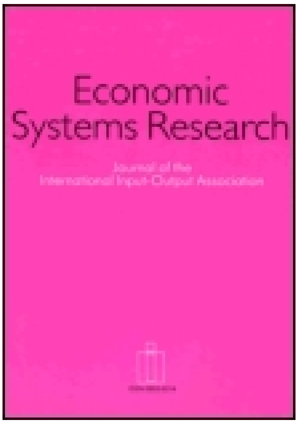

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COMPARISON OF BOTTOM-UP AND TOP-DOWN APPROACHES TO CALCULATING THE WATER FOOTPRINTS OF NATIONS

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The water footprint has been introduced as a potential sustainability indicator for human-induced water consumption, and has frequently been studied at local, national and international scales during the last decade. While water footprints are sometimes understood as a measure that includes environmental impact assessment, the water footprint as used in this paper refers to volumes of water consumed, without including weighting procedures to allow for the assessment of impacts. Two types of approaches have been applied to calculate the water footprint in the literature: bottom-up and top-down approaches. This study compares and discusses advantages and limitations of the water footprint of nations based on two input–output top-down approaches (Water Embodied in Bilateral Trade (WEBT) and Multi-regional Input–Output Analysis (MRIO)) and of the existing national water footprint accounts from the literature based on the bottom-up approach. The differences in the bottom-up and WEBT approaches are caused by inter-sectoral cut-off, because bottom-up approaches do not consider the entire industrial supply chains, while the WEBT method covers the water footprint by tracing the whole domestic supply chain of each country. The differences in the WEBT and MRIO approaches are due to an inter-regional cut-off effect, as the WEBT approach only traces domestic supply chains whereas the MRIO approach traces entire global supply chains. We found that both bottom-up and top-down approaches are heavily dependent on the quality of existing datasets, and differ substantially. The total water footprints of nations based on different approaches vary by up to 48%, and this variation is even larger at the sector level.

Keywords: Water footprint; Input–output analysis; Virtual water; Natural resources; Life-cycle analysis; Hybrid approaches

1. INTRODUCTION

Water footprints can be used for assessing the impacts of production and consumption activities on both domestic and global water resources. For example, the production and consumption activities in the UK may indirectly impose pressure on water resources in China through importing goods and services produced in China. Thus, it is very important to calculate the water footprint by taking the global supply chain effects into account. The water footprint was initially introduced by Hoekstra and Hung (2002, p. 7) as an analogy to the 'ecological footprint' showing "the volume of water needed for the production of goods and services consumed by the inhabitants of the country".

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The water footprint partly overlaps with the concept of virtual water, a term coined by Allan (1998a, 1998b, 2001) and inspired by his investigation into the suitability of virtual water imports as a partial solution to the problems of water scarcity in the Middle East. He argued that the trade of water-intensive products to the Middle East region relieved the need for the importing countries to use their own water resources to produce these products. The water footprint has been discussed as a potential sustainability indicator for human-induced water consumption and has been frequently studied at local, national and international scales (e.g. Chapagain and Hoekstra, 2004; Feng et al., 2011a, 2011b; Yu et al., 2010; Aldaya and Llamas, 2008; Hoekstra and Chapagain, 2007). Recently, the water footprint has also been used to include potential environmental impacts caused by water consumption (Pfister et al., 2009; Ridoutt and Pfister, 2010; Berger and Finkbeiner, 2010). Due to its simplicity and the accessibility of data sources, in this paper we focus on the volumetric water footprint as defined in Hoekstra et al. (2009b). The water footprint provides a consumption-based indicator of water use tracing water consumption associated with different consumption items along the whole supply chain, compared with the traditional production based water use indicator allocating water consumption to production processes. The total volume of water consumption includes three types of water defined in the literature as blue, green and grey water. Blue water is surface and groundwater; green water is the effective rainfall and soil moisture that is used directly by plants; grey water is the volume of fresh water required to dilute pollution (WFN, 2008).

In general, the ‘footprint family’, such as the ecological footprint, carbon footprint and water footprint, is a set of life cycle analysis (LCA) tools that analyze the resource requirements throughout the whole life cycle (Galli et al., 2011). LCA has been widely applied in both academic research and industrial applications in the last few decades (Vigon et al., 1993; Suh and Huppes, 2005; Guinée, 2002; ISO, 2006). Two groups of approaches have been used for LCA: bottom-up approaches (e.g. Mitchell and Hyde, 1999; Jansen and Thollier, 2006; Curran, 1996) and top-down approaches (e.g. Lenzen, 2001; Weber and Matthews, 2008; Weber et al., 2008; Minx et al., 2009; Wiedmann, 2009a). Bottom-up refers to process analysis, which uses detailed descriptions of individual production processes. Top-down refers to input–output analysis (IOA), which is an economic approach that is frequently used for environmental or LCA-type analyses. A number of researchers developed and applied hybrid approaches to LCA studies combining the advantages of both bottom-up and top-down approaches (e.g. Treloar, 1997; Lenzen, 2002; Lenzen and Crawford, 2009; Wiedmann et al., 2011b; Acquaye et al., 2011; Suh and Huppes, 2002, 2005; Suh et al., 2004). For a detailed description on hybrid approaches see Suh and Huppes (2005) and Suh et al. (2004).

To calculate the volumetric water footprint, we distinguish between the bottom-up water footprint accounting approach (e.g. Water Footprint Network, WFN) and the top-down approach based on input–output analysis. We further distinguish the top-down approaches between Water Embodied in Bilateral Trade (WEBT) and Multi-Regional Input-Output analysis (MRIO) (Peters et al., 2011b). The differences in the bottom-up and WEBT approaches capture inter-sectoral cut-off effects, because the bottom-up approach does not trace the entire industrial supply chain, while the WEBT calculates the water footprint by tracing whole domestic supply chains. The differences in the WEBT and MRIO approaches capture inter-regional cut-off effects, as the WEBT approach only traces domestic supply chains, whereas the MRIO approach traces the whole global supply chains.

2. METHODOLOGY

This section depicts the methodological frameworks of the bottom-up approach and top-down IOA approaches to calculate the total water footprint for 113 global regions, further distinguished as domestic and foreign water footprints. The total water footprint is the total water consumption of local and global water resources by the population of the study region; the domestic water footprint refers to the share of the total water footprint that consumes domestic water resources, whereas the foreign water footprint refers to the consumption of water resources situated in other countries (Chapagain and Hoekstra, 2004).

To better understand the differences between bottom-up and top-down approaches, it is important to clarify the distinction between intermediate and final use. Intermediate use refers to goods used as inputs in the production of other goods; final use refers to goods consumed by end-users such as households, government or exports. The bottom-up approach estimates water footprints by calculating the virtual water content of internationally traded goods and services from detailed process data. It has become one of the most popular approaches in water footprinting studies due to its simplicity and relatively good data availability. However, the bottom-up, process-based approach, does not distinguish between intermediate and final users, in terms of water consumption. Therefore, it cannot comprehensively describe supply chains that are crucial for allocating responsibility to the final consumer and identify driving forces. In addition, the bottom-up approach mainly concentrates on agricultural and food products, but lacks detail describing industry and products and services. The top-down approaches calculate the water footprint through tracing the whole regional, national or global supply chains depending on the accounting framework used. In the top-down approach, water consumed in production is allocated to the final rather than the intermediate consumers. However, a problem with the top-down approach is the aggregation of processes and products at the level of economic sectors and the relatively high aggregation level of different agricultural sectors provided in national accounts.

2.1. Bottom-up Approach

The first comprehensive water footprints of nations based on the bottom-up approach were calculated by Chapagain and Hoekstra (2004) for the period 1997–2001. This approach was further revised by Hoekstra et al. (2009b), and applied by Mekonnen and Hoekstra (2011) to calculate the water footprints of nations, separating out green, blue and grey water. The total water footprint of a product in volumetric units comprised two components: the direct and indirect water footprint (Hoekstra et al., 2009b). The direct water footprint is calculated as the sum of the volume of water either used or polluted (in the case of the grey water footprint). The indirect water footprint is equal to the sum of upstream effects, i.e. total water consumption during previous production stages.

$$WF_i = WF_i^d + WF_i^{sc} \qquad (1)$$

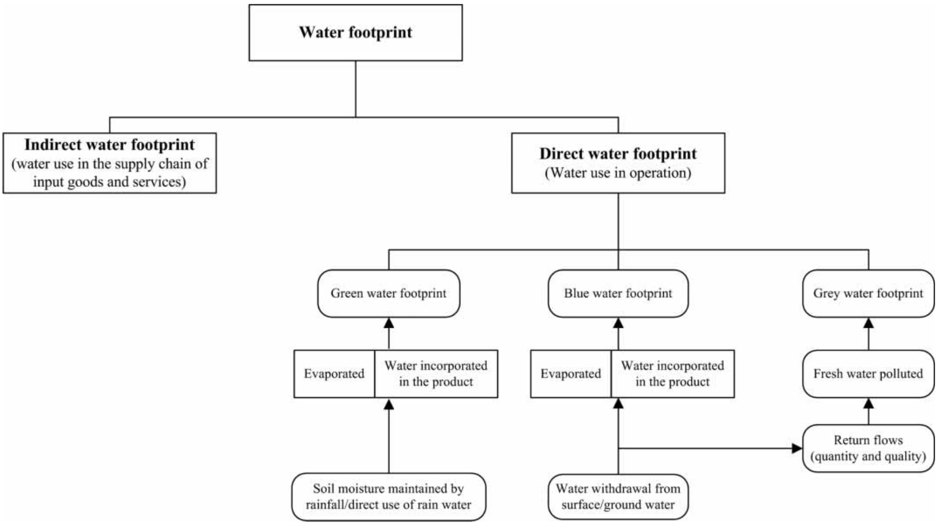
where WF_i is the total water footprint of the product at production stage i, WF_i^d is the direct water footprint of the product at stage i, and WF_i^{sc} is the indirect water footprint of the product at stage i.

Figure 1 shows how the water footprint along the production processes of one typical agricultural product is calculated. The direct water footprint of the product at stage i for product m from the operation at stage i, $WF_{i,m}^d$ is calculated as:

$$
\begin{aligned}
WF_{i,m}^d &= \frac{WU_{i,m}}{Q_{i,m}} \times \frac{v_{i,m}^f}{p_{i,m}^f} \\
&= \frac{\{Water\ evaporated_{i,m} +\ Water\ \ polluted_{i,m}\}}{Q_{i,m}} \times \frac{v_{i,m}^f}{p_{i,m}^f} \\
&= \frac{\{Water\ evaporated_{i,m}^{blue} +\ Water\ evaporated_{i,m}^{green} +\ Water\ \ polluted_{i,m}\}}{Q_{i,m}} \times \frac{v_{i,m}^f}{p_{i,m}^f} \\
&= \left\{\frac{BWevaporated}{Q_{i,m}} \times \frac{v_{i,m}^f}{p_{i,m}^f}\right\} + \left\{\frac{GWevaporated}{Q_{i,m}} \times \frac{v_{i,m}^f}{p_{i,m}^f}\right\} + \left\{\frac{Water\ \ polluted}{Q_{i,m}} \times \frac{v_{i,m}^f}{p_{i,m}^f}\right\} \\
&= WF_{i,m}^{blue} + WF_{i,m}^{green} + WF_{i,m}^{grey}
\end{aligned}
\tag{2}
$$

where $WF_{i,m}^d$, expressed in m^3/ton, is the water footprint of output m and $Q_{i,m}$ is the quantity of the product m in ton produced from the supplier i. $WU_{i,m}$ is the volume of water use in the operation of the supplier, which is made up of the volume of water evaporated and required to dilute pollution. The volume of water evaporated is further separated based on the source of water use: blue water (*BWevaporated*, evaporation from the use of surface

FIGURE 1. Water footprint of an agricultural product.



and ground water) and green water (*GWevaporated*, evaporation from the use of rain water).

The $p^f_{i,m}$ is the product fraction, and $v^f_{i,m}$ is the value fraction of the product *m*. If a supplier has more than one output product, the total water footprints of the supplier should be attributed to each product such that there is no double counting of water footprints. The distribution of water footprints among different output products is based on the concept of product fraction and value fraction; for detailed explanations please refer to Hoekstra and Chapagain (2008), and Hoekstra et al. (2009b).

A product tree has a product fraction (ratio of the weight of the individual output products to the weight of the input product) and value fraction (ratio of the market value of individual output product to the total market value of all the output products combined) at each stage of production. The total volume of water evaporated in the stage of crop growth is calculated using the maximum daily crop water requirement and the available effective rainfall are calculated using the model CROPWAT (FAO, 1992). Using the outcomes of the CROPWAT, the volumes of blue and green water evaporated are separated following the methodology presented in Chapagain and Orr (2009).

The total consumption water footprint of a region or country has two components: domestic water footprint and foreign water footprints.

$$WF_{Tot} = WF_{Dom} + WF_{Foreign} \tag{3}$$

where WF_{Tot} refers to the total water footprint; WF_{Dom} refers to the domestic water footprint; and $WF_{Foreign}$ refers to the foreign water footprint. The virtual water content of goods consumed in a country is calculated based on the share of import and domestic production of goods in a country following the methods presented in Mekonnen and Hoekstra (2011).

The domestic water footprint is calculated by:

$$WF_{Dom} = WF_{Agr} + WF_{Ind} + WF_{HH} - WF_{Dom-exp} \tag{4}$$

where WF_{Agr} is the agricultural water consumption with 106 agricultural products; WF_{Ind} is the industrial water consumption (only one aggregate industrial sector including services); WF_{HH} is the water consumption by households; $WF_{Dom-exp}$ is the water consumption of exporting goods and services produced domestically.

The foreign water footprint is equal to the virtual water imported into the region minus the volume of virtual water exported to other countries as a result of the re-export of imported products.

$$WF_{Foreign} = WF_{Imp} - WF_{Re-exp} \tag{5}$$

where WF_{Imp} is the imported virtual water to the region and WF_{Re-exp} is the export of virtual water as a result of imported goods from the region.

2.2. Environmental Input–Output Approaches

Environmental input–output analysis has been applied in water studies for about half a century. For example, an early study undertaken by Hartman (1965) examined features of input–output models in terms of their usefulness for analyzing regional water consumption and allocation; and Carter and Ireri (1970) developed a water extended interregional input–output model to assess the embedded water in product flows between California and Arizona. Examples of more recent studies of water-related input–output models include Lange's (1998) national resource accounting approach to examine water policies in Southern Africa using Namibia as a case study; Lenzen's analysis of water usage in Australia (Lenzen and Foran, 2001); Duarte et al. (2002) employed an input–output model using a Hypothetical Extraction Method (HEM) to assess the water use in the Spanish economy; Hubacek and Sun (2005) compared water supply and demand for all major watersheds in China using hydro-ecological regions to match watersheds with administrative boundaries; Guan and Hubacek (2008) extended this work by taking the pollution absorption capacity (grey water) into account using North China as a case study; Hubacek et al. (2009) carried out a study on environmental implications of urbanization and lifestyle change in China by calculating ecological and water footprints; Lenzen and Peters (2010) analyzed the direct and indirect water requirements of two Australian Cities in their domestic Hinterland in a spatially explicit model; Yu et al. (2010) carried out a study on assessing the regional and global water footprint for the UK by applying a unidirectional MRIO framework; Feng et al. (2011b) carried out a spatially explicit analysis of the UK water footprints by applying a multi-directional MRIO framework.

2.2.1. WEBT Approach

Total direct and indirect water consumption in region s in order to produce the products that are exported to region r can be determined by:

$$WF^{sr} = \mathbf{e^s}(\mathbf{I} - \mathbf{A^{ss}})^{-1}\mathbf{t^{sr}} \tag{6}$$

where WF^{sr} is the foreign water footprint of region r from region s; $\mathbf{e^s}$ is a row vector of water coefficients in region s, which is calculated by dividing direct sectoral water consumption by total sectoral input; $(\mathbf{I} - \mathbf{A^{ss}})^{-1}$ is Leontief Inverse matrix in region s; $\mathbf{t^{sr}}$ is a vector of bilateral trade from region s to region r.

Therefore, the total foreign water footprint in region r is:

$$WF^r_{Foreign} = \sum\nolimits_s WF^{sr} \tag{7}$$

and total domestic water footprint of region s can be calculated by:

$$WF^r_{Dom} = \mathbf{e^r}(\mathbf{I} - \mathbf{A^{rr}})^{-1}\mathbf{y^r} + WF^r_{hh} \tag{8}$$

where WF^r_{Dom} is total domestic water footprint in region r; $(\mathrm{I} - \mathbf{A^{rr}})^{-1}$ is the Leontief Inverse matrix in region r; $\mathbf{y^r}$ is a vector of domestic final demand in region r; WF^r_{hh} is the direct household water footprint in region r.

2.2.2. *MRIO Approach*

In a MRIO framework, different regions are connected by trade flows. The technical coefficient matrix **A** can be calculated by $a^{sr} = z_{ij}^{sr}/x_i^r$, where z_{ij}^{sr} is the trade between economic sectors from region s to region r, x_j^r is the total sectoral output in region r. The subscripts i and j denote the selling and purchasing sector, respectively. $\mathbf{y}^{\mathbf{sr}}$ is the trade from industries in region s to final consumers in regions r. A row vector of compound water coefficients is shown by:

$$\mathbf{e}^* = \begin{bmatrix} \mathbf{e}^1 & \mathbf{e}^2 & \cdots & \mathbf{e}^m \end{bmatrix}$$

Here, m indicates different regions. Thus, $\mathbf{e}^*$ is a vector of water coefficient for 113 regions.

The total water footprints of 113 world regions can be calculated by extending the water coefficients to the MRIO framework.

$$WF_{Tot} = \mathbf{e}^*\mathbf{L}^*\mathbf{Y}^* + WF_{hh} \tag{9}$$

Here, $\mathbf{L}^*$ is Leontief inverse matrix; $\mathbf{Y}^*$ is final demand matrix of 113 regions; WF_{hh} is the household water consumption.

To calculate domestic and foreign water footprint, we introduce $\mathbf{e}^{\mathbf{r}*}$, $\mathbf{e}^{*\mathbf{r}}$, and $\mathbf{y}^{*\mathbf{r}}$:

$$\mathbf{e}^{\mathbf{r}*} = [\mathbf{0} \cdots \mathbf{e}^{\mathbf{r}} \cdots \mathbf{0}]; \mathbf{e}^{\mathbf{r}*} = \left[\mathbf{e}^1 \cdots \mathbf{0} \cdots \mathbf{e}^{\mathbf{m}}\right]; \mathbf{y}^{*\mathbf{r}} = \begin{bmatrix} \mathbf{y}^{1\mathbf{r}} \\ \mathbf{y}^{2\mathbf{r}} \\ \vdots \\ \mathbf{y}^{\mathbf{mr}} \end{bmatrix}$$

where $\mathbf{e}^{\mathbf{r}*}$ is a vector only containing water coefficients in region r, with zeros for the water coefficients in all other regions, whereas $\mathbf{e}^{*\mathbf{r}}$ is a vector containing the water coefficients in all other regions with zeros for the coefficients in region r. $\mathbf{y}^{*\mathbf{r}}$ is a vector of the goods produced in the exporting regions directly consumed by the final consumers in region r.

The domestic and foreign water footprints in region r based on the MRIO framework can be calculated by Equations 10 and 11:

$$WF_{Dom}^r = \mathbf{e}^{\mathbf{r}*}\mathbf{L}^*\mathbf{y}^{*\mathbf{r}} + WF_{hh} \tag{10}$$

$$WF_{Foreign}^r = \mathbf{e}^{*\mathbf{r}}\mathbf{L}^*\mathbf{y}^{*\mathbf{r}} \tag{11}$$

2.3. Data

The FAOSTAT database provides crop productivity, areas of crop land and water requirements per unit of land for different crops, which are used for calculating the direct water use of different crops in different countries (FAO, 2010). The consumption data of agricultural products are taken from the Food Balance Sheet of FAOSTAT. The international virtual water flows are based on The Personal Computer Trade Analysis System (PCTAS)

(ITC, 2009). AQUASTAT as a part of FAO database provides industrial and commercial water use at an aggregated level (FAO, 2011). Water footprints of nations based on the bottom-up approach are taken from Mekonnen and Hoekstra (2011). The bottom-up approach considers only one layer of trade.

The 113-regions MRIO tables are based on the Global Trade Analysis Project version 7 database (GTAP, 2010) and extracted by the method described in Peters et al. (2011a). The 113-regions MRIO tables have 14 agricultural sectors and 43 industrial and service sectors. In order to be consistent with the 113-regions global MRIO model, the water use for 106 agricultural commodities provided by FAOSTAT are aggregated into 14 agricultural sectors and the highly aggregated water use for industrial and commercial sector from AQUASTAT database are disaggregated into 43 sub-sectors. This disaggregation is based on national water data provided by statistical bureaus in other sources in Australia, Canada, China, Germany, India, South Africa, Namibia, the US and the UK (ONS, 2011; Australian Bureau of Statistics, 2006; Canada, 2007; FSO, 2008; SSA, 2006; MWR, 2004; Lange, 1998; CSE, 2004; USGS, 2005). Since these national data sources still leave some gaping holes on the map, sectoral water intensities of representative countries are used for similar countries (e.g. Germany for EU-OECD countries, Australia for Oceania countries; Namibia for other African countries; China for other Non-OECD countries). To make the derived industrial water data consistent with the bottom-up approach, water intensities and sectoral total output are used for each country to parameterize the sectoral water use and scale the water use to match the water data collected from AQUASTAT.

For consistency and as a precondition for comparison, the same water data sources are used for the bottom-up and top-down approaches. Thus, the direct water use in each country/or region is the same for the proposed approaches.

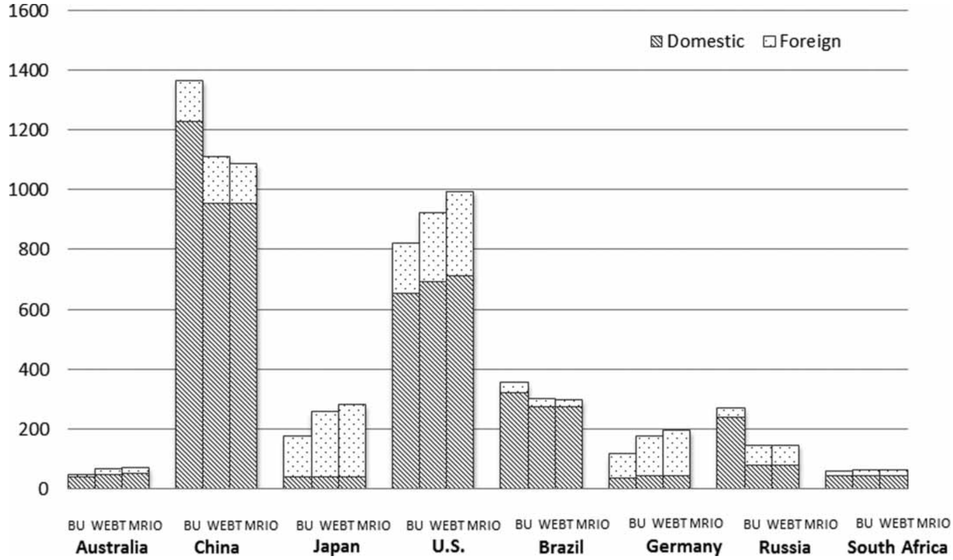
It is useful to mention the recent development of two MRIO databases including water accounting data: EXIOPOL (EXIOPOL, 2011) and OPEN - EU (Weinzettel et al., 2011). However, none of them provides a comparison of approaches.

3. RESULTS

3.1. Domestic and Foreign Water Footprints

Figure 2 shows domestic and foreign water footprints in eight key water consuming countries from different world regions. The results show that the differences in total water footprints based on bottom-up, WEBT and MRIO approaches vary between 8 and 48%. These differences are mainly caused by two issues: inter-sectoral cut-off and inter-regional cut-off. The differences in water footprints based on the bottom-up and WEBT approaches were mainly caused by inter-sectoral cut-off. In the bottom-up approach, agricultural and industry water footprints are calculated independently from each other, whereas in the WEBT approach the water footprint is calculated as being interdependent, tracing the entire domestic supply chain of interacting sectors and their respective demands. The results show that inter-sectoral cut-off may, for example, lead to a 71% difference for the domestic water footprints (as in the case of Russia) and a 72% difference in foreign water footprint (for Australia). For most selected countries, the foreign water footprints based on the WEBT approach were higher than the footprints based on the

FIGURE 2. Domestic and foreign water footprints in eight selected countries (billion m^3).



Note: BU is bottom-up analysis; WEBT is water embodied in bilateral trade analysis; MRIO is multi-regional input-output analysis.

bottom-up approach. This can be explained by the way the WEBT approach captures both direct water use and indirect water use along the domestic supply chains in foreign countries. For example, Japan's foreign water footprint based on the WEBT is 64% higher than the foreign water footprint based on the bottom-up approach because it not only includes the water consumption of producing the imported products for Japan, but also captures all upstream domestic water consumption in foreign countries.

In addition to foreign water footprints, domestic water footprints based on the bottom-up approach are larger than the water footprints based on the WEBT approach for most developing and emerging countries, such as China, Brazil and South Africa. This is due to the large amount of agricultural water use through export production of industrial goods in these countries. The differences in domestic water footprints based on the bottom-up and WEBT approaches are very small.

The differences in total water footprints based on the WEBT and MRIO approaches are much smaller than the differences based on the bottom-up and WEBT approaches due to the inter-regional cut-off effects being smaller than the inter-sectoral cut-off effects.

3.2. Sectoral Water Footprints

Figure 3 shows domestic water footprints distinguished by crops and livestock, industry and households. There are strong similarities in sectoral water footprints based on the WEBT and MRIO approaches, as the inter-regional cut-off has less effect on the composition of domestic water footprints. However, we can observe substantial differences in water footprints in crops and livestock and industry sectors between the bottom-up and the top-down approaches. This is mainly caused by a large proportion of agricultural

FIGURE 3. Sectoral domestic water footprints in eight selected countries (billion m^3).

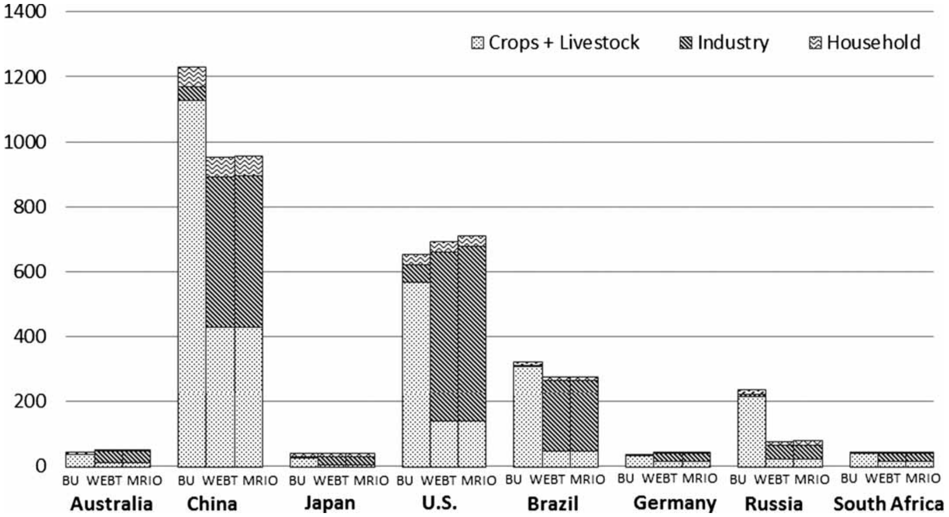
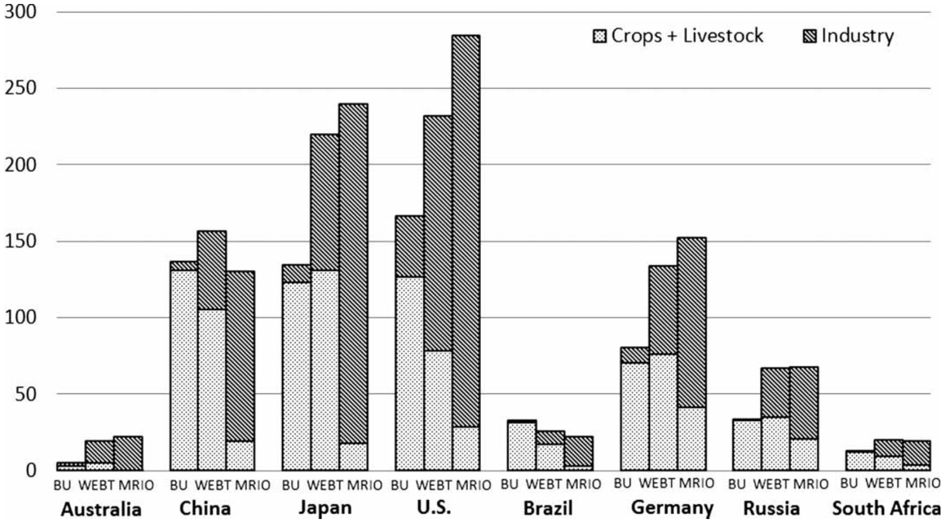


FIGURE 4. Sectoral foreign water footprints in eight selected countries (billion m^3).



water use consumed by industrial sectors when agricultural products are used as production inputs based on top-down approaches.

Although the WEBT and MRIO approaches provide similar results in domestic water footprints of nations, there are apparent differences in foreign water footprints. Figure 4 shows that the total foreign water footprints based on the WEBT approach in export dominated countries, such as China and Brazil, are much higher than the foreign water footprints based on the MRIO approach, due to the fact that when tracing the global supply chains, a large amount of imported water in China and Brazil is re-exported to other countries. However, the results were showing the opposite effects in many developed, net importing countries, such as the US, Japan and Germany, in which cases the exported water may be imported back.

Figure 4 shows huge differences in sectoral water footprints. The share of agriculture contributing to the foreign water footprint based on MRIO is much larger than the one based on WEBT. It indicates that after tracing global supply chains, more agricultural water is used in industrial sectors in the MRIO compared with the WEBT approach. Water footprints for the agricultural sector differed by up to 86% between the WEBT and MRIO approaches, while the differences are up to 60% for the industrial sector. It can also clearly be seen that the industrial water footprint based on the bottom-up approach shared a very small proportion of total foreign footprints due to the inter-sectoral cut-off.

4. DISCUSSION AND CONCLUSIONS

There are substantial differences in the results provided by the three modeling approaches. The inter-regional cut-off based on two top-down approaches could lead to a large difference in foreign water footprints and the water footprints at the sector level. MRIO provides a comprehensive system boundary, in terms of both inter-regional and inter-sectoral supply chains; imports and exports and their associated virtual water flows are captured along the whole global supply chain. The cut-off on both inter-sectoral and inter-regional supply chains based on the bottom-up approach may lead to significant differences in domestic and foreign water footprints and consequently does not allow us to properly track water consumption to final demand. For example, the consumption water footprint in China based on the bottom-up approach is about 25% higher than using the two top-down approaches; agricultural products consumed by industry sectors and then exported to other regions cannot be captured by the bottom-up approach.

On the other hand, the bottom-up approach provides a modeling framework with great detail, especially for the agricultural and food products sectors. At the national level, this approach estimates the virtual water contents for more than 100 agricultural and food products, which allows us to calculate the water footprints for individual products. The bottom-up approach also has an advantage with regard to ease of updating data as the FAO provides very detailed and annually updated trade flows of agricultural and food products for most countries. The calculations used in the bottom-up approach are based on the PCTAS database. However, as frequently discussed, imports and exports are not consistent between the exporting countries and importing countries.

In contrast, for the IO study, national IO tables are generally a few years old and might be produced in some instances only every 5 years. However, this data issue may be solved by updating the old IO tables based on the latest national accounts, which are published annually by the national statistical offices (Wiedmann et al., 2011a). Another reason for GTAP data to be updated rather slowly is because all the trade flows have to be made compatible and issues of inconsistency between import and export data occurring in COMTRADE data need to be solved.

The bottom-up approach presented here considers impact assessment as an additional step to be carried out in detailed local analyses (Hoekstra et al., 2009a). Based on ISO standards and guidelines, an environmental impact assessment can be integrated into LCA and consequently should be part of the water footprint (Pfister and Hellweg, 2009). While there is disagreement about the term "water footprint" among different research groups as well as different stakeholders, there is an agreement that pure water volumes are insufficient to take decisions about hotspots of water scarcity, as the link to water availability is missing. MRIO estimates of water footprints, in contrast to the bottom-up approach, have nations or even larger multistate regions as spatial units of analysis and therefore a specific impact assessment, as suggested by Hoekstra et al. (2009a), is not possible. In order to account for the environmental relevance of water consumption caused by the provision of goods and services, it seems inevitable to include weighting by location-specific impact assessment metrics before aggregating the water consumption to MRIO sectors and regions, e.g. as done for a bottom-up case study by Ridoutt and Pfister (2010). While detailed analysis of national water footprints including impact assessments have recently been published for 160 crops (Pfister et al., 2011), data for industrial sectors and corresponding trade analyses have still to be developed. It is clear that such global characterization of impacts cannot replace detailed local case studies, but it would enable the identification of potential hotspots for analyses of supply-chains.

In summary, using different approaches may lead to a substantial difference in terms of water footprints, even when based on the same database. Top-down approaches have a comprehensive system boundary that allows tracing whole industry supply chain effects. It can also provide relatively detailed water footprints of industrial products. However, due to the lack of detail in agricultural products and the lack of spatial detail, it is difficult to provide policy recommendations and guidance for water resource management. The bottom-up approach based on individual processes provides very detailed information on agricultural products and associated virtual water content. The cut-off effect of supply chains may lead to significant truncation error, particularly in calculating consumption water footprints for a region or country taking imports and exports into account. For the top-down approach with highly aggregate sectoral information, characterization of water consumption should be included, as tracing the origins of water consumption beyond the regional level is not possible. In this study, we find – similar to Wiedmann (2009b) – that there is a big difference in water footprints at the sector level based on bottom-up versus top-down approaches. This supports the call for utilizing hybrid approaches as suggested in LCA studies combining the advantages of both approaches. The bottom-up approach can be used to capture the direct water use of detailed agricultural products, while the MRIO approach can be used to capture the upstream supply chain effects. However, due to the bottom-up approach not being able to distinguish intermediate and final use of commodities, the system boundaries for the two approaches in a hybrid framework need to be considered very carefully, in order to avoid double counting (Suh et al., 2004; Strømman, 2009; Lenzen, 2008, 2009).

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References

Acquaye, A.A., T. Wiedmann, K. Feng, R.H. Crawford, J. Barrett, J. Kuylenstierna, A.P. Duffy, S.C.L. Koh and S. McQueen-Mason (2011) Identification of 'Carbon Hot-Spots' and Quantification of GHG Intensities in the Biodiesel Supply Chain Using Hybrid LCA and Structural Path Analysis. *Environmental Science & Technology*, 45(6), 2471–2478.

Aldaya, M.M. and M.R. Llamas (2008) *Water Footprint Analysis for the Guadiana River Basin*. The Netherlands, UNESCO-IHE.

Allan, J.A. (1998a) Watersheds and Problemsheds: Explaining the Absence of Armed Conflict over Water in the Middle East. *MERIA - Middle East Review of International Affairs*, 2, 1–3.

Allan, J.A. (1998b) Virtual Water: A Strategic Resource Global Solutions to Regional Deficits. *Ground Water*, 36, 545–546.

Allan, J.A. (2001) *The Middle East Water Question: Hydropolitics and the Global Economy*. London, I.B. Tauris.

Australian Bureau of Statistics. (2006) *Water Account – Australia*. Australian Government – National Water Commission.

Berger, M. and M. Finkbeiner (2010) Water Footprinting: How to Address Water Use in Life Cycle Assessment? *Sustainability*, 2, 919–944.

Carter, H.O. and D. Ireri (1970) Linkage of California-Arizona Input-output Models to Analyze Water Transfer Patterns. In: A.P. Carter and A. Brody, eds. *Applications of InputOutput Analysis. Proceedings of the Fourth International Conference on InputOutput Techniques*. Geneva, 8–12 January 1968. Amsterdam, London: North-Holland.

Chapagain, A.K. and A.Y. Hoekstra (2004) *Water Footprints of Nations*. Netherlands, UNESCO-IHE.

Chapagain, A.K. and S. Orr (2009) An Improved Water Footprint Methodology Linking Global Consumption to Local Water Resources: A Case of Spanish Tomatoes. *Journal of Environmental Management*, 90, 1219–1228.

CSE. (2004) *A Down To Earth Supplement – Industry*. New Delhi, India: Centre for Science and Environment.

Curran, M.A. (1996) *Environmental Life-Cycle Assessment*. New York, McGraw-Hill Professional.

Duarte, R., J. Sanchez-Choliz and J. Bielsa (2002) Water Use in the Spanish Economy: an Input-Output Approach. *Ecological Economics*, 43, 71–85.

EXIOPOL. (2011) *Externality Data and IO Tools for Policy Analysis*. Luxembourg, European Commission.

CROPWAT: A Computer Program for Irrigation Planning and Management. Rome, Italy, Food and Agriculture Organization of the United Nations.

FAO (1992). CROPWAT: A Computer Program for Irrigation Planning and Management. In: *Irrigation and Drainage Paper 46* (developed by Martin Smith). Rome, Food and Agriculture Organization of the United Nations.

FAO (2010) FAOSTAT: Food and Agriculture Organization of the United Nations.

FAO (2011) Aquastat: Food and Agriculture Organization of the United Nations.

Feng, K., Y.L. Siu, D. Guan and K. Hubacek (2011a) Assessing Regional Virtual Water Flows and Water Footprints in the Yellow River Basin, China: A Consumption-based Approach. *Applied Geography*, 32, 691–701.

Feng, K., K. Hubacek, J. Minx, Y.L. Siu, A.K. Chapagain, Y. Yu, D. Guan and J. Barrett (2011b) Spatially Explicit Analysis of Water Footprints in the UK. *Water*, 3, 47–63.

FSO. (2008) *Environmental Accounts*. Wiesbaden, Federal Statistical Office.

Galli, A., T. Wiedmann, E. Ercin, D. Knoblauch, B. Ewing and S. Giljum (2011) Integrating Ecological, Carbon and Water footprint into a 'Footprint Family' of Indicators: Definition and Role in Tracking Human Pressure on the Planet. *Ecological Indicators*, in press.

GTAP. (2010) *GTAP 7 Data Base*. West Lafayette, Indiana, Global Trade Analysis Project.

Guan, D. and K. Hubacek (2008) A New and Integrated Hydro-economic Accounting and Analytical Framework for Water Resources: A Case Study for North China. *Journal of Environmental Management*, 88, 1300–1313.

Guinée, J.B. (2002) *Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards*. Dordrecht, The Netherlands, Kluwer Academic.

Hartman, L.M. (1965) The Input-Output Model and Regional Water Management. *Journal of Farm Economics*, 47, 1583–1591.

Hoekstra, A.Y. and A.K. Chapagain (2007) Water Footprints of Nations: Water Use by People as a Function of their Consumption Pattern. *Water Resource Management*, 21, 35–48.

Hoekstra, A.Y. and A.K. Chapagain (2008) *Globalization of Water: Sharing the Planet's Freshwater Resources*. Oxford, UK: Blackwell.

Hoekstra, A.Y. and P.Q. Hung (2002) *Virtual Water Trade: A Quantification of Virtual Water Flows between Nations in Relation to International Crop Trade*. Delft, Institute for Water Education.

Hoekstra, A.Y., W. Gerbens-Leenes and T.H. van der Meer (2009a) Reply to Pfister and Hellweg: Water Footprint Accounting, Impact Assessment, and Life-cycle Assessment. *Proceedings of the National Academy of Sciences*, 106, E114.

Hoekstra, A.Y., A.K. Chapagain, M.M. Aldaya and M.M. Mekonnen (2009b) *Water Footprint Manual – State of the Art 2009*. Enschede, the Netherlands, Water Footprint Network.

Hubacek, K. and L. Sun (2005) Economic and Societal Changes in China and its Effects on Water Use. *Journal of Industrial Ecology*, 9, 187–200.

Hubacek, K., D. Guan, J. Barrett and T. Wiedmann (2009) Environmental Implications of Urbanization and Lifestyle Change in China: Ecological and Water Footprints. *Journal for Cleaner Production*, 17, 1241–1248.

ISO. (2006) *International Standard ISO 14040: Environmental Management - Life Cycle Assessment - Principles and Framework.* ISO 14040:2006(E). Geneva, Switzerland, International Organization for Standardisation.

ITC. (2009) *The Personal Computer Trade Analysis Systems (PCTAS)*. Geneva, Switzerland, International Trade Centre.

Jansen, B. and K. Thollier (2006) Bottom-Up Life-Cycle: Assessment of Product Consumption in Belgium. *Journal of Industrial Ecology*, 10, 41–55.

Lange, G.-M. (1998) An Approach to Sustainable Water Management in Southern Africa using Natural Resource Accounts: The Experience in Namibia. *Ecological Economics*, 26, 299–311.

Lenzen, M. (2001) Errors in Conventional and Input-Output-based Life-Cycle Inventories. *Journal of Industrial Ecology*, 4, 127–148.

Lenzen, M. (2002) A Guide for Compiling Inventories in Hybrid Life-cycle Assessments: Some Australian Results. *Journal of Cleaner Production*, 10, 545–572.

Lenzen, M. (2008) Double-Counting in Life Cycle Calculations. *Journal of Industrial Ecology*, 12, 583–599.

Lenzen, M. (2009) Dealing with Double-counting in Tiered Hybrid Life-cycle Inventories: A Few Comments. *Journal of Cleaner Production*, 17, 1382–1384.

Lenzen, M. and B. Foran (2001) An Input-Output Analysis of Australian Water Usage. *Water Policy*, 3, 321–340.

Lenzen, M. and R.H. Crawford (2009) The Path Exchange Method for Hybrid LCA. *Environmental Science & Technology*, 43, 8251–8256.

Lenzen, M. and G.M. Peters (2010) How City Dwellers Affect Their Resource Hinterland. *Journal of Industrial Ecology*, 14, 73–90.

Mekonnen, M.M. and A.Y. Hoekstra (2011) *Nation Water Footprint Accounts: The Green, Blue and Grey Water Footprint of Production and Consumption*. Delft, The Netherlands, UNESCO-IHE Institute for Water Education.

Minx, J.C., T. Wiedmann, R. Wood, G.P. Peters, M. Lenzen, A. Owen, K. Scott, J. Barrett, K. Hubacek, G. Baiocchi, A. Paul, E. Dawkins, J. Briggs, D. Guan, S. Suh and F. Ackerman (2009) Input-Output Analysis and Carbon Footprinting: An Overview of Applications. *Economic Systems Research*, 21, 187–216.

Mitchell, P. and R. Hyde (1999) 'Bottom-up' Approach to the Implementation of Environmental Life Cycle Assessment (LCA). *Environmentally Conscious Design and Inverse Manufacturing. Proceedings. EcoDesign '99: First International Symposium.* The Association for Computing Machinery.

MWR. (2004) *Chinese Water Resources Bulletin*. Beijing, Ministry of Water Resources People's Republic of China.

ONS. (2011) *Environmental Accounts*. London, UK: Office for National Statistics (ONS).

Peters, G.P., R. Andrew and J. Lennox (2011a) Constructing an Environmentally-extended Multi-regional Input-Output Table using the GTAP Database. *Economic Systems Research*, 23, 131–152.

Peters, G.P., J.C. Minx, C.L. Weber, and O. Edenhofer (2011b) Growth in Emission Transfers via International Trade from 1990 to 2008. *Proceedings of the National Academy of Sciences*, 108(21), 8903–8908.

Pfister, S. and S. Hellweg (2009) The water 'shoesize' vs. footprint of bioenergy. *Proceedings of the National Academy of Sciences*, 106, E93–E94.

Pfister, S., A. Koehler and S. Hellweg (2009) Assessing the Environmental Impacts of Freshwater Consumption in LCA. *Environmental Science & Technology*, 43, 4098–4104.

Pfister, S., P. Bayer, A. Koehler and S. Hellweg (2011) Environmental Impacts of Water Use in Global Crop Production: Hotspots and Trade-Offs with Land Use. *Environmental Science & Technology*, 45, 5761–5768.

Ridoutt, B.G. and S. Pfister (2010) A Revised Approach to Water Footprinting to Make Transparent the Impacts of Consumption and Production on Global Freshwater Scarcity. *Global Environmental Change*, 20, 113–120.

SSA. (2006) *Natural Resource Accounts - Updated Water Accounts for South Africa 2000*. Pretoria, Statistics South Africa.

Statistics Canada. (2007) *Industrial Water Use*. Ottawa, Environment Accounts and Statistics Division, Statistics Canada.

Strømman, A.H. (2009) Dealing with Double-counting in Tiered Hybrid Life-cycle Inventories: A Few Comments – Response. *Journal of Cleaner Production*, 17, 1607–1609.

Suh, S. and G. Huppes (2002) Missing Inventory Estimation Tool Using Extended Input-Output Analysis. *The International Journal of Life Cycle Assessment*, 7, 134–140.

Suh, S. and G. Huppes (2005) Methods for Life Cycle Inventory of a Product. *Journal of Cleaner Production*, 13, 687–697.

Suh, S., M. Lenzen, G.J. Treloar, H. Hondo, A. Horvath, G. Huppes, O. Jolliet, U. Klann, W. Krewitt, Y. Moriguchi, J. Munksgaard and G. Norris (2004) System Boundary Selection in Life-cycle Inventories using Hybrid Approaches. *Environmental Science & Technology*, 38, 657–664.

Treloar, G.J. (1997) Extracting Embodied Energy Paths from Input-Output Tables: Towards an Input-Output-based Hybrid Energy Analysis Method. *Economic Systems Research*, 9, 375–391.

USGS. (2005) *Water Use in the United States*. Reston, Virginia, US Geological Survey.

Vigon, B., D.A. Tolle, B.W. Cornaby, H.C. Latham, C.L. Harrison and T.L. Boguski (1993) *Life Cycle Assessment: Inventory Guidelines and Principles*. USA, Environmental Protection Agency (EPA).

Weber, C.L. and H.S. Matthews (2008) Quantifying the Global and Distributional Aspects of American Household Carbon Footprint. *Ecological Economics*, 66, 379–391.

Weber, C.L., G.P. Peters, D. Guan and K. Hubacek (2008) The Contribution of Chinese Exports to Climate Change. Paper presented at the International Input-Output Meeting on Managing the Environment, July9–112008, in Seville, Spain.

Weinzettel, J., K. Steen-Olsen, A. Galli, G. Cranston, E. Ercin, T. Hawkins, T. Wiedmann and E. Hertwich (2011) *Footprint Family Technical Report: Integration into MRIO Model*. Godalming, UK, The European Community, Seventh Framework Programme.

WFN (2008) Water Footprint: Introduction. http://www.waterfootprint.org (accessed 17 February 2009).

Wiedmann, T. (2009a) Carbon Footprint and Input-Output Analysis – An Introduction. *Economic Systems Research*, 21, 175–186.

Wiedmann, T. (2009b) A First Empirical Comparison of Energy Footprints Embodied in Trade – MRIO versus PLUM. *Ecological Economics*, 68, 1975–1990.

Wiedmann, T., H.C. Wilting, M. Lenzen, S. Lutter and V. Palm (2011a) Quo Vadis MRIO? Methodological, Data and Institutional Requirements for Multi-region Input–Output Analysis. *Ecological Economics*, 70, 1937–1945.

Wiedmann, T.O., S. Suh, K. Feng, M. Lenzen, A. Acquaye, K. Scott and J.R. Barrett (2011b) Application of Hybrid Life Cycle Approaches to Emerging Energy Technologies – The Case of Wind Power in the UK. *Environmental Science & Technology*, 45, 5900–5907.

Yu, Y., K. Hubacek, K. Feng and D. Guan (2010) Assessing Regional and Global Water Footprints for the UK. *Ecological Economics*, 69, 1140–1147.