and blue WF is critical, since economic opportunity costs, environmental, social, and hydrological impacts of surface and groundwater use for production differ uniquely from the costs and impacts of rain water use.

Grey water footprint (WF$_{grey}$)

Grey WF is an indicator of polluted water. As shown earlier own, it is volume of fresh water needed to blend in the load of pollutants produced during the production process based on natural background concentrations and obtainable standards of water quality. The grey WF of a process, for example, is regarded as an indicator of the degree of fresh water pollution associated with a particular process. Grey WF is computed by dividing pollutant load (L, in mass/time) by the difference between the ambient water quality standard for that pollutant (maximum acceptable concentration C_{max}, in mass/volume) and its natural concentration in the receiving water body (C_{nat}, in mass/volume):

$$\text{WF}_{\text{grey}} = \frac{L}{C_{\text{max}} - C_{\text{nat}}} \text{ (volume/time).} \tag{3}$$

The natural concentration occurs in the absence of disturbances by humans in the catchment, i.e., $C_{\text{nat}} = 0$ for man-made substances not naturally found in water. In addition, a value of zero is set for C_{nat} when pollutants' natural concentrations cannot be precisely measured, but can be projected as being low. This nonetheless takes too lightly the volume of grey water footprint of a product or service under concern. Grey WFs are calculated using standards for ambient water quality for the unloading body of freshwater which is the same as measuring standards according to the concentrations maximum allowable (Mekonnen and Hoekstra 2011).

Phases of WF assessment

Following Hoekstra et al. (2009), there are four main phases followed in assessing the water footprint of any nation, business, product, and/or service.

1. Scoping phase, which entails setting goals and objectives, of the assessment.

2. WF accounting, which entails the volumetric accounting of blue, grey, and green WF with spatial–temporal resolution.
3. Sustainability assessment phase, which entails different levels of impact from a suite of perspectives (environmental, social, and economic).
4. Response and formulation phase, which entails policy formulation and response strategies based on the outcome of sustainability assessment.

The scoping phase is important as it clearly sets the goals and objectives of the study. Government may be concerned with understanding its reliance on national or imported water resources or its dependence on water inside its region. Management of a steel manufacturing plant, for instance, may be concerned with knowing the plant's dependence on water resources along the supply chain given decreasing associated business risks and costs.

The accounting phase highlights the volumetric accounting of three kinds of water, namely, green, blue, and grey as defined earlier. It clearly shows the two components that make up a product or service's total WF (direct and indirect). Direct WF for a product is the sum of the volume of water either polluted or evaporated at the point of operation. On the other hand, indirect WF is the predecessor suppliers' sum of total WFs along the supply chain of a product. Figure 2 illustrates an example of the accounting phase of an agricultural supplier.

Sustainability assessment is informed by the outcome of the accounting phase. It covers wider social, economic, political, and other time dimensions such as size, timing, location, and color of the resultant WF. The sustainability assessment can also be called impact assessment and can be performed both on quantitative and qualitative basis. For instance, sustainability assessment of WF of a product/process/consumer/producer can inform concerned parties whether the WF contributes unnecessarily to global footprint of humanity or to specific hotspots. In a specific catchment, sustainability assessment of WF can reveal both primary and secondary impacts within that catchment, i.e., how the WF affects quality and the flow of water area specific (primary impacts) and how that ultimately impact on health, biodiversity, social equity, and welfare (secondary impacts). Important to note also is the fact that sustainability assessment compares humanity's WF and actual freshwater resources available (Hoekstra et al. 2009).

The outcome of the sustainability or impact assessment will, therefore, inform strategy formulation (policy). In other words, the response and formulation phase makes the use of the WF calculation results to inform policy decisions. Policy decisions made are aimed at reducing the primary impacts of the WF and hence the negative implications on sustainability and welfare indicators.

Approaches in water footprint accounting

According to Jeswani and Azapagic (2011), there are currently three approaches usually applied in the calculation of a WF: (1) the volumetric approach which is based on an assessment of the volume of water associated with a particular production activity; (2) the stress-weighted approach, which is based on an assessment of the amount of freshwater consumed in a production activity combined with an assessment of the implications of that consumption in terms of water stress; and (3) life cycle assessment approaches, which draw on estimates of water consumption using an inventory analysis similar to that of volumetric approach but also including an element of impact assessment.

A key problem with the volumetric WF approach is that it does not reflect the potential for water consumption to cause environmental harm. Consequently, Ridoutt and Pfister (2010) revised the WF calculation method to incorporate water stress characterization factors to make possible quantitative comparisons between different products and between stages of a product's lifecycle on the basis of environmental impact. It, therefore, implies that the stress-weighted approach and the volumetric approach share the same concept.

However, the two main differences of the two approaches are that in the stress-weighted approach: (1) green water is excluded based on the argument that its consumption does not directly contribute to water scarcity. This is because green water does not contribute directly to environmental flows and hence has a low opportunity cost (Amarasinghe and Smakhtin 2014; Ridoutt and Pfister 2010). (2) The blue water is normalized using global and regional stress factors based on the use of a Water Stress Index (WSI) to normalize water use in the calculation of the WF (Pfister et al. 2009).

In WF assessment as part of life cycle analysis (LCA), impact of water use is also based on estimates of water consumption. Inventory list of all inputs and outputs of water is created for a product or service, and water consumption is determined from the difference between inputs and outputs. One key difference is that in LCA, green water is normally considered and blue water may be subdivided into many classes according to its occurrence or quality. Grey water is not included as the impacts associated with pollution are dealt with elsewhere (Pfister et al. 2009).

Shortfalls of the methodology in application

Some key issues can be raised concerning the use of WF techniques. Some flaws with the idea, method, and clarification of outcomes can be raised. Some of the conceptual issues include the following: the dissimilarities in the categorization of different types of WF (green, blue, and

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Fig. 2 WF of an agricultural supplier; Source: Hoekstra et al. (2009), *WF* water footprint
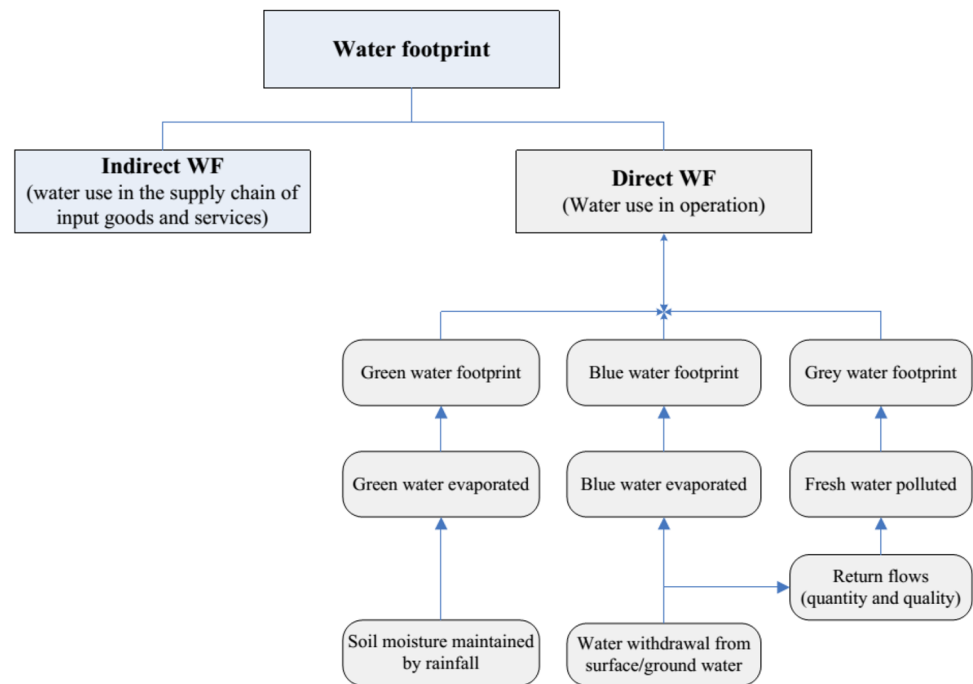
grey), the reduction of a WF to a distinct number, and supposition of parity among sources of blue water together with failure to think through production efficiency actions being evaluated (Amarasinghe and Smakhtin 2014; Brown and Matlock 2011; Ridoutt and Pfister 2010). According to Amarasinghe and Smakhtin (2014), efficiency of production activities being evaluated should have implications on their corresponding WFs. The major argument from the authors is that different kinds of water consumption should not be simply added to come up with a total WF as the opportunity cost and impacts associated with each of the components of freshwater (green, blue, and grey WF) consumption are dissimilar.

Furthermore, there is need to look at some methodological issues. For instance, the lack of clearness regarding how to account for temporal erraticism in water availability is another area that can be quizzed on the WF methodology. The volumetric methods, for example, repeatedly rely on data that are regularly unavailable or rather hard to get, which is a potential flaw of the approach. Studies have largely relied on assumptions and approximations when giant data sets have failed to explain local factors, seasonality of constructs and/or yearly deviations in water variations (Amarasinghe and Smakhtin 2014). More so, with the WF procedure, there is deficiency of lucidity principally when computing the grey WF as it mainly banks on designation of water quality principles which to some degree encompass subjective ruling which in turn may confuse comparability across dissimilar evaluations. Time and again modeling methods have trusted or used dissimilar base models of effective rainfall,

evapotranspiration, water availability, and withdrawals which can confuse comparability of WF upshots as well.

In addition, concerns have been raised on the hypothetical basis and practical values of WF (Wichelns 2013), to the use and reporting of its value (Perry 2011; van Halsema and Vincent 2012; Wichelns 2010, 2011). Major weaknesses of the WF concept often cited include: the unavailability of a systematically confirmed conceptual outline with WF figures lacking adequate reflection of other used inputs, overlooking the opportunity cost of water (as a resource) and also its bearings on livelihoods, use of WF in trade advantages (i.e., comparative advantage concept), etc. (Amarasinghe and Smakhtin 2014). Issues can also be raised against the approach in result clarifications. The volumetric approach, for instance, does not deliver a gauge of impact. Moreover, failure to contemplate opportunity costs related to the use of water and other moral, governance, social, and policy reflections connected with the valuable, limited resource is an additional flaw of the method in practice.

Given some of the criticism highlighted in this article, it is evident that generalised WFs may not be highly useful as indicators that improve understanding of water resources management. Even Perry (2014) concluded that generalised footprints are not accurate and helpful as good indicators leading to better understanding of water resources management in various sectors including agriculture (Perry 2014). In addition, issues to do with comparability of WF figures for two different products or processes have also been raised. Since WFs of two different products vary in environmental/social impacts from

the life cycle water consumption, the WFs are not comparable (Brown and Matlock 2011; Ridoutt and Pfister 2010). This observation implies that the WF concept can be more useful in ensuring sustainability of water resources when it is correctly tailored to local conditions. Incorporation of social and/or environmental characterisation factors that reflect on local water stress could potentially lead to standardized WF values which are comparable from one product to another (Brown and Matlock 2011; Pfister et al. 2009). This is even more plausible as fresh water scarcity is in most cases a localised characteristic. For instance, fresh water scarcity is not expected to be uniform across an entire region, and there is the inevitable possibility of variations.

Overall, the critique brings to light a very important point that reveals that for the WF to be a useful tool in promoting sustainable waster use in different production and consumption systems, there is the need for an all-encompassing development, and that the application should be suited to local characterization conditions. Even a study by Ridoutt et al. (2009) agrees to the noted criticism. Their study applied the WF concept to agri-food products, 250 g peanuts of M&M's brand, and a 575 g of a Dolmio pasta sauce with the aim of evaluating the usefulness of the WF concept at the product brand level. The case studies revealed several issues including: lack of correspondence between WFs and the availability of water for alternative uses in the absence of production and the difficulty associated with relating WFs to potential environmental and social harm. Their main conclusion was that the WF concept requires further development before it can be a useful and vital tool for promoting sustainable consumption and production.

The succeeding section refers to the usefulness of the concept and some recent successful applications.

Usefulness of the concept/methodology

Overall, the concept has the potential to address various water use issues and can promote sustainability in water use. Broadly speaking, the WF assessment as a tool gives several insights. It is not prescriptive to water practitioners, but also highlights possible options and the implications of the actions taken. The concept promises to have important implications for policy making at different levels or scales. The WF idea is very convenient for the management of limited water resources across the world. For example, the concept has been used by companies to provide insights on water use levels along product supply chains. This latter application of WFs is very useful as outcomes can be used to advance appreciation of related risks (regulatory, reputational and litigation, physical, and financial) which can then improve investment choices, water management

design tactics, and product development (WBCSD 2010; Zhang et al. 2013).

The WF approach is also an important instrument for pinpointing products acquired from areas of water stress and a prospective effective tool for water auditing (i.e., finding production procedures that ingest more water than others). This can be key in promoting water use efficiency in production. More so, Perry (2014) highlighted the potential usefulness of the WF concept in agricultural water management. This observation is of great importance considering that agriculture worldwide is among the largest consumers of freshwater resources. In addition, the concept has potential of being helpful in providing options for adaptation to water scarcity problems posed by climate variability and change. Crop varieties in the future can be selected based on their WFs which can improve water resource management and promote effective adaptation to water scarcity problems. The WF can also bring useful inputs necessary in resolving conflicts in using shared water resources. Specific recent applications can confirm the usefulness of the methodology. This is evident in most recent studies that have successfully applied the concept. We refer to only a few cases to highlight some of the successful applications of the WF concept in industry (primary, secondary, and tertiary industries), in product consumption, and in possible dispute resolution when major water sources are shared by nations (summarized in Table 2).

Applications in primary production activities

Several studies have relied on the WF methodology in agriculture. We refer to some recent applications in agriculture in different parts of the world. First, Pellegrini et al. (2016) applied the WF approach to olive growing in the Apulia regions for comparing WF of different cropping systems that reduce demand for water both regionally and globally. The results were that in comparison with other investigated systems, high-density system of cropping was the most competitive because of reduced total WF. Their results highlight important policy implications of the WF concept/methodology in promoting water use efficiency in olive production systems. The concept can, therefore, be applied in different cropping systems to improve water use efficiency.

In addition, de Miguel et al. (2015) also applied to the same concept successfully in assessing the sustainability of the pork industry in Spain, which is one of the largest consumers of the water resource in the country. Results indicate that when comparing the grey and green WFs of feed production in pork producing regions using pollution and water scarcity indicators, unlike imported feed, most local produced feeds are from watersheds with

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Table 2 Summary of some successful applications of the WF concept/methodology in the 21st century

Sector	Details of WF application	Successful application of WF	Country and/or region	References
Primary industry, e.g., agriculture	Applied WF to olive crop production systems	WF can be used to improve water use efficiency in olive production systems	Italy, Europe	(Pellegrini et al. 2016)
	WF applied to Pork industry	WF can be used to improve water productivity and eco-efficiency in pork industry	Spain, Europe	(de Miguel et al. 2015)
	WF applied to crop and animal production	WF can be used in improving decision making pertaining to sustainable choice of source of protein (pulses vs meat products)	Several countries, Global	(Mekonnen and Hoekstra 2012)
	WF applied to animal production (pork, beef, poultry)	WF can be used to compare water use in different animal production systems	Several countries, Global	(Gerbens-Leenes et al. 2013)
	WF applied to several crop value chains	WF can be used to detect benchmark water reduction values in crop production	Several countries, Global	(Mekonnen and Hoekstra 2014)
Secondary production (manufacturing)	WF applied to steel manufacturing in China	WF can be applied in environmental risk assessment associated with steel production	China, Asia	(Gu et al. 2015)
	WF applied to pasta production	WF can be used to assess the sustainability of business production process	Brazil, South America	(Ruini et al. 2013)
	WF applied to production of wine	WF can be used to inform on various ways of ensuring sustainable water use in Wine industry	Romania, Europe	(Ene et al. 2013)
	WF applied in processing dairy products	WF can be used to inform on how dairy products can be produced with minimal contribution to water scarcity	Australia	(Ridoutt et al. 2010)
	WF applied to textile production	WF can be used to reveal trends and intensity in water use in the textile industry	China, Asia	(Wang et al. 2013)
Service industry	WF applied to the gaming industry	WF can be applied to determine demand of freshwater resources in gaming industry	China, Asia	(Li and Chen 2014)
	WF applied in wastewater treatment	WF can be used to evaluate the environmental impacts of wastewater discharge into a river	Spain, Europe	(Morera et al. 2016)
	WF applied in wastewater treatment	WF can be used to assess the performance of wastewater treatment plants	China, Asia	(Shao and Chen 2013)
	WF applied to projected biofuel production for the transport sector	WF can be used to assess water demand changes associated with transition to biofuels in road transport	Global	(Gerbens-Leenes et al. 2012)
Other fields	WF applied in water resources sharing in the Nile Basin	WF can be used to determine equity in water resources sharing and possibly in resolving water conflicts	Egypt and Ethiopia, Africa	(Sallam 2014)
	WF applied in cotton consumption worldwide	WF can be used to evaluate contributions made by various regions to water use associated with cotton consumption	Global	(Chapagain et al. 2006)
	WF applied to consumption of crop products in Indonesia	WF can be used to detect regional differences in level and magnitude of water use in a country	Indonesia, Asia	(Bulsink et al. 2009)
	WF applied to coffee and tea consumption	WF can be applied to detect level of water use associated with tea and coffee consumption and the sources of water involved	Netherlands, Europe	(Chapagain and Hoekstra 2007)

WF water footprint

overexploited freshwater. Results also give important insight on water productivity and eco-efficiency in the pork industry in Spain. Similar studies can be applied in livestock production enterprises elsewhere to improve decision making aiming at improving water productivity in livestock production.

Another related study by Mekonnen and Hoekstra (2012) analyzed WF of animal products, taking into account different production systems and feed composition per animal in different countries. Their study alludes to the fact that animal products from grazing systems have smaller grey and blue WF than products from industrial

systems. More so, it is more water efficient to acquire fat, protein, and calories through crop products than animal products. Specifically, they found that the WF of each gram of protein, for milk, eggs, and chicken meat, was 1.5 times larger than for pulses. This is another important application considering the continual rise in the demand on global meat consumption and the need to disengage meat production from excessive water consumption.

Building on the work of Mekonnen and Hoekstra (2012) summarized earlier, Gerbens-Leenes et al. (2013) carried a comparative study of poultry, beef, and pork WF. Their study highlighted that the WF of meat products basically varies and depends on the three aspects of feed (origin, composition, and conversion efficiencies). Their study found beef to have a larger total WF than pork and pork to have a larger WF than poultry. However, the average global blue and grey WFs were found to be similar across pork, beef, and poultry products. This is another important application as results, and ceteris paribus can be useful in deciding on more suited livestock enterprises in different areas or regions within a nation based on relative water scarcity (both physical and economic scarcity).

Relating to the production of a number of crops worldwide, Mekonnen and Hoekstra (2014) applied the WF methodology to come up with a set of WF benchmark values for several crops (i.e., wheat, sugarcane, soybean, barley, rice, sorghum, potatoes, millet, maize, and cotton). Their study revealed that if the green and blue WF of crop production in the world can be reduced to the level of the best 25th and 10th percentile of current global production, global water saving in crop production would be 39 and 52%, respectively. More so, relating to a reduction in nitrogen-related grey WFs in crop production worldwide and to the level of the best 25th and 10th percentile of current global production, water pollution would be reduced by 54 and 79%. Again, their study reveals the significance of the WF if applied in global crop production intensification motives that aim to match global food demands with sustainable water use. Their benchmark values give important insight on how the WF concept can be applied to reduce water use and pollution in agriculture worldwide.

Applications in secondary production (manufacturing industry)

Many studies have also effectively used the WF in the manufacturing industry, and again, this shows how useful the concept is becoming over time. For example, Gu et al. (2015) applied the WF concept successfully in the case of the steel industry of China. Their study performed water risk assessment of the investment in the industry to the environment. Specifically, their study analysed the characteristics of the iron and steel industry in China from a life cycle assessment perspective and performed a water risk assessment based on WF calculation results. Their study concluded that the steel industry poses serious environmental risks. Such results give an important insight for policy concerning high water use in steel manufacturing in China and water resource decoupling (both impact and resource decoupling). Similar studies in less industrialized countries can yield significant policy outcomes as they can be applied to match development paths with strategies that reduce environmental risks associated with high water use in steel manufacturing and related industries.

In addition, Ruini et al. (2013) applied the WF concept to a large food company in Brazil. Their study considered the case of pasta production. In their study, the WF of a 1 kg of Barilla pasta was calculated and had a range of between 1.336 and 2.847 L of water, depending on local environmental conditions, production site, and durum wheat production practices. Their study showed that the sustainability of business production processes can be evaluated using the WF indicators.

Another study by Ene et al. (2013) applied the WF methodology to ascertain the WF of a 750 mL bottle of wine in the wine-making industry of Romania using a case study of a medium-sized production plant. Their study findings indicated that almost 99% of the total WF was related to the supply-chain water use, out of which 82, 3, and 15% were green, blue, and grey, respectively. Based on their findings, several suggestions for sustainable water use in the industry were derived. They concluded that the WF application may contribute to water saving in the wine industry among other benefits. Similar studies can be applied to improve on water-saving strategies in beer brewing and other beverage-making firms.

In an application involving production of skim milk powder, Ridoutt et al. (2010) applied the WF concept incorporating the life cycle methodology that takes into account local water stress, where production occurs in Australia. Their study revealed that normalized WF of milk products from South Gippsland, a key dairy production region in Australia, were 14.4 L/kg of total milk solids in whole milk at farm gate and 15.8 L/kg of total milk solids in Skim milk powder delivered to export destination. Their study results illustrate that dairy products can be produced with reduced potential of contributing to freshwater scarcity.

Moving onto another successful application of the WF concept in the textile industry in China, Wang et al. (2013) applied the bottom–up approach to estimate the direct blue and grey WF of China's textile industry. Their study revealed that China's textile industry had an increasing trend of blue and grey WF from the period 2001 to 2010. More so, they found the intensities of blue and grey WF of the textile industry to be declining yearly which they linked

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to efforts by the government in: issuing restriction policies on freshwater use and wastewater management (generation and discharge) and widespread adoption of water-saving wastewater treatment technologies in the industry. Their study gives important insights on water and water use intensity trends in textile industry using the WF methodology and how government policy can contribute to improved water use efficiency in the industry.

Applications in tertiary industry (service industry)

Many service industry sectors have benefited from the WF concept methodology. We refer to some examples of application. In an application in service industry, Li and Chen (2014) employed the hybrid method to ascertain the WF of a gaming industry in a water scarce area, Macao. Their findings reveal that direct water use in the industry only accounts for a small fraction of the gaming industry's WF. Their results also indicated that the exchange of water embodied in product and service between different sectors is also a useful mean to satisfy individual sector's demand for freshwater resources. In their study, the WF assessment brought some new perspectives to water management in the gaming industry and encourages a wide use of materials, goods, and services in a more sustainable way.

In addition, Morera et al. (2016) applied the WF concept in wastewater treatment. Their study illustrated the usefulness of the WF in assessing the environmental impacts and benefits from wastewater discharge into a river. Specifically, they analyzed a wastewater treatment plant which treats 4000 cubic meters of wastewater per day, using three different scenarios (no treatment, secondary treatment, and phosphorous removal). They found that using secondary treatment and chemical phosphorous reduced the WF by 51.5 and 72.4%, respectively. Their results pointed to a large decrease in the grey WF when compared with no-treatment scenario and a small blue WF when treating wastewater.

In a related study, Shao and Chen (2013) applied the WF methodology (hybrid method) to analyze a Beijing Space city wastewater treatment plant. Their case study revealed that increasing wastewater and sludge treatment rates point to the urgent need to reduce the WF of China and to improve the performance of wastewater treatment in general. The successful applications in wastewater treatment give important insights on how to make use of the WF concept to ensure sustainable water use in a highly urbanized environment. This is so, since in developing regions, urbanization has been linked with high and inefficient water use (Van der Bruggen et al. 2010).

Another research pointing to the service sector (transport sector) Gerbens-Leenes et al. (2012) used the WF concept to assess global water use associated with increasing biofuel production and use for road transport by year 2030 and evaluated potential implications for water scarcity. Their study combined data from WF analyses with information from the Alternative Policy Scenario from the International Energy Agency (IEA APS) Scenario for 2030 to analyze water demand changes related to a transition to biofuels in road transport. Their results revealed that global biofuel WF increased more than tenfold in the period 2005–2013 under the IEA APS scenario. More so, countries such as Brazil, China, and the US contributed up to 50% of the global biofuel WF. Their study gives important insights on biofuel production and possible contribution to water scarcity.

Applications in product consumption and water dispute resolutions

We also refer to successful applications of the WF concept in water resource sharing and consumption of several crop and animal products. Relating to equity in water resource sharing, Sallam (2014) used the WF concept as an indicator for equitable utilization of water resources between two countries Egypt and Ethiopia. The two countries share freshwater resources from the Nile basin. The study found that Ethiopia and Egypt's WF per capita was about 1167 and 1385 cubic meters per year and per capita, respectively. More so, the study found that the external WF of Egypt and Ethiopia was 28.5 and 2.3% of the national consumption WF, respectively. Their main conclusion was that natural, environmental, social, and economic aspects should be considered when considering and using the WF as an effective tool for resolving conflicts in shared water resources. Similar analyses in regions that share water resources, for instance, the Niger basin (shared by Guinea, Mali, and Nigeria), and Zambezi basin (shared by Zimbabwe and Zambia) can be used to improve water resources sharing terms which can mitigate conflicts.

In addition, the WF concept has been successfully applied in product consumption. For instance, Chapagain et al. (2006) applied the WF concept in the analysis of the WF associated with global cotton consumption. Using the analysis period of 1997–2001, their study revealed that the consumption of cotton products required 256 g m^3 of water per year, out of which 42, 39, and 19% were blue, green, and grey water, respectively. More so, they revealed that about 84% of WF of cotton consumption in the European Union 25 region was located outside Europe. Major impacts of the EU25 region WF were found to be concentrated in Uzbekistan and India. Their main conclusion pointed to the fact that, with lack of proper cotton pricing mechanisms, cotton consumers have little incentive of taking responsibility for the impacts on remote water systems.

Concerning crop products consumption, Bulsink et al. (2009) applied the WF concept to assess the WF associated with consumption of crop products in Indonesia. Their study found huge regional differences in WF related to the consumption of crop products. Provincial WF varied between 859 and 1895 cubic meters per capita per year.

More so, in almost similar study, Chapagain and Hoekstra (2007) analysed the WF associated with cotton and tea consumption in The Netherlands. Their calculation of the WF was based on crop water requirements in the major coffee and tea exporting regions and water requirements in subsequent processing stages of the products. Their study found that in The Netherlands, a cup of coffee cost about 140 L of water while that of tea costs about 34 L of water. More so, it was found that total WF of Dutch tea and coffee consumption accounted for about 27 billion cubic meters of water per year which is equivalent to 37% of annual Meuse runoff. The water needed to consume tea and coffee in The Netherlands was found not to be Dutch water. Fruitful applications in product consumption give important insights relating to virtual water trade and possible implications on water scarcity in regions involved.

Successful application of the methodology in various sectors is a good sign that the concept can be very useful in improving water resources' governance, management, sustainability in various economic sectors, and hence in sustainable development. The concept has a very huge potential if adopted accordingly to improve eco-efficiency and productivity in water use, i.e., improving economic and social benefits from water use with relatively lower (relative water resource decoupling) or decreasing (absolute water resource decoupling) volumes of water and with minimal adverse impacts to the environment (impact decoupling). Widespread adoption worldwide even in least developed world can be encouraged to promote responsible production and consumption.

Conclusions and implications

This study reviewed the literature on the WF concept/ methodology as applied at different scales and highlighted some relevant areas to improve an understanding of the concept/methodology by a wider audience especially those outside the scientific world. The study relied on an extensive search of current literature on the subject to come up with review results. The review highlighted important steps, phases, and approaches taken in WF accounting at different levels (i.e., nation, product, or process). More so, the review noted some of the criticism, strengths, and successful applications of the WF concept.

From the shortfalls of the WF concept and methodology, it is evident that generalised WFs may not be highly useful as indicators that improve understanding of water resources management. For instance, WFs of two different products may vary in environmental/social impacts from the life cycle water consumption, and hence, their WFs may not be comparable. Largely, the critique of the WF concept and methodology highlighted in this paper brings to light a very important point that for the WF to be a useful tool in promoting sustainable waster use in different production and consumption systems, there is the need for an all-encompassing development, and that the application should be suited to local characterization conditions.

On the other hand, the usefulness and recent applications of the WF concept/methodology reveal that it is very simple to comprehend and apply. The concept/methodology has been applied at different scales, evaluated and improved, since it was first introduced in 2002. The concept/methodology is very useful in making assessment of water use in different production activities for a proper management of scarce water resources. Several studies have successfully applied the concept/methodology of WF at the national, industry, and product levels and managed to come up with important recommendations that may promote efficiency in water use in good and service production and consumption. From the review, it is evident that the WF concept/methodology has been successfully applied in different sectors including primary production, manufacturing, service industry, product consumption, and water dispute resolutions. Precisely, the review results highlight the important fact that the WF methodology is a very essential tool for the management of global water resources and for promoting sustainability in human-induced water (green, grey, and blue) use at various levels. More so, the WF concept can be applied to mitigate conflicts in water resource sharing.

In conclusion, a proper application of the WF concept/ methodology can contribute significantly to sustainable water resources management and governance and hence to a sustainable development. This is plausible, since wider application of the concept/methodology can contribute significantly to water resource and impact decoupling (reducing adverse environmental impacts associated with water use in the process of development and promoting efficiency in water use for a more sustainable development). Therefore, an understanding of the WF methodology and concept by a wider array of development practitioners is critically important to enhance the potential positive impacts of the concept and methodology in development. More widespread adoption of the concept in developing regions especially least developing regions is, therefore, encouraged.

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