Front. Earth Sci. 2020, 14(1): 201–208
https://doi.org/10.1007/s11707-019-0760-1

RESEARCH ARTICLE

Grey water footprint for global energy demands

Jing MING[1,2,3], Xiawei LIAO (✉)[4,5], Xu ZHAO[6]

1 Chengdu University of Information Technology, School of Atomospheic Sciences, Chengdu 610225, China
2 Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China
3 University of Chinese Academy of Sciences, Beijing 100049, China
4 School of Environment and Energy, Peking University Shenzhen Graduate School, Shenzhen 518055, China
5 College of Environmental Sciences and Engineering, Peking University, Beijing 100871, China
6 Key Laboratory of Integrated Regulation and Resource Development on Shallow Lake of Ministry of Education, College of Environment, Hohai University, Nanjing 210098, China

Abstract With a Multi-Regional Input-Output model, this study quantifies global final energy demands' grey water footprint (GWF) based on the latest available data. In 2009, 9.10 km^3 of freshwater was required to dilute the pollutants generated along the life-cycle supply chain of global energy final demands to concentrations permitted by relevant environmental regulations. On a national level, final energy demands in China, USA, India, Japan, and Brazil required the largest GWF of 1.45, 1.19, 0.79, 0.51, and 0.45 km^3 respectively, while European countries have the highest energy demands GWF per capita. From the producer perspective, the largest GWF was generated in BRIC countries, i.e., Russia (1.54 km^3), China (1.35 km^3), India (0.92 km^3) and Brazil (0.56 km^3) to support global final energy demands. Because of global trading activities, a country or region's final energy demands also give rise to water pollutants beyond its territorial boundaries. Cyprus, Greece, Luxembourg, and Malta almost entirely rely on foreign water resources to dilute water pollutants generated to meet their final energy demands. Energy demands in BRIC countries have the least dependency on external water resources. On a global average, 56.9% of GWF for energy demands was generated beyond national boundaries. Energy demands in the global north are inducing water pollutions in the global south.

Keywords water-energy nexus, water pollution, water footprint, multi-regional input-output analysis

1 Introduction

Reliable energy provision is critical to human society's development and prosperity (Nerini et al., 2018). During the last two decades, energy productions' impacts and dependencies on water resources have gained increasing recognitions among the academic community and policy makers (Gleick, 1994; Vassolo and Doll, 2005; Marsh, 2008; Rio Carrillo and Frei, 2009). International Energy Agency estimated that energy production accounted for 15% of the global water withdrawal in 2010, at 583 billion m^3 (IEA, 2012).

A large amount of scholarly work has thus been done to quantify the water uses for energy productions, both directly for on-site processes and indirectly as upstream inputs, at various geographical locations (Fthenakis and Kim, 2010; Macknick et al., 2012; Pan et al., 2012; Meldrum et al., 2013; Liao et al., 2016). Spang et al. (2014) reviewed the existing literature and compared energy production's water uses in over 150 countries. Mielke et al. (2010) concluded that energy production consumes 27% of the US society's total water consumption, only second to the Agriculture sector. Cai et al. (2014) calculated that water withdrawal for energy production in China has increased from 8.98 BCM in 2000 to 28.78 BCM in 2011, and is projected to further grow by 77% by 2030.

Besides water quantity, energy production, especially fossil fuel extraction, discharges a significant amount of water pollutants (Mishra et al., 2008), which receives far less attention so far. Various water pollutants, such as Chemical Oxygen Demand (COD) and petroleum, are generated along the life cycle of energy productions, at coal mines for example. Zhang and Anadon (2013) calculated that energy production in China discharge 8.3% of the national wastewater. However, crucial information such as wastewater concentrations and water pollutant types were all unknown. Studies looking at the energy sector's impacts on water quality are still lacking.

Water footprint is an indicator of comprehensive water

Received December 10, 2018; accepted April 15, 2019

E-mail: xiawei.liao@ouce.ox.ac.uk, lxw753951@gmail.com

use along the supply chain that not only looks at the direct water use, but also indirect water uses (Hoekstra et al., 2011). Water footprint has three components: green water that refers to water precipitated and stored in the soil; blue water includes water resources from river systems and groundwater aquifers and gray water. To investigate the energy sector's impact on water quality, gray water footprint is a useful indicator that has been widely used (Chapagain et al., 2006; Hoekstra et al., 2011), which is defined as the total gray water that is required throughout the life-cycle supply chain to meet energy demands, for instance, from coal extraction to thermoelectric power productions. It therefore provides a framework that unifies the comparison between water quantity and water quality. Not only the on-site water pollution, but also the indirect water pollution is included in the GWF accounting framework. Moreover, GWF also enables comparison between different types of pollutants of different concentrations into different conditions of water bodies in different geographical locations. Therefore GWF is a useful indicator that can be used in spatial analyses (Pellicer-Martínez and Martínez-Paz, 2016).

Many scholars have adopted GWF to quantify different anthropogenic systems' impacts on water quality on different geographical scales. On the local scale, Serrano et al. (2016) quantified the virtual gray water flows within the European countries; Wang et al. (2013) quantified the textile industry's gray water footprint in China; Cai et al. (2017) quantified Mainland China's gray water footprint and concluded that gray water footprint has been historically overlooked. They also found out that petroleum processing and coking contributed to around 7% of Mainland China's total grey water footprint. Zeng et al. (2013) used grey water footprint to assess quality-driven water scarcities in Beijing and other regional and local studies have also been done in other locations (Zhi et al., 2015; Pellicer-Martínez and Martínez-Paz, 2016). On the global scale, most studies on grey water footprint have been focused on agricultural sectors. For example, Liu et al. (2017) quantified the GWF of global maize production while Chapagain et al. (2006) quantified that of global cotton consumption. Regarding the energy sector, its global water footprint studies have only focused on the blue water component. For example, Gerbens-Leenes et al. (2009) investigated the blue water footprint of different types of bioenergy from 12 crops globally; Mekonnen and Hoekstra (2012) shed light on the blue water footprint of hydropower productions. Mekonnen et al. (2015) conducted a global assessment of the consumptive (blue) water footprint of electricity and heat while Holland et al. (2015) investigated the blue water footprint of global energy demands from a global trade perspective. Against this backdrop, few studies have quantified the grey water footprint (GWF) that is required to fulfill the final energy demands on a global scale.

Furthermore, as energy products can be traded across territorial boundaries, GWF embodied in the traded products can also be transferred among countries and regions accordingly. In doing so, countries and regions can outsource their water pollution in order to meet their own energy needs (Zhang et al., 2011; Zhao et al., 2015; Zhao et al., 2016), which imposes pressure on quality-induced water stresses in the pollution importing countries. This study also quantifies such inter-national pollution outsourcings for energy demands, indicated by GWF transfers, with a widely used consumption-based model, i.e., Multi-Regional Input-Output (MRIO).

2 Method and data

2.1 Method

MRIO has been widely used to examine the life cycle environmental requirements or impact of a given sector's final demands (Liang et al., 2007; Wiedmann, 2009; Zhao et al., 2015). For an economy of country r, the total output x^r (in vector form) is produced for intermediate inputs between different sectors and final consumption by households, governments, and so forth. The intermediate inputs include domestic purchase Z^{rr} and the sum of international purchase by different countries s (export from country r to s), $\Sigma_{s\neq r}Z^{rs}$. Likewise, there are domestic purchases y^{rr} and international purchases $\Sigma_{s\neq r}Z^{rs}$ for final consumption. Hence, the total output x^r is the sum of intermediate and final consumption.

$$x^r = Z^{rr} + \Sigma_{s\neq r}Z^{rs} + y^{rr} + \Sigma_{s\neq r}y^{rs}. \quad (1)$$

We assume that bilateral trades between countries are all directed toward final consumption (Peters and Hertwich, 2008), thus the international trade of intermediate consumption is assigned to the international trade of final consumption. Accordingly, $\Sigma_{s\neq r}y^{rs}$ is replaced by $\Sigma_{s\neq r}e^{rs} = \Sigma_{s\neq r}Z^{rs} + y^{rs}$, where $\Sigma_{s\neq r}e^{rs}$ represents the international purchase of final consumption.

$$x^r = Z^{rr} + y^{rr} + \Sigma_{s\neq r}e^{rs}. \quad (2)$$

According to Leontief (1941), the technical coefficient $A = Z/x$ equals the intermediate inputs of each sector per unit of their output. Equation (2) can be expressed as:

$$x^r = A^{rr}x^r + y^{rr} + \Sigma_{s\neq r}e^{rs}, \quad (3)$$

$$x^r = (I - A^{rr})^{-1}(y^{rr} + \Sigma_{s\neq r}e^{rs}). \quad (4)$$

To study the grey water footprint for the final consumption of all sectors in region r, first we introduce m^r, the vector of total gray water footprint, including both direct and indirect gray water use, to produce a unit of final consumption using water resources from country r.

$$m^r = d^r(I - A^{rr})^{-1}, \quad (5)$$

where m^r is the gray water footprint intensity embodied in every unit of final consumption while $d^r = w^r/x^r$ is the vector of direct gray water use intensity of country r that represents the direct gray water use per unit of output in each sector.

There are two categories of GWF of country r. First, water pollutants are discharged in region r and require physical water to dilute. This part of gray water constitutes grey water footprint for both local consumption ($GWF^{rs} = m^r \times y^{rr}$ and exports ($GWF^{rs} = m^r \times \Sigma_{s \neq r} e^{rs}$. Secondly, GWF for country r's imports can be expressed as: $GWF^{sr} = \Sigma_{s \neq r} m^s \times e^{sr}$, where $m^s = d^s(I - A^{ss})^{-1}$.

To better illustrate the process of quantifying GWF in the energy sectors, we suppose there is a two-country economy, country r and country s. let there be three producing sectors (1, 2, 3) in both country r and country s. While we suppose sector 2 is the energy sector. The results of GWF can be shown as followed.

$$GWF = \begin{Bmatrix} GWF^{rr} & GWF^{rs} \\ GWF^{sr} & GWF^{ss} \end{Bmatrix}, \tag{6}$$

where $GWF^{rr} = d^r(I - A^{rr})^{-1} f^{rr}$, $GWF^{ss} = d^s(I - A^{ss})^{-1} f^{ss}$, $GWF^{rs} = d^r(I - A^{rr})^{-1} e^{rs}$, and $GWF^{sr} = d^s(I - A^{ss})^{-1} e^{sr}$. Equation (6) can be further shown with sector details.

$$GWF = \begin{Bmatrix} GWF_{11}^{rr} & GWF_{12}^{rr} & GWF_{13}^{rr} & GWF_{11}^{rs} & GWF_{12}^{rs} & GWF_{13}^{rs} \\ GWF_{21}^{rr} & GWF_{22}^{rr} & GWF_{23}^{rr} & GWF_{21}^{rs} & GWF_{22}^{rs} & GWF_{23}^{rs} \\ GWF_{31}^{rr} & GWF_{32}^{rr} & GWF_{33}^{rr} & GWF_{31}^{rs} & GWF_{32}^{rs} & GWF_{33}^{rs} \\ GWF_{11}^{sr} & GWF_{12}^{sr} & GWF_{13}^{sr} & GWF_{11}^{ss} & GWF_{12}^{ss} & GWF_{13}^{ss} \\ GWF_{21}^{sr} & GWF_{22}^{sr} & GWF_{23}^{sr} & GWF_{21}^{ss} & GWF_{22}^{ss} & GWF_{23}^{ss} \\ GWF_{31}^{sr} & GWF_{32}^{sr} & GWF_{33}^{sr} & GWF_{31}^{ss} & GWF_{32}^{ss} & GWF_{33}^{ss} \end{Bmatrix}. \tag{7}$$

For country r, the life-cycle GWF of its energy sector can be shown as Eq. (8):

$$GWF_2^r = GWF_{12}^{rr} + GWF_{22}^{rr} + GWF_{32}^{rr} + GWF_{12}^{sr} + GWF_{22}^{sr} + GWF_{32}^{sr}, \tag{8}$$

where GWF_2^r is the life-cycle GWF of country or region r's sector 2, i.e., energy sector in this case.

2.2 Data and treatment

World input-output table in 2009 can be obtained from The World Input-Output Database (WIOD). In WIOD, grey water uses for 35 national sectors are both calculated and compiled based on Mekonnen and Hoekstra's extensive work (Mekonnen and Hoekstra, 2010a, 2010b, 2011a, 2011b) (Detailed sector classification can be found in Supplementary Information). The water use data were derived from the multi-year average. Data from 2009 are used as the latest available grey water information. The database covers 39 countries/regions including 27 EU countries and 12 non-EU countries/regions, i.e., Australia, Brazil, Canada, China, India, Indonesia, Japan, South Korea, Mexico, Russia, Turkey, and USA. The rest of the world is aggregated into a single region RoW (Rest of the World). Among all the 35 sectors, final demands of three sectors are energy-related, i.e., 'mining and quarrying', 'coke, refined petroleum and nuclear' and 'electricity, gas and water supply'. Due to data unavailability, we are not able to disaggregate 'electricity, gas and water supply' to more detailed sectors. However, this study constitutes the first attempt quantifying the life-cycle water pollution by global energy demands whose results lay foundation for further studies upon required data are available.

3 Results

3.1 Global energy demands' GWF

In 2009, global final energy demands GWF amounted to 9.01 km^3, which is to say 9.01 km^3 of freshwater was required to dilute all the water pollutants produced throughout the life-cycle processes to meet the global energy needs.

It can be seen from Fig. 1, besides USA and Japan, GWF of final energy demands was the highest among BRIC countries in 2009, i.e., Brazil (0.45 km^3), Russia (0.30 km^3), India (0.79 km^3) and China (1.45 km^3). This maybe correlated to lax regulations in developing countries compared to the developed ones. Large amounts of GWF were also generated by final energy demands in the USA (1.19 km^3) and Japan (0.51 km^3), which can be explained by their citizens' more affluent living standards. It should be noted that the aggregated GWF of energy demands of the Rest of the World was still slightly below that of China, at 1.41 km^3.

Malta's final energy demands generated the lowest GWFs at 0.50 $\times 10^6$ m^3 in 2009, followed by Luxembourg (1.74 $\times 10^6$ m^3), Cyprus (3.32 $\times 10^6$ m^3), Estonia (4.06 $\times 10^6$ m^3) and Slovenia (6.73 $\times 10^6$ m^3).

To consider the equality among different societies, it is important to also look at the per capita value of final energy demands' GWF. When population is taken into

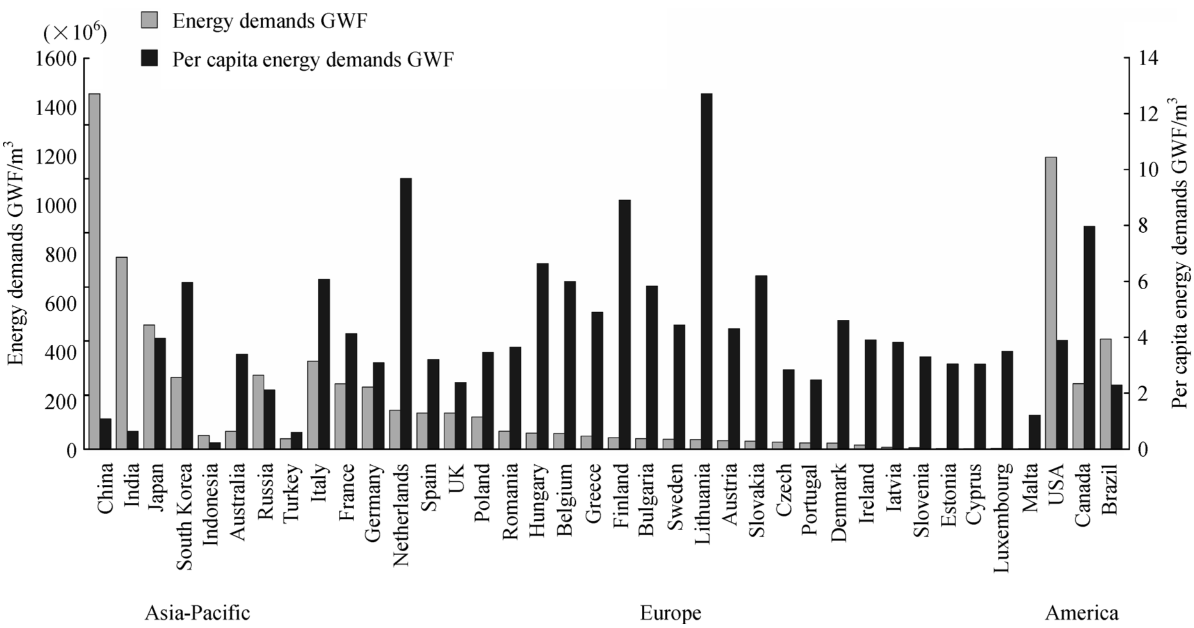

Fig. 1 National (per capita) Energy Demands GWF.

consideration, the pattern reversed significantly. It can be seen from Fig. 1 that countries in Europe and North America have the largest GWF for final energy demands per capita. The top 5 countries were Lithuania (12.72 m^3/capita), the Netherlands (9.68 m^3/capita), Finland (8.91 m^3/capita), Canada (7.96 m^3/capita) and Hungary (6.64 m^3/capita). On the contrary, developing countries with large populations ranked among the bottom. The bottom 5 countries were Indonesia (0.24 m^3/capita), Mexico (0.37 m^3/capita), Turkey (0.61 m^3/capita), India (0.65 m^3/capita), and China (1.09 m^3/capita).

3.2 Sectoral distributions by both origin and destination

Three economic sectors in the WIOD are considered related to energy provisions in this study: ‘mining and quarrying (MQ)’, ‘coke, refined petroleum and nuclear fuel (CPN)’ and ‘electricity, gas and water supply (EGW)’. Globally, MQ required the largest GWF at 4.80 km^3 in 2009 while EGW required the least amount of GWF (1.93 km^3). Final demands in the CPN sector required 2.37 km^3 of GWF.

The upper diagram in Fig. 2 demonstrates different countries’ energy demands GWF in the three sectors. From the consumer perspective, MQ, CPN, and EGW respectively required the largest amount of GWF in USA (768.94 $\times 10^6$ m^3), India (371.54 $\times 10^6$ m^3) and China (598.89 $\times 10^6$ m^3).

From the producer perspective, to support global energy demands, the largest amount of GWF was generated in BRIC countries for all three energy sectors. For global demands in MG, 1.03, 0.45 and 0.22 km^3 of GWF was generated in Russia, China and India respectively. CPN demands generated 0.50, 0.43, and 0.29 km^3 of GWF in India, Brazil, and Russia (followed by 0.26 km^3 in China). The top 3 countries generating the largest GWF for global EGW were China (0.63 km^3), Russia (0.21 km^3), and India (0.20 km^3).

3.3 External GWF of national energy demands and corresponding GWF transfers

Through importing energy products, countries and regions can outsource their water pollution to other places and thus give rise to water-quality-induced water stresses beyond their territorial boundaries. According to our quantification as demonstrated in Fig. 3, a few small European countries, i.e., Cyprus, Greece, Luxembourg, and Malta, completely depended on other countries to assimilate water pollutants discharged to meet their energy demands, so did many other developed countries and regions in Europe and Asia (South Korea and Japan). India and Brazil had external GWF smaller than 20%, thus they were more self-sufficient than any other country.

However, looking at the absolute values, USA, China, Japan, Italy, and South Korea outsourced the largest amounts of GWF to other countries (731.24, 528.30, 469.76, 342.26, and 288.43 $\times 10^6$ m^3). Three East Asian countries stand out in this category. Unsurprisingly, even though Cyprus, Luxembourg, and Malta completely depended on external GWF, the absolute amounts of the GWF generated to meet their final energy demands were quite small, at 3.32, 1.73, and 0.50 $\times 10^6$ m^3.

When we look at the specific GWF transfers between countries as in Fig. 4, it is surprising to find that, except for the USA outsourcing 100.20 $\times 10^6$ m^3 of GWF to its

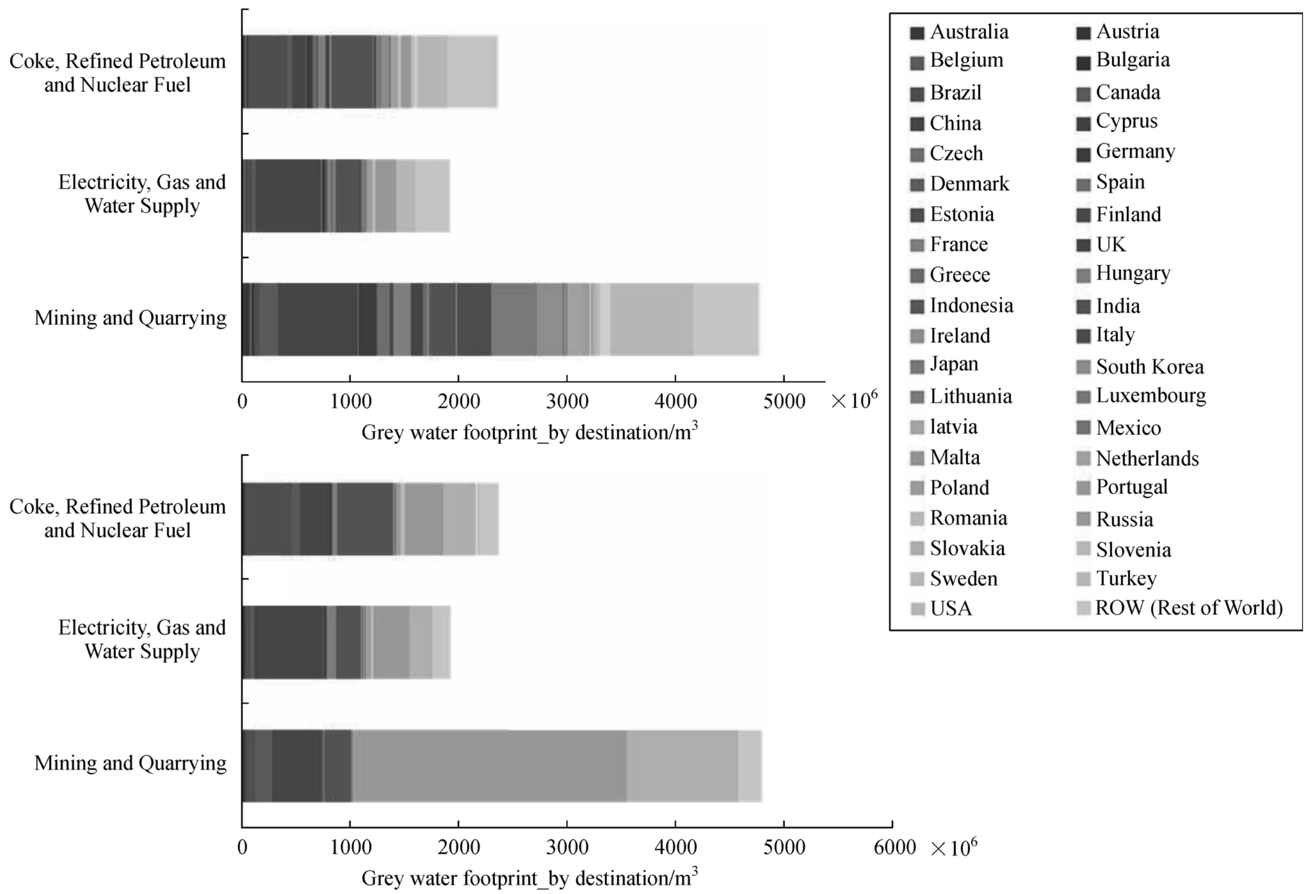

Fig. 2 Sectoral distribution of energy demands GWF by destination and origin country/region.

neighboring country Canada, the other top five GWF transfers were all transferred from Russia, to Italy (148.46 $\times 10^6$ m^3), Germany (92.78 $\times 10^6$ m^3), France (85.89 $\times 10^6$ m^3), and China (72.91 $\times 10^6$ m^3). In other words, those four countries all outsourced pollutants that required significant volumes of freshwater in Russia to assimilate. Such results can be explained given Russia's position as the world's leading energy exporter.

4 Discussion and conclusions

4.1 Discussion

Ensuring energy and clean water for all have been identified as two sustainable development goals (SDG2 and SDG6) by the United Nations (United Nations, 2015). However, at times, achieving these two may be at odds with each other (Nerini et al., 2018). While water consumption for energy production has been brought to the forefront of policy and scientific discussions, it is important to also look at the water quality degradation induced by the energy sector.

According to our quantification, three BRIC countries (China, India, and Brazil) and two of the world's largest economies (USA and Japan) generated the largest GWFs to meet their final energy demands. It can be explained by either their relatively large energy demands (USA and Japan) or lax in related environmental regulations (BRIC countries). However, China and India both ranked very low in terms of per capita energy demands GWF. Countries in Europe, i.e., Lithuania, Netherlands, Finland, required the largest per capita GWF for their energy demands. Populous countries like India and China require large amounts of GWF for their final energy demands due to their significantly larger populations. Looking at the per capita values addresses inter-country development inequalities and the different affluent levels of people's living standards.

Due to global trading activities, energy demands in one country/region led to water pollution beyond its boundaries. Over half (56.9%) of the global GWF for energy demands, at 5.18 km^3, were used for trading activities. USA, China, and Japan, the world three largest economies, have outsourced the largest amounts of water pollution to other countries for their respective energy demands, requiring external GWF of 731.24, 528.30, and 469.76 $\times 10^6$ m^3. On the contrary, BRIC countries, Russia, China, India, and Brazil, together with Canada were the top 5 GWF exporters. 1244.93, 424.56, 263.51, 187.83, and

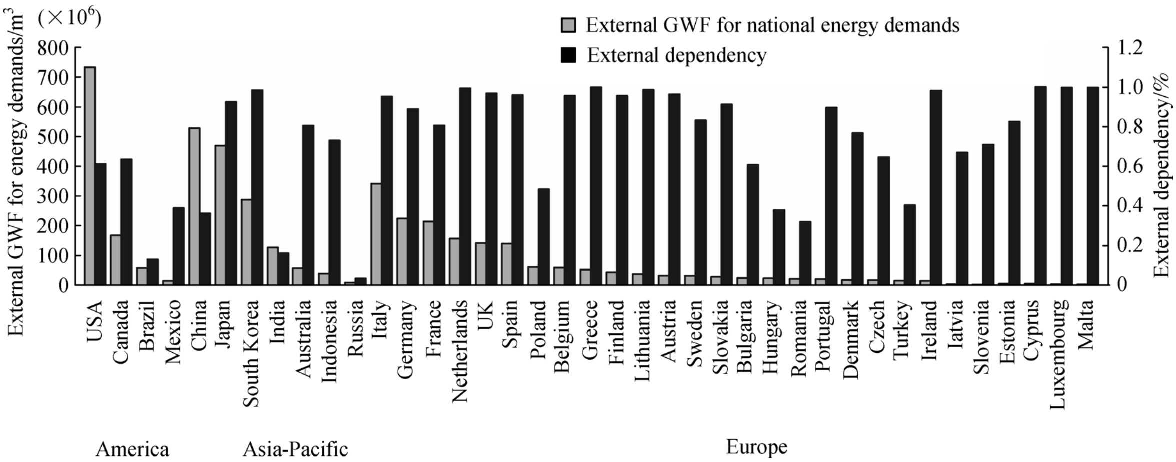

Fig. 3 External GWF for national energy demands.

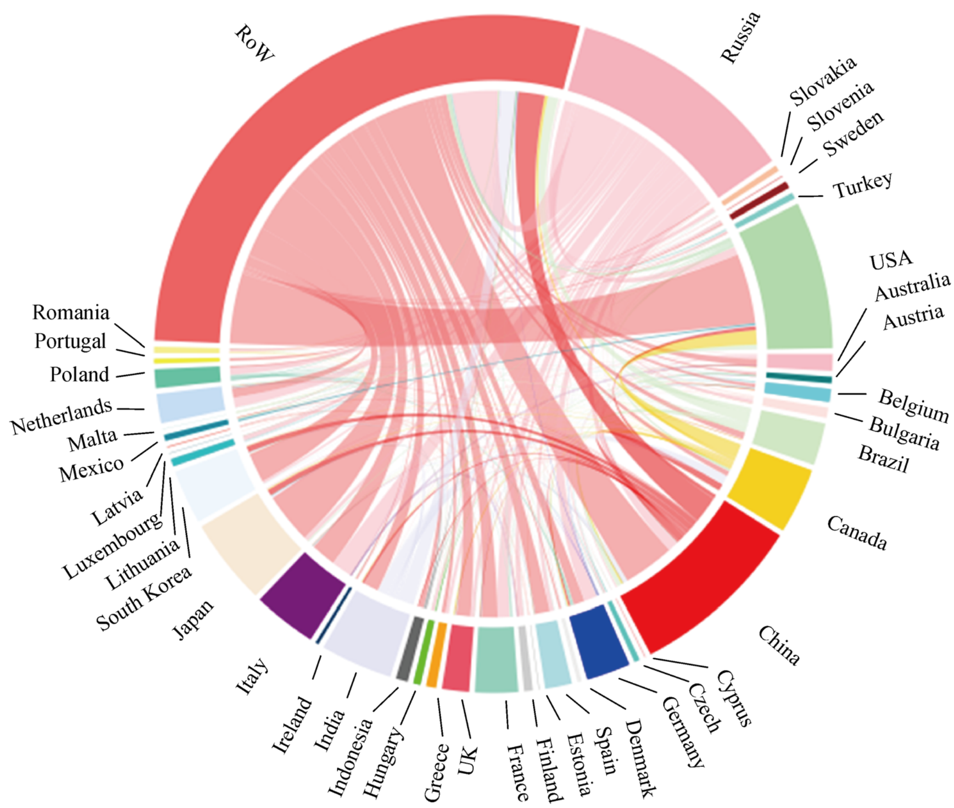

Fig. 4 International GWF transfers for final energy demands.

170.59 $\times 10^6$ m^3 of GWF was generated in Russia, China, India, Canada, and Brazil, respectively, to support energy demands beyond their boundaries. Especially in developing countries, environmental regulations are relatively loose. It is important for those countries to recognize such environmental externalities and factor them into the prices of traded energy products. Holland et al. (2015) quantified that 18.31 km^3 of freshwater is consumed annually for global energy demands. We estimated that approximately another 10 km^3 is needed for the dilution of the water pollutants discharged throughout the life cycle of those energy demands.

Although GWF is a useful indicator that unifies water quality and quantity indicators and enables the comparison of different water pollutants (Pellicer-Martínez and Martínez-Paz, 2016), it should be noted that significant uncertainties exist in terms of GWF accounting. First, GWF accounting varies substantially due to different selection criteria of water quality standards as well as water pollutants (Mekonnen and Hoekstra, 2015). Moreover, estimating GWF often uses a single pollutant, nitrogen in most cases, but other pollutants in the discharged wastewater might need larger amount of freshwater to dilute (Liu et al., 2017). Lastly, validation of GWF accountings is difficult since direct measurement is not possible (Liu et al., 2012). Therefore findings of international Grey Water footprint studies should be interpreted qualitatively rather than quantitatively. Another limitation of this work is the relatively coarse sector classification in the WIOD database and we did not disaggregate the three energy-related sectors due to data paucity, especially on a global level. Nonetheless, this study marks the first study which quantifies global energy demand's impact on water quality. Finally, although 2009 is the latest year for which global gray water use data are available, future research should be carried out upon more updated data becoming available.

4.2 Conclusions

With a Multi-Regional Input-Output model, we for the first time quantify water degradation induced by global energy demands using the indicator grey water footprint (GWF). According to our quantifications, global energy demands in 2009 have generated water pollutants that needed 9.1 km^3 of freshwater to assimilate to permissible concentrations in the environment. The largest GWF was generated in BRIC countries to support global final energy demands. Because of global trading activities, on a global average, 56.9% of GWF for energy demands was generated beyond national boundaries. Energy demands in the global north are inducing water pollutions in the global south.

Appendix Detailed sectoral classification

Number	Sector Name
1	Agriculture, Hunting, Forestry and Fishing
2	Mining and Quarrying
3	Food, Beverages and Tobacco
4	Textiles and Textile Products
5	Leather, Leather and Footwear
6	Wood and Products of Wood and Cork
7	Pulp, Paper, Paper, Printing and Publishing
8	Coke, Refined Petroleum and Nuclear Fuel
9	Chemicals and Chemical Products
10	Rubber and Plastics
11	Other Non-Metallic Mineral
12	Basic Metals and Fabricated Metal
13	Machinery, Nec
14	Electrical and Optical Equipment
15	Transport Equipment
16	Manufacturing, Nec; Recycling
17	Electricity, Gas and Water Supply
18	Construction
19	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel
20	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles
21	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods
22	Hotels and Restaurants
23	Inland Transport
24	Water Transport
25	Air Transport
26	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies
27	Post and Telecommunications
28	Financial Intermediation
29	Real Estate Activities
30	Renting of M&Eq and Other Business Activities
31	Public Admin and Defense; Compulsory Social Security
32	Education
33	Health and Social Work
34	Other Community, Social and Personal Services
35	Private Households with Employed Persons

References

Cai B M, Zhang B, Bi J, Zhang W J, (2014). Energy's thirst for water in China. Environ. Sci. Technol. 48, 11760–11768

Cai B, Wang C, Zhang B (2017). Worse than imagined: unidentified virtual water in China. J Clean Prod, 196: 681–691

Chapagain A K, Hoekstra A Y, Savenije H H G, Gautam R (2006). The water footprint of cotton consumption: an assessment of the impact of worldwide consumption of cotton products on the water resources in the cotton producing countries. Ecol Econ, 60(1): 186–203

Fthenakis V, Kim H C (2010). Life-cycle uses of water in U.S. electricity generation. Renew Sustain Energy Rev, 14(7): 2039–2048

Gerbens-Leenes W, Hoekstra A Y, van der Meer T H (2009). The water footprint of bioenergy. Proc Natl Acad Sci USA, 106(25): 10219–10223

Gleick P (1994). Water and Energy. Annu Rev Energy Environ, 19(1): 267–299

Hoekstra A Y, Chapagain A K, Aldaya M M, Mekonnen M M (2011) The water footprint assessment manual: Setting the global standard. Earthscan. London, UK

Holland R A, Scott K A, Florke M, Brown G, Ewers R M, Farmer E, Kapos V, Muggeridge A, Scharlemann J P W, Taylor G, Barrett J, Eigenbrod F (2015). Global impacts of energy demand on the freshwater resources of nations. Proc Natl Acad Sci USA, 112(48): E6707–E6716

International Energy Agency (IEA) (2012). World energy outlook. Paris, France

Leontief W (1941) The Structure of the American Economy, 1919–1939 (2nd Edition). New York: Oxford University Press

Liang Q M, Fan Y, Wei Y M (2007). Multi-regional input–output model for regional energy requirements and CO_2 emissions in China. Energ Policy, 35(3): 1685–1700

Liao X, Hall J W, Eyre N (2016). Water use in China's thermoelectric power sector. Glob Environ Change, 41: 142–152

Liu C, Kroeze C, Hoekstra A Y, Gerbens-Leenes W (2012). Past and future trends in grey water footprints of anthropogenic nitrogen and phosphorus inputs to major world rivers. Ecol Indic, 18: 42–49

Liu W, Antonelli M, Liu X, Yang H (2017). Towards improvement of grey water footprint assessment: with an illustration for global maize cultivation. J Clean Prod, 147: 1–9

Macknick J, Newmark R, Heath G, Hallett K C (2012). Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. Environ Res Lett, 7(4): 045802

Marsh D M (2008) The water-energy nexus: a comprehensive analysis in the context of New South Wales. Dissertation for the Doctoral Degree. Sydney: University of Technology

Mekonnen M M, Gerbens-Leenes P W, Hoekstra A Y (2015). The consumptive water footprint of electricity and heat: a global assessment. Environ Sci Water Res Technol, 1(3): 285–297

Mekonnen M M, Hoekstra A Y (2010a) The green, blue and grey water footprint of farm animals and animal products, Value of Water Research Report Series No.48, Volume I and II. UNESCO-IHE, Delft, the Netherlands

Mekonnen M M, Hoekstra A Y (2010b) The green, blue and grey water footprint of crops and derived crop products. Value of Water Research Report Series No.47, Volume I and II. UNESCO-IHE, Delft, the Netherlands

Mekonnen M M, Hoekstra A Y (2011a) National water footprint accounts: the green, blue and grey water footprint of production and consumption. Value of Water Research Report Series No.50, Volume I and II. UNESCO-IHE, Delft, the Netherlands

Mekonnen M M, Hoekstra A Y (2011b) The water footprint of electricity from hydropower. Value of Water Research Report Series No.51. UNESCO-IHE, Delft, the Netherlands

Mekonnen M M, Hoekstra A Y (2012) The blue water footprint of electricity from hydropower. Hydrol. Earth Sys. Sci. 16: 179–187

Mekonnen, M.M., Hoekstra, A.Y. (2015) Global gray water footprint and water pollution levels related to anthropogenic nitrogen loads to fresh water. Environ. Sci. Technol. 49: 12860–12868

Meldrum J, Nettles-Anderson S, Heath G, Macknick J (2013). Life cycle water use for electricity generation: a review and harmonization of literature estimates. Environ Res Lett, 8(1): 015031

Mielke E, Anadon L D, Narayanamurti V (2010) Water Consumption of Energy Resource Extraction, Processing, and Conversion. Belfer Center for Science and International Affairs, Harvard Kennedy School: Cambridge, MA, US

Mishra V K, Upadhyaya A R, Pandey S K, Tripathi B D (2008). Heavy metal pollution induced due to coal mining effluent on surrounding aquatic ecosystem and its management through naturally occurring aquatic macrophytes. Bioresour Technol, 99(5): 930–936

Nerini F F, Tomei J, To L S, Bisaga I, Parikh P, Black M, Borrion A, Spataru C, Broto V C, Anandarajah G, Milligan B, Mulugetta Y (2018). Mapping synergies and trade-offs between energy and the Sustainable Development Goals. Nat Energ, 3(1): 10–15

Pan L Y, Liu P, Ma L W, Li Z (2012). A supply chain based assessment of water issues in the coal industry in China. Energy Policy, 48: 93–102

Pellicer-Martínez F, Martínez-Paz J M (2016). Grey water footprint assessment at the river basin level: accounting method and case study in the Segura River Basin, Spain. Ecol Indic, 60: 1173–1183

Peters G P, Hertwich E G (2008). CO_2 embodied in international trade with implications for global climate policy. Environ Sci Technol, 42 (5): 1401–1407

Rio Carrillo A M, Frei C (2009). Water: a key resource in energy production. Energ Policy, 37(11): 4303–4312

Serrano A, Guan D, Duarte R, Paavola J (2016). Virtual water flows in the EU27: a consumption-based approach. J Ind Ecol, 20(3): 547–558

Spang E S, Moomaw W R, Gallagher K S, Kirshen P H, Marks D H (2014). The water consumption of energy production: an international comparison. Environ Res Lett, 9(10): 105002

United Nations (2015) Transforming our world: the 2030 Agenda for Sustainable Development, Geneva

Vassolo S, Doll P (2005). Global-scale gridded estimates of thermoelectric power and manufacturing water use. Water Resour Res, 41 (4): W04010

Wang L, Ding X, Wu X (2013). Blue and grey water footprint of textile industry in China. Water Sci Technol, 68(11): 2485–2491

Wiedmann T (2009). A review of recent multi-region input–output models used for consumption-based emission and resource accounting. Ecol Econ, 69(2): 211–222

Zeng Z, Liu J, Savenije H H (2013). A simple approach to assess water scarcity integrating water quantity and quality. Ecol Indic, 34: 441–449

Zhang C, Anadon L D (2013). Life cycle water use of energy production and its environmental impacts in China. Environ Sci Technol, 47(24): 14459–14467

Zhang Z, Yang H, Shi M (2011). Analyses of water footprint of Beijing in an interregional input–output framework. Ecol Econ, 70(12): 2494–2502

Zhao X, Liu J, Liu Q, Tillotson M R, Guan D, Hubacek K (2015). Physical and virtual water transfers for regional water stress alleviation in China. Proc Natl Acad Sci USA, 112(4): 1031–1035

Zhao X, Liu J, Yang H, Duarte R, Tillotson M R, Hubacek K (2016). Burden shifting of water quantity and quality stress from megacity Shanghai. Water Resour Res, 52(9): 6916–6927

Zhi Y, Yang Z, Yin X, Hamilton P B, Zhang L (2015). Using gray water footprint to verify economic sectors' consumption of assimilative capacity in a river basin: model and a case study in the Haihe River Basin, China. J Clean Prod, 92: 267–273