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Accounting global grey water footprint from both consumption and production perspectives

Xu Zhao [a,*,1], Xiawei Liao [b,1], Bin Chen [c,**], Martin R. Tillotson [d], Wei Guo [e], Yiping Li [a]

[a] Key Laboratory of Integrated Regulation and Resource Development on Shallow Lakes, Ministry of Education, College of Environment, Hohai University, Nanjing, 210098, China
[b] School of Environment and Energy, Peking University Shenzhen Graduate School, Shenzhen, 518055, China
[c] State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing, 100875, China
[d] Water@leeds, School of Civil Engineering, University of Leeds, Leeds, LS2 9JT, UK
[e] School of Environmental Science and Engineering, Southern University of Science and Technology, Shenzhen, 518055, China

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ABSTRACT

Grey water footprint (GWF) accounting has previously been conducted at the global level using a bottom-up approach but lacking detailed industrial information. Here we applied a multi-region input-output approach based on the World Input-Output Database (WIOD) to quantify global GWF of 40 countries/regions with 35 economic sectors. The GWF from both the production perspective (GWFP), and the consumption perspective (GWFC) are quantified. The results show that the global GWFP/GWFC was 1507.9 km^3 in 2009. Except for the "Agriculture, Hunting, Forestry and Fishing" sector, the industrial sectors with the largest GWFC were "Food, Beverages and Tobacco", "Construction", "Chemicals and Chemical Products", and "Textiles and Textile Products". The BRIC countries (Brazil, Russia, India, China) had a larger GWFP than their GWFC, which accounted for over half of global GWFP (53.6%), and their GWFP was mainly generated from the production of domestic final demand. In contrast, the OECD29 and EU27 groups of countries i.e. the country groups consisting mainly of economically advanced nations, had larger GWFC than their GWFP. Overall, the OECD29 and EU27 outsourced 134.8 km^3 and 64.4 km^3 of their grey water respectively, mostly to large newly advanced economies such as the BRIC group of countries, which, in turn, were collectively outsourcing 112 km^3 of grey water. Quantitative approaches are thus suggested for development, aimed at shared responsibility for water pollutant discharge among poor exporters and wealthy consumers.

1. Introduction

It is widely recognised that the ever growing demand for goods and services for human consumption are the main drivers of water resource depletion and water pollution (Hoekstra and Mekonnen, 2012; Munksgaard et al., 2005; Zhao et al., 2016a). Further, the spatially uneven distribution of consumption and water resource depletion has been identified as having a substantial impact on countries/regions with water intensive production (Feng et al., 2014; Liu et al., 2015; Orlowsky et al., 2014; Zhao et al., 2015). Highlighting such issues has added a global dimension to regional water management (Vörösmarty et al., 2015). However, despite severe water pollution problems around the world, most studies seeking to understand the impact of trade and consumption on water only consider water quantity and ignore water quality (van Vliet et al., 2017; Zhao et al., 2016a).

One of the helpful concepts used to describe human impacts on water quantity and water quality is that of the water footprint (WF). The WF of a product may be defined as the volume of freshwater use, measured directly and indirectly, through the supply chain to support the final demand of a particular product (Hoekstra et al., 2011). Three components are included in WF accounting: the blue and green WF refer to the use of blue water (groundwater and

Abbreviations: WF, water footprint; GWF, grey water footprint; GWFP, grey water footprint from the production perspective; GWFC, grey water footprint from the consumption perspective; IGWF, internal grey water footprint; GVWE, grey virtual water exports; GVWI, grey virtual water imports; WIOD, World Input-Output Database.

* Corresponding author.
** Corresponding author.
E-mail addresses: xuzhao@hhu.edu.cn (X. Zhao), chenb@bnu.edu.cn (B. Chen).
[1] These authors contributed equally to this work.

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surface water) and green water (soil water) to support final demand. These two components represent the impact of human consumption in terms of water quantity. In contrast, the grey WF (GWF) is a measure of the volume of water required to assimilate the pollution load generated as a result of final demand of a particular product back to ambient levels and, as such, is a water quality indicator (Chapagain et al., 2006; Hoekstra et al., 2011). Hence, the GWF unifies the impact of *both* water quantity and quality into a homogeneous unit: freshwater volume. The GWF also allows the comparison of environmental impacts produced by pollutants discharged into waterbodies with different natural conditions (Pellicer-Martínez and Martínez-Paz, 2016). It has been quantified at different spatial levels (Cazcarro et al., 2016; Serrano et al., 2016; Zhi et al., 2015), as well as at global level (Hoekstra and Mekonnen, 2012; Liu et al., 2012, 2017).

The accounting of WF (including GWF) may be approached from two perspectives. Accounting from the production perspective includes the production of goods/services for domestic consumption, and those for export (Hoekstra and Mekonnen, 2012; Peters, 2008). Regional water management has traditionally focused on local water supply i.e. managing water to support the water demand of local production (Lenzen et al., 2013). However, WF accounting from the production perspective takes this a step further to divide local water supply into domestic use (internal WF) and export use (Hoekstra and Mekonnen, 2012). As a result, the internal and external driving force of local water supply due to final demand can be shown (Zhao et al., 2016b). In contrast, accounting from the consumption perspective includes water used in the production of all goods/services intended for local consumption (internal WF), including imports (external WF). From the consumption perspective, all water use, no matter whether it is within or outside the regional boundary, occurring along the chains of production and distribution are allocated to the final product consumer (Wiedmann, 2009). Hence, the consumption perspective can show the impacts on water resources of consumers in one region from the same or another region, thus informing consumer responsibility. Overall, it is important to address both perspectives to understand how the environmental costs of water pollution are redistributed from the countries/regions of consumers to that of producers.

In terms of the quantification of WF (including GWF), two approaches are commonly taken i.e. the bottom-up and top-down approach. Global GWF accounting has previously been conducted using the bottom-up approach for agricultural products from both production and consumption perspectives (Hoekstra and Mekonnen, 2012). Compared to the top-down approach, the bottom-up approach is less sensitive to trade data and enables a detailed inventory of the agricultural sector (Hoekstra and Mekonnen, 20102), but is more difficult to quantify for the industrial sector owing to the complexity of the supply chain (Feng et al., 2011). However, the breakdown of the industrial sector is important in GWF accounting because of the substantial amount of waterborne pollutants discharged by the sector, such as from the textiles, chemicals, and papermaking industries. A top-down approach based on input-output analysis allows the quantification of the GWF with details of industrial sectors. In addition, the top-down approach allows the quantification of the GWF in a unified framework from both consumption and production perspectives. Recent studies have shown that a multi-region input-output (MRIO) analysis is an appropriate methodology for quantifying the WF (including the GWF) from the consumption perspective (Lenzen et al., 2013; Serrano et al., 2016). However, as far as we know, studies which have quantified the global GWF from both production and consumption perspectives under an MRIO framework are rare.

In this study we account for the global GWF from the production perspective (GWFP for short) and the consumption perspective (GWFC for short) using the top-down approach. A global MRIO table, the World Input-Output Database (WIOD), was used to study the global GWF. The WIOD covers 40 countries/regions and 35 economic sectors, including 1 agricultural sector, 17 industrial sectors, and 17 service sectors (Timmer et al., 2015). GWFP may be further divided into the internal GWF (IGWF) and grey virtual water exports (GVWE), and GWFC is subdivided into IGWF and grey virtual water imports (GVWI). The implications from the results of GWFC and GWFP, as well as the comparison between the two perspectives, are also discussed.

2. Data

The WIOD (www.wiod.org) provides the MRIO table from 1995 onwards and (blue, green, and grey) water use data between 1995 and 2009 (Genty, 2012; Timmer et al., 2015). It is currently the only database providing grey water use for a range of sectors (Serrano et al., 2016). There are 35 sectors for each country/region including 1 agricultural sector, 17 industrial sectors, and 17 service sectors (See Fig. 2 for details). Hence, this study made use of the data from the WIOD for 2009 in order to acquire the most up-to-date grey water use data (http://www.wiod.org/database/eas13). The MRIO table in the WIOD lists 40 countries/regions (see Fig. 2 for details), including 27 EU countries, 29 OECD countries, and the BRIC countries (Brazil, Russia, India and Mainland China); see Table 1 for details. The economic activities of Chinese Taipei was separated from Mainland China (hereafter China for short), according to the data provided. Other countries/regions not in the list were categorized as Rest of World (ROW).

In the WIOD, grey water use for different sectors was estimated using different methods depending on data availability (Genty, 2012). The grey water use of crop and livestock production was quantified based on non-point source pollution of nitrogen, according to Mekonnen and Hoekstra (2010a; 2010b). The sum of grey water use for crop and livestock production was aggregated and assigned to the "Agriculture, Hunting, Forestry and Fishing" sector in the WIOD (Genty, 2012). The grey water use of hydropower was estimated based on Mekonnen and Hoekstra (2011b), and assigned to the "Electricity, Gas and Water Supply" sector. The grey water use for industrial production (excluding hydropower) was a measure of the part of the return flow which is discharged into the environment without prior treatment with the assumption that the dilution factor is 1 (Mekonnen and Hoekstra, 2011a). The total industrial grey water use was then distributed to WIOD sectors based on the share of water use in the database generated by the EXIOPOL project[2] (Genty, 2012; EXIOPOL, 2011).

3. Methodology

In a fundamental input-output framework, the total output of different sectors in region r in column vector form x^r is the sum of intermediate input in matrix form Z^{rr} and final demand in column vector form f^r, shown as follows:

$$x^r = Z^{rr}i + f^r \quad (1)$$

where $\mathbf{i}$ is a column vector of 1.

In order to reflect the functional relationship between final

[2] EXIOPOL is an integrated project funded by the European Commission to build an input-output framework linking other socio-economic models to estimate environmental impacts of economic activities.

Table 1
Comparison of grey water footprint among EU27, OECD29, and BRIC countries.

Groups	Countries	GWFC Unit: km^3	GWFP Unit: km^3	IGWF Unit: km^3	GVWIUnit: km^3	GVWEUnit: km^3	GWFC per capitaUnit: m^3
EU27	Austria, Belgium, Bulgaria, Cyprus, Czech, Germany, Denmark, Spain, Estonia, Finland, France, UK, Greece, Hungary, Ireland, Italy, Lithuania, Luxembourg, Latvia, Malta, Netherlands, Poland, Portugal, Romania, Slovak, Slovenia, Sweden	167.2	102.8	61.1	106.1	41.7	335
OECD29	Australia, Austria, Belgium, Canada, Czech, Germany, Denmark, Spain, Estonia, Finland, France, UK, Greece, Hungary, Ireland, Italy, Japan, Korea, Luxembourg, Latvia, Mexico, Netherlands, Poland, Portugal, Slovak, Slovenia, Sweden, Turkey, USA	496.4	361.6	258.7	237.7	102.9	416
BRIC	Brazil, Russia, India, China	695.4	807.5	643.8	51.6	163.7	241

demand and total output, the technical coefficient$A^{rr}$is introduced. The relationship between Z^{rr}, A^{rr}, and x^r can be denoted as$Z^{rr}i = A^{rr}x^r$, where $A^{rr}$is the technical coefficient of region *r* in matrix form, acquired through dividing the total output of each sector by their intermediate inputs. Hence, equation (1) becomes $x^r = A^{rr}x^r + f^r$. The above equation can be further transformed to the fundamental input-output formula $x^r = (I - A^{rr})^{-1}f^r$, where $(I - A^{rr})^{-1}$ is the Leontief Inverse Matrix showing the total output of different sectors necessary for one unit of final demand.

In a generalized environmental input-output model for a single region, the environmental accounts (in our case, the sectoral grey water use accounts) are added as an additional row to the input-output table to link the economic sectors to grey water use. In order to acquire the GWF of region *r*, we first introduce the direct grey water use intensity of region *r*, d^r, which represents the direct grey water use per unit of output in each sector, i.e.$gwu^r = \widehat{d}^r x^r$. Here, $gwu^r$is the sectoral grey water use of region *r* in column vector form, and $\widehat{d}^r$ is the direct grey water use intensity of region *r* in diagonal form. Combining the above equation with the fundamental input-output formula, we can obtain the GWF of region *r* derived from its final demand:

$$gwf^r = \widehat{d}^r (I - A^{rr})^{-1} \widehat{f}^r \tag{2}$$

To quantify the GWF of many countries/regions from both consumption and production perspectives, we applied the “Water Embodied in Trade” (WET) approach based on the generalized environmental input-output model. Full details of this approach may be found in Feng et al. (2011) and Zhao et al. (2015), and herein we provide a simplified illustration of the methodology. The basic framework of WET for *p* regions in matrix form can be shown as:

$$\begin{bmatrix} x^1 \\ \vdots \\ x^r \\ \vdots \\ x^p \end{bmatrix} = \begin{bmatrix} A^{11} & \cdots & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & & \vdots \\ 0 & \cdots & A^{rr} & \cdots & 0 \\ \vdots & & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & \cdots & A^{pp} \end{bmatrix} \begin{bmatrix} x^1 \\ \vdots \\ x^r \\ \vdots \\ x^p \end{bmatrix} + \begin{bmatrix} y^1 + \sum_{s \neq 1} e^{1s} \\ \vdots \\ y^r + \sum_{s \neq r} e^{rs} \\ \vdots \\ y^p + \sum_{s \neq p} e^{ps} \end{bmatrix} \tag{3}$$

where $y^r$is the domestic final demand of region *r* in vector form, and $\sum_{s \neq r} e^{rs}$is the exports of region *r* to fulfill the final demand of different regions *s*.

The IGWF of a region may be defined as the grey water use derived from domestic production to support the final demand of the region. Under the WET framework, the IGWF of region r may be denoted as $igwf^r = \sum \widehat{d}^r (I - A^{rr})^{-1} \widehat{y}^r$. The GVWE of a region is defined as the grey water use derived from the production of exported products from that region, and the GVWE of region r may thus be denoted as $gvwe^r = \sum \widehat{d}^r (I - A^{rr})^{-1} \sum_{s \neq r} \widehat{e}^{rs}$. The GVWI is defined as the grey water use derived from the production of imported products for local final demand, and the GVWI of region *r* can therefore be shown as$gvwi^r = \sum \sum_{s \neq r} \widehat{d}^s (I - A^{ss})^{-1} \widehat{e}^{sr}$, where $\widehat{d}^s$ is the direct grey water intensity of region *s* in diagonal matrix form, $\widehat{e}^{sr}$is the export from region *s* to fulfill the final demand of different regions *r* in diagonal matrix form, and $A^{ss}$is the technical coefficient of region *s* in matrix form.

By combining the IGWF and GVWE we can derive the GWFP of region *r*, $gwfp^r = igwf^r + gvwe^r$, and the GWFC of region *r* is the combination of IGWF and GVWI, $gwfc^r = igwf^r + gvwi^r$.

4. Results

4.1. Global grey water footprint from the production perspective

Total and sectoral GWFP of different countries/regions were collected from the WIOD (Genty, 2012). The total global GWFP was 1507.9 km^3, with China identified as having the largest GWFP, with a total of 536.6 km^3, followed by the USA and India with 193.2 km^3 and 174.6 km^3 respectively. Other countries with large GWFP's were Russia (65.0 km^3), Canada (33.6 km^3), Brazil (31.4 km^3) and Indonesia (31.0 km^3). In terms of country groups, the GWFP of the BRIC countries accounted for over half of global GWFP (53.6%), and the GWFP of the OECD29 and EU27 bloc amounted to 24.0% and 6.8%, respectively.

In terms of sectoral GWFP, almost all GWFP was allocated to seven sectors including “Agriculture, Hunting, Forestry and Fishing”, “Basic Metals and Fabricated Metal”, “Chemicals and Chemical Products”, “Pulp, Paper, Printing and Publishing”, “Food, Beverages and Tobacco”, “Textiles and Textile Products”, and “Other Non-metallic Mineral”. The “Agriculture, Hunting, Forestry and Fishing” sector had the largest GWFP, accounting for 60% of total GWFP, followed by the “Basic Metals and Fabricated Metal” and “Chemicals and Chemical Products” sectors accounting for 13% and 11% of GWFP, respectively.

Environmental externality and responsibility cannot be discussed without addressing interpersonal equity. Taking into account the per capita value, Canada had the largest GWFP, generating 997.8 m^3/person of grey water. This is attributed to the relatively low population of Canada. With the exception of the USA (629.8 m^3/person), Chinese Taipei (507.3 m^3/person), and China (403.8 m^3/person), the top 10 countries/regions with the largest per capita GWFP were all from Eastern and Southern Europe, including Bulgaria (685.7 m^3/person), Hungary (535.5 m^3/person), Slovenia (466.0 m^3/person), Russia (455.0 m^3/person), Poland (413.9 m^3/person), and Romania (370.3 m^3/person).

GWFP can be divided into IGWF and GVWE to identify internal and external drivers to local grey water production; in total GVWE constitutes 24.6% of total GWFP. The share of GVWE varies among countries/regions from 12.3% (Greece) to 87.9% (Netherlands). The countries/regions with the largest GWFP had a relatively lower share of GVWE, for example China (22.8%), USA (20.6%), India

(12.4%), and Russia (17.6%). Obviously, these countries are large economies and produce mainly to fulfill domestic consumption.

4.2. Global grey water footprint from the consumption perspective

When examined from a consumption perspective, the GWFC embodied in a country/region's final demand indicates how much grey water would be generated in order to meet its final consumed goods and services. Since the total GWFC is equal to the total GWFP globally, GWFC also refers to the redistribution of grey water use generated from the production side to the consumption side through the supply chain. The national/regional GWFC's are presented in Fig. 1a. For specific countries/regions, China tops the list with a GWFC of 440.0 km^3, accounting for nearly 30% of GWFC. The USA is ranked second with a GWFC of 214.8 km^3, and other countries ranked sequentially among the top 5 are India, Russia and Germany. The GWFC of the top five countries accounted for 60% of global GWFC. In terms of country groups, we found the EU27 accounted for 11% of global GWFC, and the results were 33% and 46% for OECD29 and BRIC, respectively. These findings indicate a large amount of GWFC was generated by the so-called “emerging economies”.

When taking into account the per capita value (Fig. 1b), North America had the highest GWFC per capita, with Canada and the USA ranking first and second respectively. In 2009, the consumption of an average Canadian and American citizen generated water pollution requiring 914.8 m^3/person and 700.2 m^3/person freshwater respectively. Excepting Chinese Taipei, Russia, and Bulgaria, the top 10 countries/regions with the largest GWFC per capita were all from the OECD29, including Canada, USA, Australia (551.9 m^3), Slovenia (515.4 m^3), Netherlands (514.6 m^3), Luxembourg (506.3 m^3), and Belgium (477.9 m^3). Some countries had a large total GWFC but small per capita amount, for instance India ranked third in terms of its national GWFC but had the lowest per capita amount of only 133.9 m^3. Similarly, the inverse relationship can be seen in some countries, for example in 2009 Luxembourg generated only 0.25 billion m^3 GWFC in total, equating to 506.3 m^3 per person.

In terms of sectoral distribution, the top five sectors contributing the most to global GWFC were “Agriculture, Hunting, Forestry and Fishing”, “Food, Beverages and Tobacco”, “Construction”, “Chemicals and Chemical Products”, and “Textiles and Textile Products”. These five sectors were responsible for 31.0%, 21.0%, 9.8%, 5.3%, and 4.4% respectively of GWFC throughout the world in 2009, amounting to 71.5% of GWFC. The national/regional level of sectoral distribution are shown in Fig. 2. At national/regional level the pattern varies; the contribution of “Agriculture, Hunting, Forestry and Fishing” to national/regional GWFC ranged from 15% (Bulgaria) to 52% (Latvia). For “Food, Beverages and Tobacco”, the contribution ranged from 10% (Romania) to 38% (Finland), for “construction” from 0.1% (Luxembourg) to 21% (China), for “Chemicals and Chemical Products” between 2% (China) and 24% (Malta), and for “Textiles and Textile Products” between 1% (Hungary) and 20% (Turkey).

4.3. External and internal grey water footprint from the consumption perspective

The GWFC may be divided into IGWF and GVWI. Globally, the GVWI was 371.4 km^3 accounting for 24.6% of the total GWFC. The top five countries/regions with the largest GVWI were the USA (61.4 km^3), Japan (26.0 km^3), China (25.8 km^3), Germany (25.0 km^3), and Canada (12.7 km^3). The share of GVWI varied significantly at national/regional scale (Fig. 3), ranging from 5.9% (China) to 98.8% (Netherlands). The EU27 bloc had the largest share of GVWI; globally the top five countries with the largest GVWI were the Netherlands, Malta, Luxembourg, Cyprus, and Ireland. As a result, the GVWI for the EU27 bloc constituted 63.5% of the total GWFC. In contrast the BRIC countries were among the main countries having the largest share of IGWF. Over 90% of GWFC in China (94.1%) and India (94.1%) were generated within their own territories, as well as 83.5% in Indonesia, 82.9% in Russia, and 82.2% in Brazil. The share of IGWF varied greatly between the EU27 and BRIC countries, probably because the BRIC countries have larger land areas and relatively self-dependent economies.

4.4. Global outsourcing of grey water

If one country imports more grey water than it exports to other countries through its trade balance i.e. is a net importer of grey water, we can say that this country is outsourcing its water pollution to other countries. Conversely, if a country exports more grey water than it imports, i.e. is a net exporter of grey water, we can say this country is being outsourced by other countries. In 2009, there were 10 countries/regions being outsourced compared to 30 outsourcing countries/regions (Fig. 4). As can be seen in Fig. 4, the top 5 outsourcing countries were Japan, USA, Germany, UK and South Korea, while the top 5 countries/regions being outsourced were China, India, Poland, Brazil, and Canada.

Grey water outsourcing shows different patterns per country/region (Fig. 5). For example, as the largest outsourcing country, Japan outsourced 24.6 km^3 of grey water in 2009. Breaking down the aggregate result, Japan outsourced 24.7 km^3 of grey water to 34 out of 40 countries/regions, but had only 0.1 km^3 of grey water outsourced to it by 6 countries/regions. The two countries Japan outsourced most to were China and USA, which accounted for 46.1% and 18.3% of total grey water outsourcing from this country. It is also worth noting that the volume of grey water outsourced by Japan to China (11.4 km^3) was even higher than grey water consumption within Japan for producing goods and services (6.4 km^3). As the second largest outsourcing country, the USA outsourced 34.7 km^3 of grey water to 12 countries/regions, but was also being outsourced by 28 countries/regions to the tune of 13.1 km^3, resulting in total outsourcing of 21.6 km^3 grey water. The USA mainly outsourced grey water to China, India and Canada, accounting for 77.4% of its total grey water outsourcing to a total of 12 countries/regions. However, USA was being outsourced a large amount of grey water mainly from Japan, Mexico, and Korea, accounting for 66.2% of its total grey water being outsourced. The top three countries outsourcing the largest share of grey water were Malta, the Netherlands, and Cyprus where net exports represented 96%, 90%, and 88% of consumption-based GWF respectively.

The largest net grey water exporting country, i.e. country being outsourced, was China with 96.7 km^3 from the other 41 countries/regions contained in our study (Fig. 5). This volume corresponds to 18% of GWFP for China, and was close to the GWFP of the EU27 (102.8 km^3). The top three countries/regions that outsourced to China were the USA (19.9 km^3), Japan (11.4 km^3), and Germany (6.6 km^3). These three countries were also the top three outsourcing countries examined by our study. Beyond China, the volume being outsourced fell to 12 km^3 for the second largest country India, and to 3.7 km^3 for the third largest, Poland. The top three countries that being outsourced the largest share of their GWFP were Bulgaria, Hungary, and Poland. Net exports of grey water for these three countries represented 38%, 24%, and 23% of GWFP, respectively.

5. Discussion

The quantification of GWFC showed that the top 10 countries/regions with the greatest GWFC were also the most populous

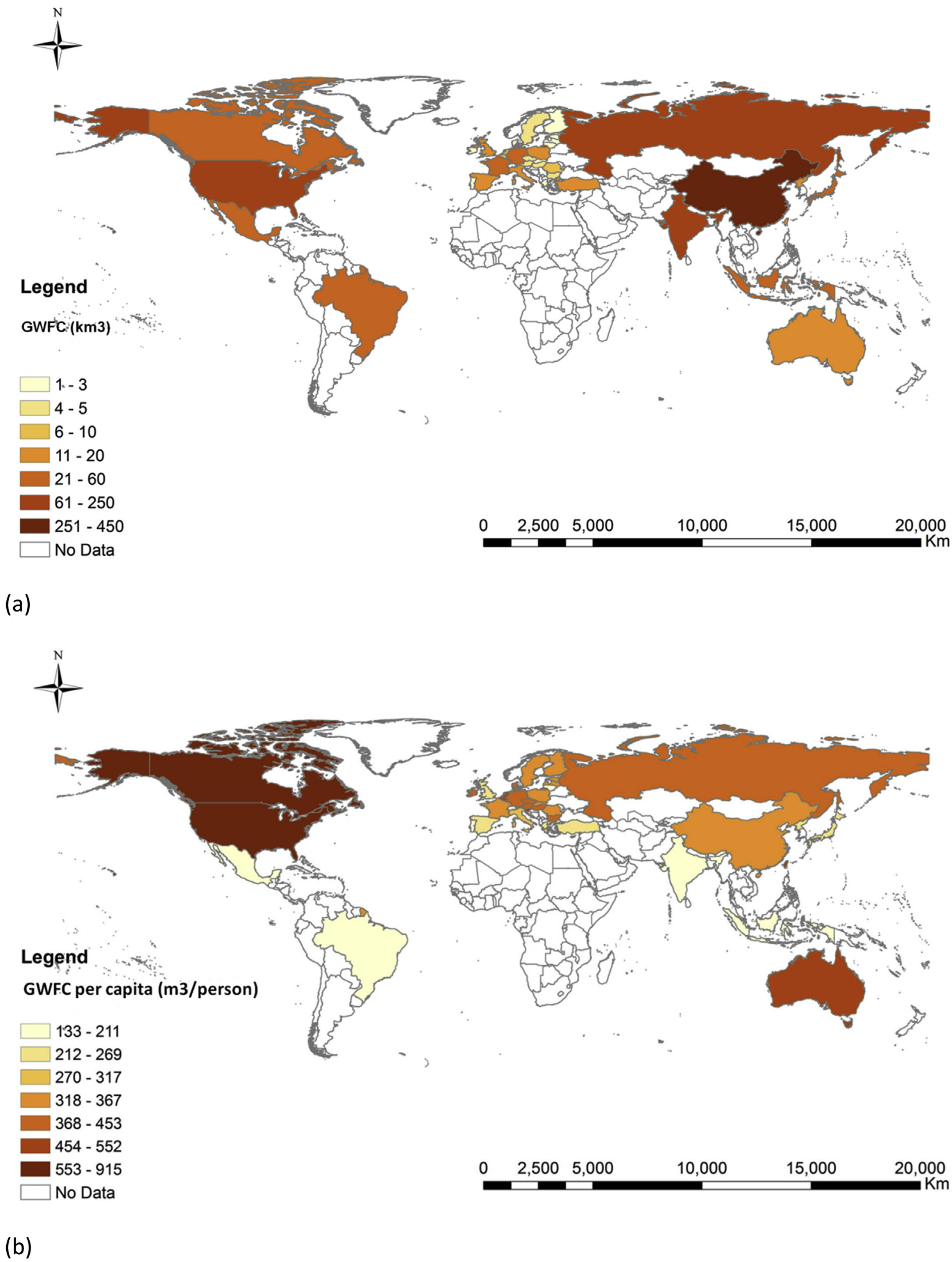

Fig. 1. Greywater footprint from the consumption perspective (GWFC) of 40 countries/regions, (a) national/regional total, (b) per capita.

(Fig. 6). This is simply because these countries require tremendous amounts of products to satisfy final demand of their populations. Final demand may be met through either domestic production or imports of externally produced goods and services. Similarly, the GWFC may either be mostly generated within the country/region with larger IGWF, or outside the country/region with larger GVWI. The GWFC of the newly advanced economies of China, India, Russia, Brazil (i.e. the BRIC countries), as well as Indonesia, was mostly

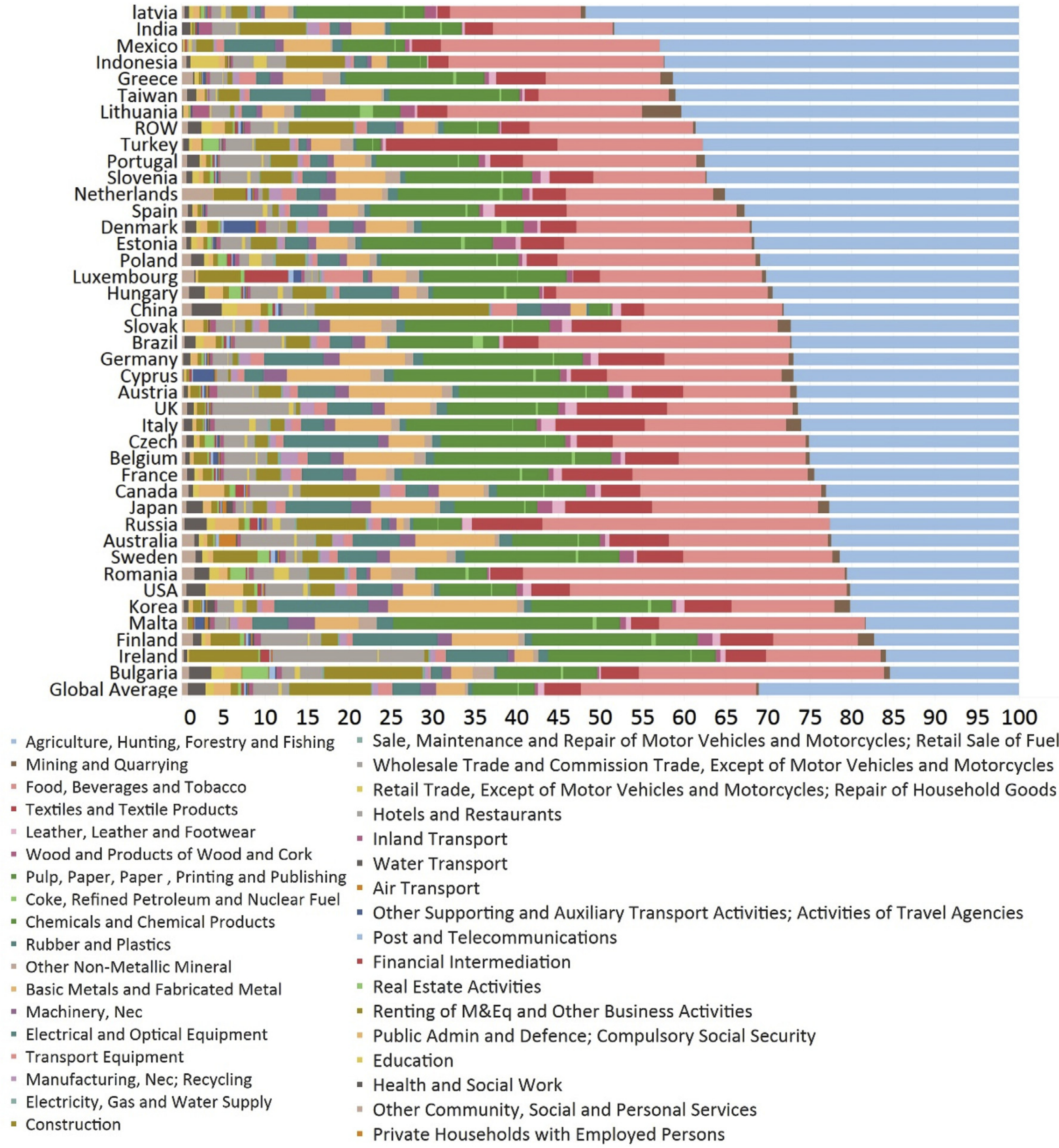

Fig. 2. Sectoral distribution of national/regional GWFC.

generated within the national boundary, with the share of IGWF in GWFC making up 94.1%, 94.1%, 82.9%, 82.2%, and 83.5%, respectively. Similarly, the USA and Canada were found to depend mainly on domestic production, but also generated a substantial share of GVWI accounting for 28.6% and 41.2% of their GWFC, respectively. Therefore, the BRIC countries, the USA, and Canada could substantially reduce their GWFC by reducing their IGWF i.e. regulating production related pollutant discharges associated with domestic final demand within their national boundaries. This is important because the total IGWF of these 7 nations (842.4 km^3) made up over half the global GWFC, i.e. 55.9%.

Conversely, the GWFC of Japan and Germany, also at the top of the global GWFC list, was found to depend mainly on external production, with shares of GVWI accounting for 75.5% and 83.5% of their respective GWFC. These two countries, along with other developed nations such as USA, UK, Italy, the Netherlands, and France, are at the top of the list of grey water outsourcing countries/regions. The OECD29 and EU27 i.e. the country groups consisting mainly of economically developed nations, outsourced 134.8 km^3 and 64.4 km^3 of their grey water mostly to large developing countries such as BRIC, which imported 112 km^3 of grey water. Overall, countries which rely mainly on external production in order to meet domestic final demand raises the question of who is responsible for discharge of waterborne pollution, and how this burden shifting could/should be shared (Davis and Caldeira, 2010; Zhao et al., 2016a). Similar questions have been raised in relation to CO_2 emissions, but rarely for water quality issues (Peters, 2008; Wiedmann, 2009). One of the few exceptions is from Zhao et al. (2016a), who studied the megacity Shanghai as a case to show how wealthy consumers have largely transferred water quality stress to other Chinese provinces. As a result, they suggested taking measures at national/regional, industrial, and consumer levels to obtain shared responsibility between wealthy consumers and often poorer exporters, as well as promoting greater demand-side

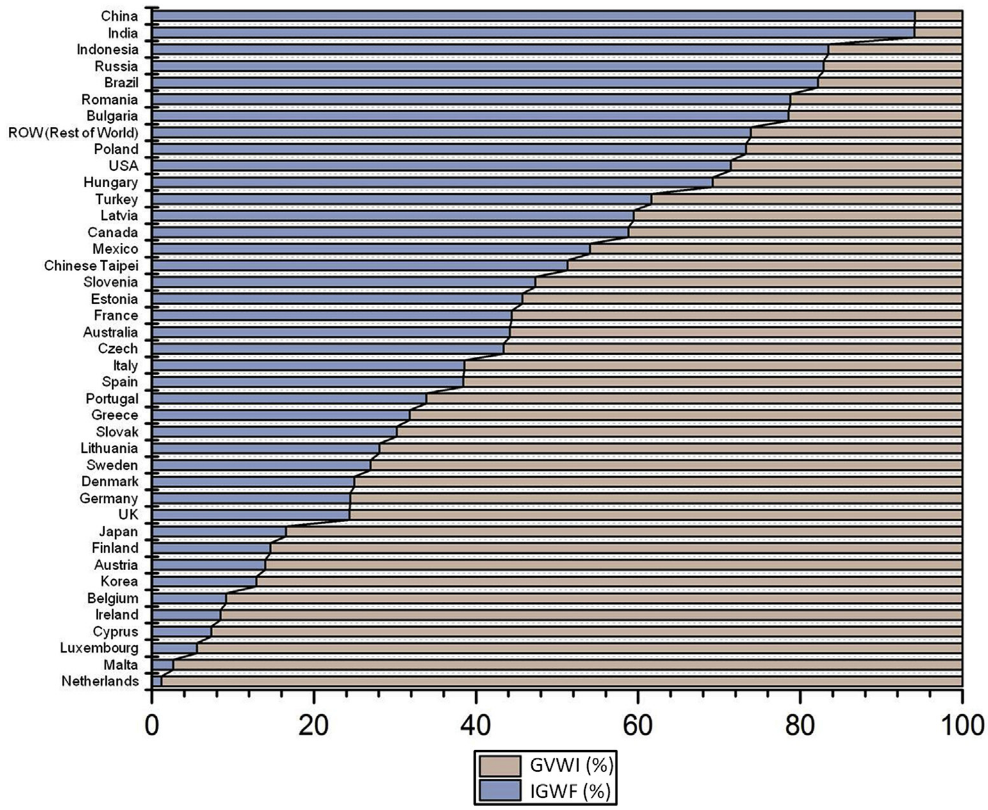

Fig. 3. The share of internal grey water footprint (IGWF) and grey virtual water import (GVWI).

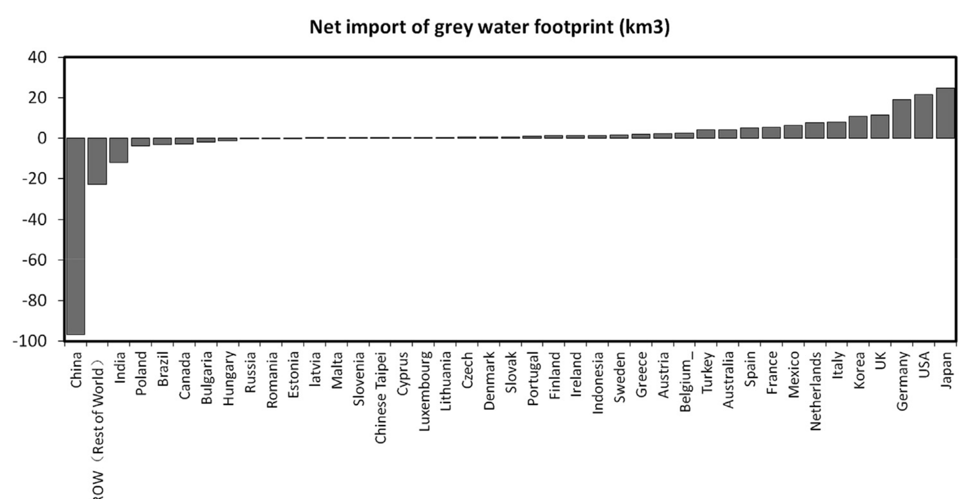

Fig. 4. Net import of grey water footprint (km^3).

management (Zhao et al., 2016a). Based on the results of the present study, we recommend similar measures could be adopted at the global level for mitigating water quality stress induced by consumption in developed countries/regions. As a result, quantitative approaches could be developed aimed at shared responsibility for water pollution among poorer exporters and wealthy consumers.

Overall, GWF is an appropriate tool for global assessment of water pollution because it is a homogenous indicator enabling comparison of water pollution impacts spatially and across regions/countries (Pellicer-Martínez and Martínez-Paz, 2016). However, the concept itself has a number of limitations which currently constrain its accuracy for global assessment. First, the results of GWF will vary substantially based on the selection of different water quality standards and data sources of natural pollutant concentrations (Mekonnen and Hoekstra, 2015). Second, GWF is generally assessed using individual classes of pollutant. Assessments of GWF have overwhelmingly been focused on nitrogen-related pollutants, despite the cocktails of pollutants known to exist in polluted waterbodies, and which may therefore significantly underestimate the GWF (Liu et al., 2017). For example, Liu et al. (2017) found that the volume of freshwater needed to dilute phosphorus inputs is

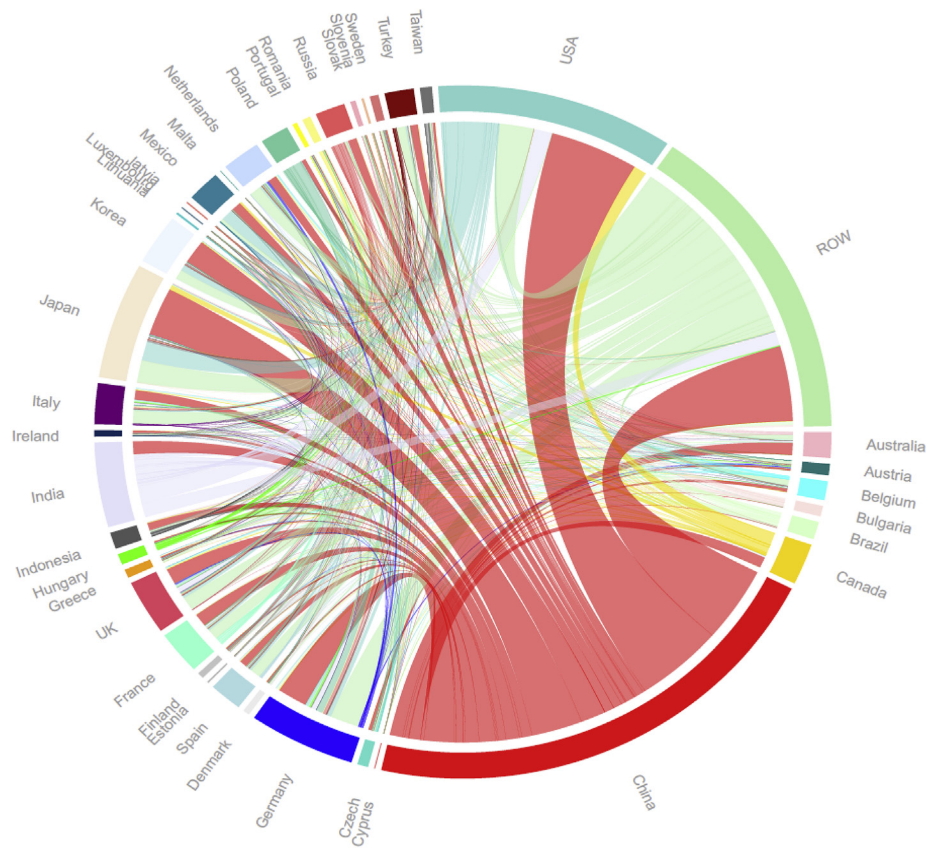

Fig. 5. Grey water outsourcing among 40 countries/regions (the ribbons and links in the same color as the country/region mean the country/region was a net exporter of grey virtual water, otherwise it was net importer of grey virtual water. For example, the red ribbon and links from China shows China was a net exporter of grey virtual water to other countries/regions). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

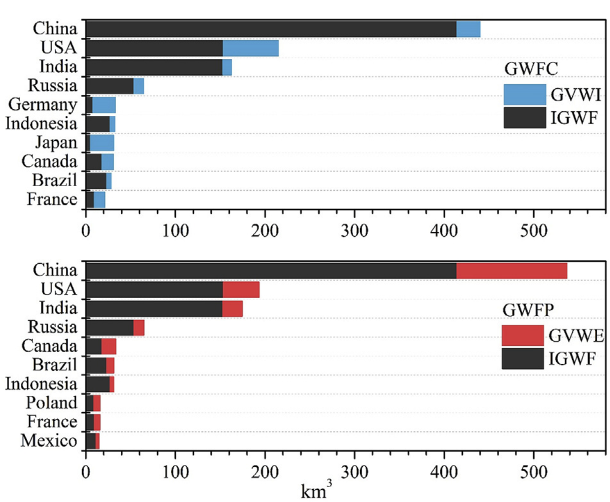

Fig. 6. Comparison of the top 10 GWFC and GWFP countries.

much higher than for nitrogen loads. Third, it is difficult to validate the results of GWF since the indicator cannot be measured directly (Liu et al., 2012). However, despite all these limitations, GWF still has great potential as a sustainability indicator for water pollution at different spatial levels (Pellicer-Martínez and Martínez-Paz, 2016). The present study also contains the well documented limitations typical of input-output analyses and MRIO approaches. In particular, regional and sectoral aggregation of MRIO tables exists, and a higher degree of aggregation tends to more severe issues around quantification accuracy (Lenzen et al., 2013). Last, but not least, both the data of grey water use by sector and MRIO table need updating to include more recent years. MRIO data is often outdated on release because of the problems of dealing with incomplete, conflicting, and misaligned data (Lenzen et al., 2012). Discharges of water pollutants by sector and ambient water quality standards to quantify grey water use by sector are often not available, or cannot be accessed, for many countries (Liu et al., 2017). Overcoming the limitations of the GWF concept and the relative models is therefore key to developing the acceptability of GWF in the policy domain.

6. Conclusions

We have quantified the global GWFC/GWFP for 40 countries/regions from both the production and consumption perspectives. Although the GWFC and GWFP have the same value at global level, they were found to vary greatly among different countries/regions. Generally, the results from the production perspective (GWFP) helped to identify country/regional hotspots with potential water quality problems, and further manifest the internal (IGWF) and external (GVWE) driving forces to local water pollution discharge. We found that most of the GWFP was concentrated in a small number of geographically large countries/regions; with about 59% of the global GWFP found in North America and BRIC countries. Despite their large IGWF, these countries also topped the list for the largest GVWE, sharing 59% of the global GVWE, meaning that the pollutant discharge of these countries was largely driven by external market forces. The results from the consumption perspective (GWFC), allocating water pollution discharge to the final consumer of products and services, confirms previous research that developed countries (e.g. Japan, Germany) and country groups (OECD29, EU27) have outsourced their pollution to developing countries (e.g. the BRIC countries) to a large extent.

The MRIO approach provides a unified framework to account for the GWF from both production and consumption perspectives enabling detailed information on industrial sectors. Globally, industrial sectors accounted for 40.0% of the GWFP, but 56.1% of GWFC. Most industrial sectors (13 out of 17) had smaller GWFP but higher GWFC due to their demand for intermediate products (raw materials) which discharge large amounts of water pollution. Hence, it is necessary to take a life-cycle perspective for key industrial sectors to make sure the supply of raw materials in undertaken in an environmentally conscientious way (Lenzen et al., 2007). Our results identified these key industrial sectors from the GWFC point of view: sectors such as "Food, Beverages and Tobacco", "Construction", and "Textiles and Textile Products" are recommended to take additional responsibility for their upstream grey water use. The top-down approach from the consumer perspective thus provides an appropriate tool for such analysis. However, it is essential to reduce the high levels of uncertainty derived from estimating complex production chains from the consumption perspective using the MRIO approach (Peters, 2008). To reduce such uncertainty, further efforts need to be made towards developing the global MRIO table with more detailed sectoral information, as well as developing corresponding and updated data for sectoral grey water use at the national level. In addition, improvements in the scientific robustness of GWF is important in its use as a tool for waterborne pollutant mitigation (Liu et al., 2017).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.04.037.

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