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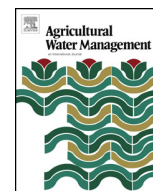
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Water footprints: Path to enlightenment, or false trail?

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ABSTRACT

Virtual water and water footprints have gained recognition as indicators to guide action on issues related to water scarcity. I argue that water footprints are fundamentally different from carbon footprints, as local reductions in carbon emissions have global benefits, while global attempts to reduce water footprints will have neither necessary beneficial impacts in areas of local water scarcity, nor global impacts on atmospheric water content. In addition, water footprints have little or no meaning for purposes of setting policy regarding national water use or international trade. Furthermore, the calculation procedures adopted in most estimates of water footprints are flawed. Finally, I suggest that water footprints are incorrectly assessed on an absolute, rather than a relative basis. Water analysts are fortunate to have hydrology, a science with agreed procedures and standards, to use in describing the physical impacts of interventions in the hydrologic cycle. Generalised water footprints are neither accurate nor helpful indicators for gaining a better understanding of water resource management.

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1. Introduction

Competition for water, unsustainable use of groundwater, polluted, and depleted lakes and rivers, damaged ecosystems and dried-up estuaries are recurrent themes of agency and donor reports, journal articles, and international conferences. Such problems are evident in many regions where precipitation is low or erratic, such that vegetative growth is limited by water availability. Population growth, changes in diet, increasing incomes, and climate change are generally expected to increase these pressures.

Trade offers a solution to differential resource endowments between regions and countries. Since some countries have inadequate land (e.g., Singapore) or water resources (e.g., Yemen) to be self-sufficient in agricultural commodities, importing food and fibre is an essential element of their economy. Some twenty years ago, Prof. Tony Allan (Allan, 1997) introduced the phrase “virtual water”, noting that many goods, especially agricultural products, require large quantities of water in their production: for example, producing a kilogram of wheat typically utilizes a tonne of water. Trade in agricultural products, he argued, can be viewed as trade in the water utilised in the production process.

According to the virtual water perspective, if a country has fully committed its water resources, importing a kilogram of wheat negates the need to import a tonne of water. Yet, the traded products actually contain very little water. Most of the water used to produce a crop is transpired through the leaves, or evaporated from

wet leaves or soil. Both these processes—the first essential to crop growth, the second a non-productive consequence of making water available to the crop—convert locally available water into water vapour that contributes to the hydrologic cycle at uncertain future times and places. Thus, crops embody “virtual” water just as an industrial product might be said to embody “virtual” labour, capital, or intellectual property rights.

In the early 2000s, the virtual water perspective was extended to the idea of a “water footprint” (Hoekstra and Huynen, 2002). This involves two key additions to Allan's original approach. First, the footprint of a product (e.g., a bottled drink) involves the water used to produce the agricultural ingredients, plus the water used to produce the container, the water required to generate power consumed in the production process, and the water used in other aspects of production and marketing. Second, water footprint analysis considers both ends of the trade in virtual water—where the water embodied in a product comes from, and where it goes (Hoekstra et al., 2012).

In parallel with the extension of virtual water into the notion of a water footprint, the insight provided by the concept has evolved from an idea of “economic efficiency” (whereby countries with very scarce water resources can redirect water to higher valued uses, while importing lower valued crops, or reducing consumption to more sustainable levels) to one of “fairness” (in which countries with very high per capita water footprints are seen as excessive consumers, while other countries remain “water poor”). For example, Lillywhite et al. (2010) write:

If the UK were to adopt an ethical policy on water, it should commit to assisting non-industrialised economies to increase their sustainable intensification of water use as a precautionary measure

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to reduce impacts on water resources, economies, and on farmers.

Such recommendations involve value judgements (ethical, sustainable, precautionary) that I do not address here. Rather, I focus on the meaning and measurement of a water footprint, and in particular the uncertainties in estimating the underlying virtual water content of agricultural crops, which is typically the largest component of an estimated water footprint. I consider also the partitioning of a water footprint into “green” and “blue” components.

2. Water and carbon footprints

Knowing the water footprints of the commodities we grow, manufacture, and consume provides an indicator of our dependence on water, and allows estimation of national, sectoral, and individual contributions to the global demand for water. In recent years, the water footprint perspective has attained rather similar status to that of a carbon footprint.

Ercin and Hoekstra (2012) present a detailed comparison of the similarities and differences between carbon and water footprints, noting:

Although there are similarities in the way both footprints are defined and calculated, they differ in important ways as well. **The location and timing within the year of [greenhouse gas] emissions, for example, are not relevant, whereas location and timing of water consumption and pollution matter critically.**

The highlighted comment is of considerable importance. Any (local) carbon dioxide emissions contribute to the (global) stock of carbon dioxide in the atmosphere. The location of the source is not relevant because our concern is with the global total. We expect that reducing the consumption by 1 kg of a commodity with a carbon footprint of 2 gm kg^{-1} will reduce global carbon emissions by 2 kg, with a corresponding impact on the amount of carbon in the atmosphere. Whether the commodity is produced in Iowa or Adelaide is irrelevant. We do not need to know the location of production to evaluate the global impact of carbon emissions.

Water footprints are in some ways the opposite. Emitting water vapour locally into the atmosphere is not a global concern, as the amount of water vapour in the atmosphere is a rather stable outcome of the earth's energy balance. However, the local source of water vapour is a matter of concern, particularly in water-stressed areas. With carbon footprints, our concern is aggregate emissions and the source is irrelevant. With water footprints, aggregate “emissions” are irrelevant and the source is the critical issue.

The above quotation suggests that some water footprint proponents understand this important difference between carbon and water footprints. Yet many authors present estimates of water footprints without noting whether a producing area is water plentiful or water short. For example, statements such as the following appear on the Water Footprint Network website:

For drinking one standard cup of coffee in the Netherlands we need about 140 L of water, by far the largest part for growing the coffee plant.¹ Hoekstra and Mekonnen (2012a) write that “Understanding the water footprint of a nation is highly relevant for developing well-informed national policy.” Elsewhere in that article, as indeed in the two manuals published by the Water Footprint Network (Hoekstra et al., 2009; Hoekstra et al., 2011) there are caveats and cautions that estimated water footprints should be seen in context. Yet, as can be seen from the list of options described in the latter document, at Table 5.4 (p. 109), reductions in the capture and consumption of rainfall, and reductions in the consumption of irrigation water are advocated, and are presumed to

be virtuous and desirable, given global concerns regarding water scarcity. Even where water is plentiful the recommendation is similar:

We acknowledge that reducing the aggregate [water footprint] in environmentally stressed catchments deserves priority, but given the competition over the globe's freshwater resources, increasing water productivities (lowering product water footprints) in non-stressed basins can be an instrument to reach that goal. (Hoekstra and Mekonnen, 2012b)

Lowering product water footprints in such circumstances, thus allowing more water to run unproductively to the sea, has no economic or social merit². This limited view of water use is evident in the body of publications on water footprints³. Many authors suggest that because human activities result in water scarcity, we must reduce the water footprints of our production and consumption activities.

Water and carbon footprints share a common weakness with respect to policy implications (Gawel and Bernsen, 2011a, 2011b, 2013). Both are essentially one dimensional estimates of impact. In the case of coffee noted above, we do not know whether, if the consumer gives up a daily cup of coffee:

- a) Decreased coffee production will occur in a water-short or a water-plentiful country;
- b) The water “saved” will be left in a river or aquifer, or reallocated to a lower (or higher) valued use; or
- c) The coffee consumer will instead drink some other beverage with a lower (or higher) water footprint in a more (or less) water stressed area.

Procedures to recognise the significance of scarcity are yet to be agreed among proponents of water footprints. Ridoutt and Huang (2012) propose a method of computing “weighted” water footprints that evaluate the components of the footprint depending on whether the source of water has limited or abundant water supplies. However, Hoekstra and Mekonnen (2012b) reject this idea, writing:

A mere focus on reducing [water footprints] in water-stressed catchments displays a limited perspective on the question of what is globally sustainable and efficient water use.

According to Chenoweth et al. (2013) the Water Footprint Network opposes such adjustments because the volumes of water then reported would not represent “real” volumes, and also because “a weighted water footprint... may lead to an over-emphasis on reducing water use in water stressed catchments, thus preventing investment in improved efficiency in water-abundant areas.” In sum, there is no agreed approach to incorporating scarcity into the calculation of water footprints, other than the partition of water into “blue” and “green” components. The procedure for that analysis is assessed later in this paper, but here it can be noted that there is no necessary relationship between colour and scarcity (“blue” water in Canada is far more plentiful than “green” water in Egypt, for example).

While some authors are sceptical of the potential significance of the virtual water concept for addressing environmental issues (Meran, 2011), others have proposed “integrating” water, carbon,

¹ <http://www.waterfootprint.org/?page=files/CoffeeTea>, viewed October 17, 2013

² Admitting that such a policy might have a positive outcome would undermine the presumption that a reduced water footprint is desirable in the same, unqualified way that reducing a carbon footprint is desirable.

³ Publications from the Water Footprint Network and independent scholars contribute to a substantial body of literature on the subject: Science Direct (searched December 11, 2012) finds more than 400 papers including “water footprint” in the title, and almost 13,000 web hits.

and ecological footprints into a family of footprints. Galli et al. (2012) report:

Of the three indicators, the Ecological Footprint was found to have the widest spectrum of applicability. . . [T]he Carbon Footprint was found directly able to address the EU Climate Objectives, though its range of applicability was found to be very narrow. The water footprint was found to have a restricted range of applicability and to be sufficiently informative for the EU water policies only.

Despite these rather serious caveats, the authors conclude that: . . . the Footprint Family was found to cover a wide-enough spectrum of policies and, particularly for what concern sustainable production and consumption issues, it is believed to be informative for policy and decision makers to a satisfactory extent.

Only through a more comprehensive analysis of changes in production elsewhere can the physical implications of an intervention that changes a local water or carbon footprint be properly understood. In the economy more generally—beyond the already quite complex physical accounts—matters become even more complicated and obscure.

3. Economic and policy implications of water footprints

Some analysts disagree with the idea that water footprints convey useful policy information. Wichelns (2010a, 2010b, 2010c, 2010d) argues that the relevance of water footprints to the selection of appropriate policies is quite limited. Policy makers must consider the social, political, and economic aspects of water use in any setting. Water footprints, alone, contain too little pertinent information to guide policy decisions.

Water scarcity (or abundance) is an important component of policy analysis, but it is not sufficient. Whether it is appropriate for a water-short country to export water-intensive crops (or vice versa) is a function of the range of alternative uses for its land, labour, human, and physical capital, infrastructure, and water. It is the relative availability and productivity of the spectrum of inputs that determine the appropriateness of selecting which crops to grow for local consumption or export, and which crops to import. Wichelns (2010c) further criticises a specific application of the water footprint approach in Spain, which has adopted the water footprint analysis as an essential element of regional policy and planning (Garrido et al., 2010).

Ansink (2010) refutes claims that trade in virtual water “levels” the unequal distribution of the resource, or reduces the potential for conflict, which are elements of the original rationale for the virtual water perspective. Roth and Warner (2008) argue that “water trade” is not politically neutral, and cannot be separated from the debate regarding agriculture and food strategies, and the political dimensions of such issues. Gawel and Bernsen (2013) suggest the virtual water perspective has limited usefulness as a guide to policy, and that water-related problems should be solved locally, and not through global governance schemes or trade barriers.

The theory of comparative advantage suggests that if two countries have relative differences in production processes, expressed as differences in opportunity costs, there will be scope for trade that will benefit both countries. The theory does not suggest that if country A has more water than country B (per hectare or per capita), then country A should export water-intensive agricultural goods to country B (Wichelns, 2010d).

4. Green, blue, and grey water

It has been argued (Falkenmark and Rockstrom, 2005) that the virtual water embodied in agricultural products can usefully be divided into green, blue, and grey water components. In this

scheme, green water is the water retained in the upper layer of the soil profile following rainfall events, and which is subsequently drawn on by a plant's root system. Irrigation scientists have traditionally called this “effective rainfall”—that proportion of rainfall that directly contributes to plant transpiration.

Blue water is that which either runs off into streams or lakes, or percolates below the root zone into an aquifer. Among other potential uses, blue water is a source of irrigation water. Precisely because it can be controlled, blue water is seen as being more “valuable,” as it can be stored, delivered, withheld, or redirected to other purposes.

The grey water footprint of a product is calculated as the water required to dilute one or more pollutants in return flows to achieve a specified usable water quality standard. This idea was elegantly formulated and elaborated by Keller and Keller (1995). The major limitation of this notion (Perry, 2007) is that the “usable” quality changes arbitrarily with the nature of the downstream use. For example, the grey water footprint of an industry might be minimal if the downstream use is hydropower or navigation, but substantial if the downstream use involves swimming, fishing, or drinking. The notion of a grey water footprint is further limited by the absence of an agreed water quality standard to use when estimating dilution requirements.

As noted above, the water footprint of a product comprises all the water consumed in its production. In most cases, the water footprint is dominated by the water required to produce agricultural commodities, and it is here that the distinction between green and blue water is of interest. The partition of rainfall into blue and green depends on many factors. For example, a larger portion of rainfall on a lightly vegetated slope will runoff in comparison with an area that is heavily vegetated or shaped to induce infiltration. Deeply rooted vegetation can exploit a larger root zone than shallow rooted vegetation, thus converting more precipitation to green water. Somewhat paradoxically, irrigation with blue water increases green water availability and consumption because it results in a healthier, deeper root system.

Water that is held in the unsaturated layer between the root zone and the (saturated) aquifer has no colour status, but will eventually be blue if, as a result of further rainfall or excessive irrigation, it reaches an underlying aquifer or appears as a spring, further down slope. Yet the water might become green again if the underlying aquifer is recharged and rises toward the root zone. If the aquifer is saline and unusable, again the colour is indeterminate, and if the saline aquifer rises toward the surface and discharges into drains, it could be considered as “grey” water, requiring dilution. Thus, the final colours are at best complicated. As demonstrated below, even the first-order estimate of a water footprint and its partitioning into blue and green components, according to the procedures adopted by most analysts and recommended by the Water Footprint Network, can produce highly variable results.

Hydrologists (see for example, Scanlon et al., 2007) are aware that land use affects the relationship between precipitation, evapotranspiration, recharge to and discharge from aquifers, and stream flows. For a hydrologist, these are all components of the scientific framework they apply to the analysis of water resources, governed by the law of continuity of mass.

The water footprint perspective does not recognize the inherent complexity in describing and managing water resources. The means of exploiting more green water (water harvesting to increase infiltration, or planting crops that extract more water from the root zone) will reduce blue water availability in streams and aquifers. But the implication of the water footprint approach for the inexperienced policymaker is that there are two independent sources of water, green and blue, that can be exploited separately and without concern for hydrologic principles or externalities.

5. Computing the components of the water footprint

Carbon and water footprints often are promoted for their potential to “raise awareness” among policymakers and the public at large, regarding environmental issues. Given that objective, some degree of scientific rigour might appropriately be sacrificed in the effort to inform and develop constituencies for reform. However, some authors assert strongly that water footprints are based on science.

In their comparison of water and carbon footprints, [Ercin and Hoekstra \(2012\)](#) are critical of the confusing lack of standard procedures for computing carbon footprints, especially when compared to the clarity of the approach for computing water footprints:

Unlike the carbon footprint, which emerged in practice, the water footprint was born in science. . . In 2009, about seven years after the first use of the water footprint concept, the Water Footprint Network published the first version of the [global standard for water footprint accounting] ([Hoekstra et al., 2009](#)). Two years later the second version was published ([Hoekstra et al., 2011](#)). This standard, which was produced in a process of consultations with organizations and researchers worldwide and subjected to scientific peer review, has comprehensive definitions and methods for water footprint accounting ([Hoekstra et al., 2011](#), p. 6)

The following sections examine the soundness of the method for calculating crop water footprints, based on the procedures set out in the water footprint manuals cited above. First, the total crop water consumption estimated from remotely sensed field data is compared to the total as estimated using the approach recommended in both manuals ([Hoekstra et al., 2009, 2011](#)). Second, the difficulty of partitioning the footprint between “blue” and “green” is demonstrated by comparing results reported in the 2009 manual with those reported for the same scenario in the 2011 manual. I then describe the appropriate conceptual framework for assessing whether an activity increases or reduces the aggregate water footprint of an area under analysis.

5.1. Computing the water footprint of an irrigated crop

The procedure to compute the virtual water content of an irrigated crop is identical in both the 2009 (Appendix I, p 91) and 2011 (Appendix I p 131) versions of the manual:

- The reference evapotranspiration for the geographical area concerned is calculated using standard procedures, based on the Penman–Monteith approach—most commonly as described in FAO 56 ([Allen et al., 1998](#)), for the period during which a crop is grown.
- Crop factors are applied to the estimates of reference evapotranspiration. Thus if reference ET for the first ten days after planting of a crop is 50 mm, and the crop factor during its first ten days of growth is 0.2, then computed ET for the crop would be 10 mm (50 mm × 0.2).
- The computed ET represents the maximum ET for a fully irrigated crop, with no nutrient stress, pest damage or other constraints to growth.

This procedure is automated and standardised through the use of CROPWAT, a computer program published by FAO⁴, which has suitable datasets (climate and crop factors) pre-formatted for use in many scenarios. Historically, this procedure, or a close variant, was the only option for estimating crop ET at significant scales. Indeed, most irrigation projects and water distribution plans are based on

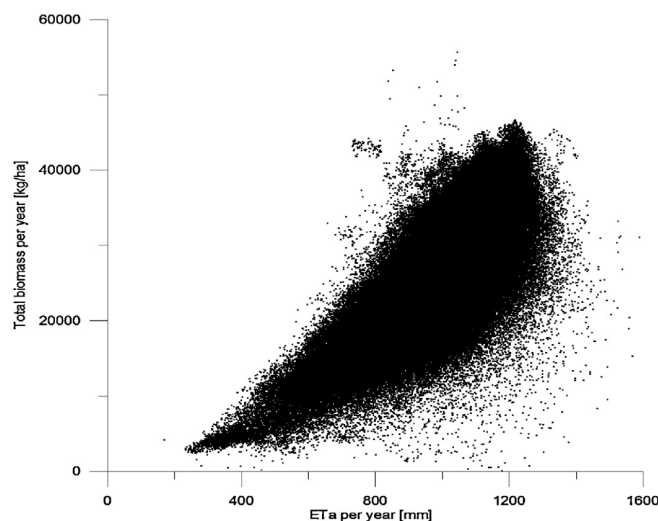


Fig. 1. Scatter plot of yield versus ET for sugar cane in Inkomati basin.

Table 1

Estimated water footprint of sugarcane based on CROPWAT and SEBAL.

	ET _{green}	ET _{blue}	ET _{tot}
	mm/Growing season		
CROPWAT8	638	959	1597
SEBAL	638	384	1050

the demand implied by this potential ET of a crop under optimum conditions. Actual ET depends on the extent to which these ideal conditions are met, and may often be considerably less.

More recently, remote sensing provides spatially and temporally disaggregated estimates of ET (and indeed of E and T) and estimates of biomass. Such data can significantly refine estimates of water footprints.

Fig. 1 provides sample data for commercial, pivot-irrigated sugarcane production in the Inkomati basin (South Africa) in 2003. The total area under sugarcane (about 65,000 ha) is sampled in pixels of 6.25 ha, yielding about 10,000 observations. The data were computed in a study using the SEBAL algorithm ([Bastiaanssen et al., 1998](#)) reported by [Hellegers et al. \(2009\)](#). This example pertains to a single, perennial crop, irrigated with a uniform technology. Crop husbandry (given the linkages to the sugar industry) is relatively uniform and good, and the incentive structures also are uniform, as data come from one region.

The graphed data demonstrate the near-linear production frontier, the maximum observed biomass formation (about 45,000 kg ha⁻¹) and the maximum observed ET (about 1300 mm). The average measured ET in the study is 1050 mm. The remote sensing study also provides data for use in estimating the “green” water content of the sugarcane. The average ET from unirrigated agricultural land in the area for the study year is 666 mm. Taking this as an empirical estimate of the “green” contribution to the sugarcane, we would conclude (based on the remote sensing data) that the blue water contribution is 384 mm (1050 – 666 mm).

In Table 1, these figures are compared to corresponding numbers derived from applying CROPWAT to the data for the area, as proposed in both versions of the water footprint manual referenced above⁵.

⁴ See <http://cropwat.software.informer.com> for an overview of the history and procedures in CROPWAT, which is now at version 8.

⁵ I am indebted to Giovanni Munoz of FAO for extracting the climatic data and running the CROPWAT program, while retaining responsibility for my interpretation of the results.

Table 2

Data from 2009 manual on partitioning of water footprint into green and blue water.

CROPWAT option	ET _{green}	ET _{blue}	ET _{tot}
	mm/Growing season		
Crop water requirement	168	628	796
Irrigation schedule	432	361	793

Comparing these results to those obtained using SEBAL shows agreement to within 5% between the estimated “green” water contributions (666 mm compared to 638 mm), while the CROPWAT procedure overestimates total ET by about 50%. In this example, the estimate of the “blue” water contribution is 150% higher when using the CROPWAT model.

Some caveats are in order. First, these differences do not in any way suggest that CROPWAT produces “wrong” estimates of potential ET or its composition, but rather that field measurements of actual crop ET are always likely to be smaller than the potential crop ET. Second, the very close agreement between the “green” water component of total ET (in the CROPWAT analysis) and estimated effective rainfall from the SEBAL analysis is reassuring, though unexpectedly precise, as there was somewhat less rainfall during the year in which the SEBAL analysis was conducted than the average rainfall assumed in the CROPWAT analysis. However, accurate estimates of effective rainfall are difficult to obtain, as they depend on both the volume and distribution of rainfall events. Furthermore, effective rainfall on a fully vegetated, irrigated field may be different than the ET from a partially vegetated, rainfed land.

5.2. Partitioning the footprint into “green” and “blue” water

The previous example estimates the colour composition of the footprint for a perennial crop. For annual crops, where antecedent and post-season soil moisture content may be significant, the analysis is more complicated. A comparison of data presented in the 2009 and 2011 manuals, reportedly for completely identical circumstances, provides an interesting case study.

CROPWAT offers two options for calculating irrigation requirements. The “crop water requirement” option computes the difference between potential crop ET and effective rainfall for each ten day period, producing (as demonstrated above) an estimate of the green water contribution, and the additional blue (irrigation) water required to meet the full potential crop ET. Alternatively, the “irrigation schedule” option delivers irrigation according to user-specified rules (e.g., fixed schedule and fixed quantity, or variable schedule depending on soil moisture depletion) and computes ten-daily soil water balances, crop ET, and blue and green water consumption based on this schedule.

The first option estimates the minimum blue water requirement to ensure water is fully adequate to meet crop demand. The second is a more realistic representation of a typical irrigation system in terms of water actually delivered to the field and possible periods of excessive or deficit water availability. In the second case, the initial soil moisture status is specified by the user, and CROPWAT maintains a soil water balance, and reports the post-season soil moisture.

The reported partitioning between green and water for sugar-beet grown in Valladolid from the 2009 manual (p. 96) are shown below:

In the 2011 manual (Table 2. 5, p. 141) the results are reported as follows—based on exactly the same reference materials (MARM, 2009) and period (2000–2006).

The results are similar with respect to the total ET and the resultant total water footprint, but quite different with respect to the ratio of blue water to green water. In this case, the green water contribution in the irrigation schedule calculation has reduced from

Table 3

Data from 2011 manual on partitioning of water footprint into green and blue water.

CROPWAT option	ET _{green}	ET _{blue}	ET _{tot}
	mm/Growing season		
Crop water requirement	168	628	796
Irrigation schedule	125	668	793

432 (2009 manual) to 125 mm (2011 manual), and is now quite comparable to the green water component estimated in the crop water requirement calculation (168 mm in each case) (Table 3).

The probable, though unexplained reason for the change is that in the 2009 manual, 260 mm depletion of the initial soil water is assigned to the “green” water component of the water footprint, while in the 2011 manual this initial soil moisture is assigned to the “blue” component. (The sentence in the text referring to the “quite different” ratios of blue to green water remains in the 2011 manual, though it is redundant in the latter case).

Whether any initial soil water is from earlier rainfall (green) or an earlier irrigation event (blue), or a mixture of both, and whether it would be replenished by post-season rainfall (green) or untimely late-season irrigation events (blue) has significant implications for the computed contributions of green and blue water. Hess (2010) depicts similar variations in the estimated contribution of “green” water to rainfed crops in the UK, and also questions the appropriateness of the USDA methodology for computing rainfall-runoff relationships. Hess concludes that the USDA method does not perform well in UK conditions.

These uncertainties demonstrate the lack of robustness in the computation of the green and blue partition—the blue water footprint is 85% higher in the second estimate of the irrigation scheduling option. Yet both estimates are equally valid in the absence of specific information regarding the source and disposition of moisture in the soil before and after the irrigation season.

In sum, the computational procedures proposed in the water footprint manuals exhibit several shortcomings:

- For irrigated crops, the assumption that crop ET from whatever source is equal to potential crop ET is incorrect for any crop that yields significantly less than potential. When plants are stressed, transpiration slows, so that actual ET is less than potential ET.
- Because actual ET will generally be less than potential ET, while the contribution of rainfall is fixed, any overestimation of ET is assigned to the blue water component.
- The sources and uses of moisture in the soil before and after the crop season affect estimates of the contribution of green and blue water to total consumption.

The accuracy of a water footprint can be impacted also by post-harvest losses. For example, if only one-half of the crops produced in a field reach the market (Institute of Mechanical Engineers, 2013), the estimated water footprint for the marketed portion of the crop will be higher than it should be by a factor of two.

5.3. Relative and absolute “green” water footprints: the importance of context

Deurer et al. (2011) and Herath et al. (2011) examine water footprints in New Zealand, comparing procedures in the 2009 manual to methods that reflect traditional hydrologic principles. In their study of kiwi fruit, they find that the water footprint methodology assesses water consumption at 100 L per tray of fruit, while a hydrologic analysis estimates a net contribution to recharge of 500 L per tray. The hydrologic approach recognizes that kiwi fruit production consumes less water than the natural vegetation it replaces, while the water footprint method does not. Other authors have

noted the importance of adjusting the datum, in order to measure the change in water consumption from an alternative ET scenario, rather than a zero base (Scanlon et al., 2007; Pfister et al., 2009). Such an adjustment is not described in the Water Footprint Manual.

The same conclusion is reached more generally for rainfed crops in temperate areas. For example, most of the landscape in the UK would be forested today, if the trees had not been removed long ago to enable agriculture. The hydrologic impact of the conversion to crop and livestock production has been to decrease in situ ET (green water consumption), while increasing runoff (blue water production).

Several authors have suggested that meat production consumes more water than grain production. Mekonnen and Hoekstra (2010) report that while cereal production requires $16,441 \text{ kg}^{-1}$, bovine meat production requires $154,151 \text{ kg}^{-1}$. The implication is that meat production is more water-intensive than grain production. Closer examination reveals a much more complicated picture. As most livestock production occurs on land that might otherwise have been consuming more water in its natural, forested state, the downstream effect of expanding any agriculture in such areas is likely to be an increase in the available runoff (blue water). Opting to produce meat for calories may then release more water downstream than a strategy based on grain production. This is not to suggest that meat is an “environmentally” preferable source of calories. Rather, one must consider the scarcity or abundance of water and land, as well as downstream water uses to evaluate the significance of any environmental impact when compared to the status of these variables in the absence of grain or meat production. Simply comparing the water footprints of grain and meat does not provide helpful environmental information.

6. Discussion and conclusions

Water footprints are conceptually different to carbon footprints. Carbon entering the atmosphere causes harm, no matter where it is generated. By contrast, water consumption does not matter globally, but may be of concern locally. Perhaps the most notable similarity between carbon and water footprints is that each indicator describes only one variable in an array of potentially important interactions, so that neither provides sufficient information to guide action or fully inform policy makers.

It is overly simplistic and misleading to suggest that water footprints should be reduced without considering the context and purpose of water use. The use of “blue” water is neither more nor less desirable than using “green” water, provided that water governance in the location under consideration is acceptable, as viewed by residents of the region. A general reduction in demand for a water-intense commodity carries no guarantee that the smaller demand for water will manifest itself in an area where water consumption is excessive. Even if it does, the affected farmers still have an incentive to use available water to maintain their production, productivity and incomes. We do not need water footprints to discover where water is poorly managed or where the environment is threatened by excessive water use. Such situations are observed and resolved locally, through the introduction of adequate water governance.

Discovering the (very approximate) extent of the dependence of a country or an activity on “imported” water, especially for a country that is water-short, is an insight into current or future exposure to risk. It explains (as Allan has described) how this “silent” trade has mitigated water stress and facilitated adjustment to scarcity, just as trade mitigates labour scarcity in relatively developed countries, and technological scarcity in less developed countries.

The proponents of water footprint analysis have produced many long and detailed reports on the virtual trade in water (Chapagain et al., 2004) and estimated the “savings” resulting from

such trade (De Fraiture et al., 2004; Chapagain and Hoekstra, 2004; Chapagain et al., 2005; Hoekstra, 2008). They suggest that policy-makers, planners, companies, and individuals should assess their choices and modify their actions on the basis of estimated water footprints and virtual water flows (Galli et al., 2012; Lillywhite et al., 2010). However, there is little evidence that beyond a statement such as “country A achieves food security by importing food that was produced with irrigation or grown in rainfed conditions in country B,” there is any policy relevance in the discussion of water footprints.

Taken alone, water footprints are not sufficient indicators for selecting policy options, just as wage rates alone cannot determine if a country should import cars, build hotels or produce more films. Wage rates play a part in the complex set of issues that determine appropriate policies, but until other factors of production and their opportunity costs are considered, we cannot determine if labour-intensive activities are desirable. Similarly, water footprints alone do not offer helpful insight regarding development strategies, and the extent to which they contribute at all relates solely to the local management of the local water resource.

The notions of green and blue water imply that soil moisture, groundwater, and surface flows are separate, distinct, and independent sources of water, whereas they are interdependent components of the same hydrological system. Furthermore, the methods recommended for calculating water footprints are flawed. Many estimates of crop water consumption are excessive, because analysts do not distinguish sufficiently between actual and potential ET, and the over-estimated portion of the water footprint most often is assigned to the “blue” component. Furthermore, estimated water footprints reflecting the incremental impact of agriculture suggest that in some cases, less water is consumed by crops and livestock than by native vegetation. In such settings, the smaller water footprint of crop and livestock production is such that agricultural development actually generates a water saving.

We know from the science of hydrology that all aspects of the hydrologic cycle are linked, and that interventions in river basins and aquifers at one location will have impacts elsewhere. Some scholars and practitioners promote “integrated” water management, which had its origins, though perhaps not its current emphasis, in precisely these interdependencies. Water footprint analysis, by contrast, is a dis-integrated approach that reflects an over-simplification of complex issues.

Finally, the usefulness of the water footprint “lens” for identifying and addressing water problems is doubtful. Many specialists are aware that current water management practices are damaging ecosystems and over-drafting aquifers, and that some water policies mis-allocate water to low-valued uses. They also know the difficulty of achieving and implementing the political decisions that must underpin effective solutions. Water footprint analysis adds little to the discussion of these important policy issues. It might even divert attention from the proper hydrologic analysis on which sustainable and productive water management must be based.

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