Virtual Water Flows in the EU27

A Consumption-based Approach

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Summary

The use of water resources has traditionally been studied by accounting for the volume of water removed from sources for specific uses. This approach focuses on surface and groundwater only and it ignores that international trade of products with substantial amounts of embodied water can have an impact on domestic water resources. Using current economic and environmental data, we conduct a consumption-based assessment of virtual water flows in the European Union (EU27). We find that the total water footprint (WF) of 2,280 cubic meters (m^3) per capita for the EU27 mostly consists of green water use (precipitation stored as soil moisture), which is omitted in the conventional water accounting. Blue water (surface and groundwater.) and gray water use (the volume of freshwater needed to dilute pollutants to meet the applicable water quality standards), which are targeted by current EU water policies, only make up 32% of the total WF. We also find that Europeans imported 585 cubic kilometers (km^3) (10^9 m^3) of virtual water, or around 28% of global virtual water trade flows, in 2009. Within Europe, Germany is a key net importer of water through the trade of products in agriculture, the food industry, the chemical sector, and electricity generation. Countries in Southern and Eastern Europe have specialized in water-intensive agriculture and are key exporters of virtual water despite experiencing physical scarcity of water. Our results suggest that there is a need to reconsider water policy in the EU to address water transfers occurring through trade and to grasp the interlinkages between green, blue, and gray water—which are likely to become more important in water-scarce parts of Europe, with a changing climate.

Introduction

Water is one of the world's most important natural resources. Water use has grown twice faster than population over the last century (FAO and UN 2007), and it is predicted to increase further by 50% in developing countries and by 18% in developed countries by 2025 (WWAP 2006).

Water use has also grown rapidly in the European Union (EU). The EU27 has 7.3% of the world population (World Bank 2014) and 4% of global water resources (FAO 2015). Yet the EU27 directly consumes 10% of global water resources. There are substantial disparities in water use and availability within Europe. Northern European countries such as Finland and Sweden have much more water per capita than the United Kingdom, Italy, Spain, France, Romania, or Germany, for example. According to the European Environment Agency (EEA) (EEA 2012a), water resources are already under pressure in many parts of Europe. The World Business Council for Sustainable Development (WBCSD) (WBCSD 2008) highlights that groundwater is being used at a faster rate than it can be replenished in 60% of the European cities with more than 100,000 inhabitants. The EU Water Framework Directive (Directive 2000/60/EC) (WFD hereafter) acknowledged these concerns when stating that "waters in the Community are

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under increasing pressures from the continuous growth in demand for sufficient quantities of good quality water for all purposes."

The Water Framework Directive seeks to ensure good status of water quality and quantity in the EU27 by 2015 by harmonizing water management in member states and by establishing joint management of transboundary water bodies. But water crosses borders not only physically, but also virtually, embodied in internationally traded products. Monitoring national water extraction is not enough to understand the global drivers of water use and consumption in a country, given that the water resources are impacted along the whole production chain. The growing trade in goods and services at the global and regional levels lead to environmental impacts at different scales and locations of global supply chains, calling for the development and use of tools that can inform actors about these impacts. Hoekstra and Mekonnen (2012) demonstrate how river basins are insufficient as a reference tool for managing water resources. In contrast, virtual water flow approaches make visible how water is "reallocated" along supply chains.

Value chains generate economic growth and income to societies, but in the interconnected global economy, they also entail adverse impacts on natural resources and the environment. The inter-relations and transmission channels of impacts between economic activities and natural resources can be examined by using input-output (I-O) models to calculate indicators such as the water footprint (WF) and virtual water. (Allan 1997, 1999) defined virtual water as the volume of water required for the production of a commodity traded for consumption in other regions. Since then, the notion of virtual water has been widely used in the literature (Merrett 2003; Zimmer and Renault 2003; Hoekstra and Hung 2005; Yang et al. 2007).

In a context of growing global interdependence on water resources, we focus on the WF, a consumption-based indicator of freshwater use that looks at both direct and indirect water use (Hoekstra et al. 2011). The WF of a nation or region is the total amount of freshwater that is used to produce the goods and services consumed by its inhabitants: it is the sum of domestic water use and net virtual water import (Hoekstra et al. 2011). Virtual water and WF can be split into green, blue, and gray components. Green water refers to precipitation stored as the soil moisture. Blue water encompasses surface and groundwater. Finally, gray water refers to the volume of freshwater needed to dilute pollutants to meet the applicable water quality standards (Hoekstra et al. 2011). Green water has no competing economic uses (Yang et al. 2007), but blue water can be used for competing agricultural, industrial, and urban uses.[1] Gray water has limited competing uses given that it does not refer to consumptive water use, but rather to deterioration of water quality.

Research on WFs has made important contributions to water assessment in agriculture and industry and has fostered communication among water researchers in different fields. But, as Tillotson and colleagues (2014) explain, there is a further need to enhance assessment accuracy, improve sustainability assessment methodology, develop databases, address uncertainties, and prioritize application by government and, in practical sectors, in WF research.

There is already a substantial literature examining virtual water flows and WFs. Some of the studies in the literature use a top-down approach (Lenzen and Peters 2010; Feng et al. 2012; Steen-Olsen et al. 2012) of the environmental I-O analysis (IOA) that calculates WFs by accounting for virtual water flows in the regional, national, and global supply chains. Other studies follow a bottom-up approach (Hoekstra and Mekonnen 2012; Vanham and Bidoglio 2013) that calculates footprints on the basis of detailed process data on the virtual water content of internationally traded goods and services. Feng and colleagues (2011, 373) suggest that the bottom-up approach "has become one of the most popular approaches in water foot-printing studies due to its simplicity and relatively good data availability . . . [although] it concentrates mainly on agricultural and food products and does not distinguish between intermediate and final users." Some studies (Shao and Chen 2013) have also used a combination of top-down and bottom-up approaches, called the hybrid method, to determine water footprints.

There is a growing use of IOA to quantify direct and indirect water demand by assessing regional or/and inter-regional supply chains (Hubacek et al. 2009; Wiedmann 2009; Zhao et al. 2003; Feng et al. 2012; Cazcarro et al. 2012; Lenzen et al. 2013; Guan et al. 2014a; Jiang et al. 2015; Meng et al. 2013). Some of the research has examined virtual water flows in the EU, either focusing on specific member states (Aldaya et al. 2008; Van Oel et al. 2009; Sonnenberg et al. 2009; Ercin et al. 2013) or the region as a whole (Steen-Olsen et al. 2012; Vanham and Bidoglio 2013). Notably, Steen-Olsen and colleagues (2012) estimate the European blue water footprint for 2004 using a multiregional input-output (MRIO) model using the GTAP 7 database.

In a similar vein, we quantify the total water footprint and virtual water transfers in 2009 within the European Union using an environmentally extended MRIO and the World Input-Output Database (WIOD) database. Our article complements the results of Steen-Olsen and colleagues (2012) by estimating the total WF as the sum of green, blue, and gray water footprints and by providing new estimates for green and gray water footprints.[2] Our estimates capture the total water use for economic activities and highlight that the current EU water policy only addresses a small part of it—blue and gray water. This is particularly problematic in the face of climate change, which creates pressures to substitute decreasing green water resources with blue water. Our article also contributes to WF studies for Europe by providing a new, more nuanced understanding of how different countries and sectors impact on the quantity and quality of water resources in Europe.

Our results are relevant for European water policy and decision making because the MRIO methodology helps in linking the impacts on water resources to final consumption (associated with imports and domestic consumption) and production (associated with exports and domestic consumption) and distinguishing between producer and consumer responsibilities in the context of growing globalization and economic integration. The quantitative estimates of the impact of actors (at the sector and country level) involved in global value chains on the depletion and pollution of water can inform integrated water management.

Our article uses an environmentally extended MRIO (EE-MRIO) analysis to estimate WFs and virtual water flows in the EU27, demonstrating that large volumes of virtual water are exchanged in Europe in the context of varying scarcity and availability, and that the scale of these flows is significant. With only 7% of the world population (World Bank 2014), the EU27 was responsible for over 28% of the imports of virtual water flows in 2009 in the world. This, together with the uneven distribution of water resources, makes the EU27 an interesting case of study. Our methodology helps in estimating the amount of water consumed in the different stages of production processes, and we examine the water impact of economic activities in the EU showing that the production process of final goods has important impacts on the natural resources in many countries.

Methods and Data

We use an EE-MRIO model to examine environmental resource flows along the supply chains. It is a top-down approach often used by international institutions, such as the Organization for Economic Cooperation and Development (OECD), United Nations, and Eurostat, for the development of environmental accounts and models that link economic activities and impacts on natural resources (Eder et al. 2006).

Our MRIO analysis of WFs and virtual water flows uses data from the WIOD for 2009 as its main source. A large number of articles has used the MRIO methodology to assess emissions linked to international trade (Peters and Hertwich 2008; Wiedmann 2009; Davis and Caldeira 2010) and the trade-linked flows of natural resources, such as water and land (Yu et al. 2010; Steen-Olsen et al. 2012). The WIOD provides information for 35 economic sectors in 40 countries and a region called Rest of the World (ROW) as well as for five categories of final consumption by households, not-for-profit organizations serving households, government, capital investment, and changes in inventories (see WIOD [2012] and Timmer et al. [2012] for more information on the WIOD). Though there are several MRIO databases available at the moment, the WIOD is particularly attractive for the study of virtual water flows in Europe for three reasons. First, it provides country-specific information for 27 EU member states. Second, though it has its limitations, the WIOD is the only database providing green, blue, and gray water use for a significant number of sectors. Third, the homogeneity of the economic and environmental information provided for more than 15 years allows replicating the analysis for different countries and periods of time.

Data on direct green, blue, and gray water use in sectors and countries was obtained from the WIOD environmental accounts (Genty 2012) and is based on the WF studies carried out by Mekonnen and Hoekstra (2011,2012). Population information was taken from the 2009 World Development Indicators of the World Bank for calculating per capita figures (World Bank 2014).

Uncertainties involved in using EE-MRIO models are a subject of growing interest (Wiedmann et al. 2011; Peters et al. 2011). The uncertainties can originate from sources of data and from the adjustments made to obtain the WIOD. As Genty (2012) indicates, there are no international data sets on water use, so it is estimated using the data that are available. The calculations involve uncertainties affecting the data we used in this study. For example, data on agricultural water use were rescaled using the WF data from Mekonnen and Hoekstra (2011, 2012), and water use was distributed to industrial sectors using the information from the EXIOPOL database (see Genty [2012] on the calculation of water use). Although it is difficult to estimate uncertainty in our model comprehensively, our findings compare with those of the other studies on WF and virtual water flows in Europe (Hoekstra and Mekonnen 2012; Steen-Olsen et al. 2012; Chen and Chen 2013).

This article employs an I-O approach (Leontief 1941), which defines the total output of each sector expressed by the vector $\mathbf{x}$ as follows (equation 1):

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{y} \tag{1}$$

where A is a technical coefficient matrix and $\mathbf{y}$ is a vector of total final demand by sector.[3] Total output can also be expressed in terms of the well-known Leontief inverse as follows (equation 2):

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\,\mathbf{y} = \mathbf{L}\mathbf{y} \tag{2}$$

Proops (1988) extended equation (2) by quantifying the effect of economic activity to natural resources. Defining $\hat{\mathbf{w}}$ as a diagonal matrix of direct water intensity per sector (water use per production) and expressing the vector $\mathbf{y}$ as a diagonal matrix $\hat{\mathbf{y}}$, we get the matrix $\mathbf{W}$, where the sum by columns displays the volume of water directly and indirectly used by each sector (equation 3):

$$\mathbf{W} = \hat{\mathbf{w}}\,\mathbf{L}\hat{\mathbf{y}} \tag{3}$$

Following Miller and Blair (2009), MRIO can be analytically expressed as follows (equation 4):

$$\begin{pmatrix} \mathbf{W}_{11} & \mathbf{W}_{12} & . & . & \mathbf{W}_{1r} \\ \mathbf{W}_{21} & \mathbf{W}_{22} & . & . & \mathbf{W}_{2r} \\ . & . & . & . & . \\ \mathbf{W}_{s1} & . & \mathbf{W}_{ss} & . & \mathbf{W}_{sr} \\ . & . & . & . & . \\ \mathbf{W}_{r1} & \mathbf{W}_{r2} & . & . & \mathbf{W}_{rr} \end{pmatrix} = \begin{pmatrix} \hat{\mathbf{w}}_{11} & 0 & . & . & 0 \\ 0 & \hat{\mathbf{w}}_{22} & . & . & 0 \\ . & . & . & . & . \\ . & . & . & \hat{\mathbf{w}}_{ss} & . \\ . & . & . & . & . \\ 0 & 0 & . & . & \hat{\mathbf{w}}_{rr} \end{pmatrix} \begin{pmatrix} \mathbf{L}_{11} & \mathbf{L}_{12} & . & . & \mathbf{L}_{1r} \\ \mathbf{L}_{21} & \mathbf{L}_{22} & . & . & \mathbf{L}_{2r} \\ . & . & . & . & . \\ \mathbf{L}_{s1} & . & \mathbf{L}_{ss} & . & \mathbf{L}_{sr} \\ . & . & . & . & . \\ \mathbf{L}_{r1} & \mathbf{L}_{mr2} & . & . & \mathbf{L}_{rr} \end{pmatrix} \begin{pmatrix} \hat{\mathbf{y}}_{11} & \hat{\mathbf{y}}_{12} & . & . & \hat{\mathbf{y}}_{1r} \\ \hat{\mathbf{y}}_{21} & \hat{\mathbf{y}}_{22} & . & . & \hat{\mathbf{y}}_{2r} \\ . & . & . & . & . \\ \hat{\mathbf{y}}_{s1} & . & \hat{\mathbf{y}}_{ss} & . & \hat{\mathbf{y}}_{sr} \\ . & . & . & . & . \\ \hat{\mathbf{y}}_{r1} & \hat{\mathbf{y}}_{r2} & . & . & \hat{\mathbf{y}}_{rr} \end{pmatrix} \tag{4}$$

Table 1 World regional water consumption distribution

		EU27	Asia and Pacific	North America	ROW	India	China	Latin America	Total
Domestic consumption (DC)	Absolute (10^9 m^3)	557	1,240	1,199	3,253	1,238	1,259	682	9,428
	Per capita (m^3)	1,112	1,903	3,522	1,319	1,020	946	2,175	1,383
Virtual water exports (VWX)	Absolute (10^9 m^3)	132	157	260	817	106	429	197	2,099
	Per capita (m^3)	264	241	764	331	87	322	628	308
Virtual water import (VWM)	Absolute (10^9 m^3)	585	412	364	378	52	230	78	2,099
	Per capita (m^3)	1,168	632	1,069	153	43	173	249	308
Water footprint (WF) (consumption based approach)	Absolute (10^9 m^3)	1,142	1,652	1,563	3,631	1,290	1,489	760	11,527
	Per capita (m^3)	2,280	2,536	4,592	1,472	1,062	1,118	2,424	1,691
Direct water use (DW) (production based approach)	Absolute (10^9 m^3)	689	1,397	1,458	4,071	1,344	1,688	879	11,527
	Per capita (m^3)	1,375	2,144	4,284	1,650	1,107	1,268	2,805	1,691

Note: Domestic production refers to the consumption of domestic water resources to meet the internal final demand of a region, virtual water exports indicate the consumption of domestic water resources in one region to meet the final foreign demand of another region; virtual water imports show the consumption of foreign water resources from one region to meet the domestic final demand of another region, the water footprint measures the impact that the final demand of a region has on global water resources (DC+VWM), and direct water use accounts for the consumption of domestic water resources to meet internal and foreign demands (DC+VWX).m^3 = cubic meters; EU = European Union; ROW = Rest of the World.

where $\mathbf{W_{rs}}$ are matrixes with each element $\mathbf{W_{rs}^{ij}}$ showing the volume of water used (directly and indirectly) by sector i in region r to meet final demand of sector j in region s. $\hat{w}_{rr}$ are direct water intensities in each country r, $\mathbf{L_{rs}}$represents the Leontief inverses, and $\hat{\mathbf{y}}_{\mathbf{rs}}$ are diagonal matrixes of final demand of region s on r. Accordingly, it is possible to obtain WF for a particular region s $\mathbf{wf_s}$, that is, water consumption measured from the consumption responsibility approach:

$$wf_s = \sum_{\mathbf{r}} \mathbf{e}'\mathbf{W_{rs}}\mathbf{e} = \mathbf{e}'\mathbf{W_{ss}}\mathbf{e} + \sum_{\mathbf{r}\neq\mathbf{s}} \mathbf{e}'\mathbf{W_{rs}}\mathbf{e} = w_s^{dom} + vwm_s$$

where $\mathbf{e}$ is a vector of ones, w_s^{dom} is the volume of water that is used to produce goods consumed domestically, and vwm_s is the water embodied in products produced outside the borders of region s. Similarly, the direct water consumption using the production responsibility approach (dw_s) for a region s is:

$$dw_s = \sum_{\mathbf{r}} \mathbf{e}'\mathbf{W_{sr}}\,\mathbf{e} = \mathbf{e}'\,\mathbf{W_{ss}}\mathbf{e} + \sum_{\mathbf{r}\neq\mathbf{s}} \mathbf{e}'\mathbf{W_{sr}}\mathbf{e} = w_s^{dom} + vwx_s$$

where vwx_s is the volume of water resources withdrawn and exported from country s to other country.

This methodology helps in linking economic activities in sectors with impacts on water resources. It also helps to differentiate between the production and consumption based accounting for water use.

Results

Global water use was approximately 9,428 cubic kilometers (km^3) or approximately 1,383 cubic meters (m^3) per capita in 2009. Domestic consumptive water use of 557 km^3 in the EU27 accounted only for around 5% of the global total water use, but amounted to 1,112 m^3 per capita. Domestic water use in other world regions of North America, Asia-Pacific, India, China, and the ROW was clearly higher than that in the EU27 (see table 1). However, although domestic consumptive water use makes an important contribution to WFs of all regions, global virtual water flows are also important. In overall terms, around 20% of water is traded virtually and regions such as the EU27 and China import and export a substantial proportion of their water (Guan et al. 2014b).

Figure 1 depicts virtual water flows between world regions. The EU27 imports 585 km^3 (billion m^3) of virtual water (28% of total virtual water imports) from other regions in the world; it is the largest importer of virtual water; importing 67.9%, 16.2%, and 16% of green, blue, and gray water, respectively. Notably, the virtual water imports of the EU27 in 2009 exceeded the domestic water consumption in the region. The regions exporting the most virtual water are ROW (39%) and China (20%). They export virtual water primarily to the developed regions, such as the EU, Asia and Pacific, and North America. North America, Asia and Pacific, and the EU15 are net importers or all colors of water. Most blue water footprint is generated by domestic consumptive water use. China contributes 44% of gross gray virtual water export, meaning that the pollution of Chinese water resources is, to a large part, caused by the supply of goods to North America, Asia and Pacific, and the EU. Note that the detailed figures for each of the water components appear in the Supporting Information available on the Journal's website.

The consumption-based approach to accounting for EU27 water use leads to a clearly higher estimate of total water use than the production-based approach because of the significant

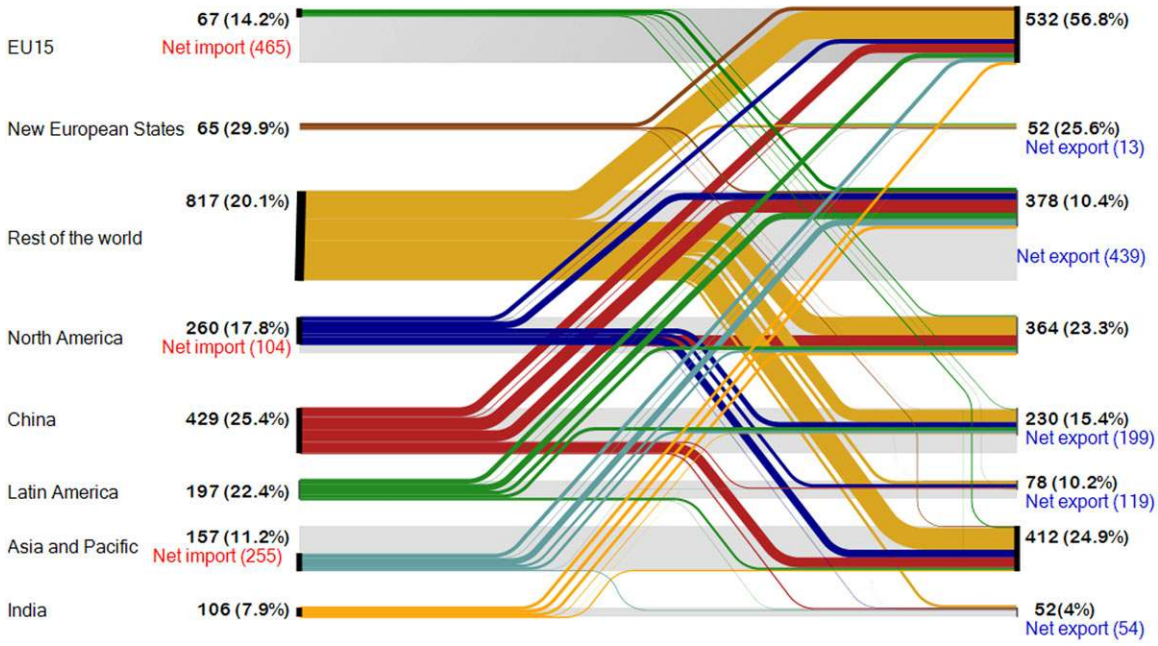

Figure 1 Global virtual water flows. Flows (10^9 m3) go from left to right and widths of arrows indicate the volume of water exchanged. Figures indicate total exported virtual water and total imported virtual water, the difference between them being either net export or net import. Percentages on the left show total exported virtual water as percentage of water embodied in total production, whereas percentages on the right display total virtual water imported as percentage of water embodied in total consumption. Study carried out using WIOD database for 2009. m^3 = cubic meters; WIOD = World Input-Output Database.

net import of virtual water into the EU27. The consumption-based approach (WF) leads to an estimate of 2,280 m^3 of total water use per capita in the EU27 in 2009. But there is also substantial importing and exporting of virtual water within Europe, and not just between Europe and other world regions. Some member states of the EU27 are substantial importers of virtual water, whereas other member states export large amounts of virtual water despite facing absolute water scarcity. Countries like Denmark, Czech Republic, Bulgaria, Poland, Belgium, or Spain export more than 20% their available domestic water resources. Small countries like Cyprus, Malta, or Luxembourg import large volumes of water compared to their domestic water resources. Germany emerges as the largest importer of virtual water in the EU27.

The largest per capita WFs in the EU27 are in Sweden (3,484 m^3), Luxembourg (3,214 m^3), Austria (3,084 m^3), and Belgium (3,028 m^3) (figure 2, table S1 in the supporting information on the Web). These countries have specialized in water-intensive economic activities: They are significant exporters of water through electricity generation, pulp and paper production, and agricultural production. When the amount of water per unit of gross domestic product (GDP) is considered, Ireland and Luxembourg are the most productive water users (80 m^3 per thousand dollars USD and 103 m^3 per thousand dollars USD, respectively), and Bulgaria and Romania stand out as the least productive ones (773 m^3 per thousand dollars USD and 762 m^3 per thousand dollars USD, respectively).

Within the EU27, Germany and the Great Britain are the greatest net importers of virtual water and Poland and Spain are its main exporters (figure 3). Spain exports virtual water primarily to Germany, Great Britain, and France. Poland exports virtual water primarily to Germany. This can also be derived from tables S3 to S8 in the supporting information on the Web that contain information on the water use measured using the production- and consumption-based approaches. Most European countries portray larger total water consumption figures when using the consumption-based approach: This means that the large virtual water exporters are also significant importers of water from other countries in Europe and in other world regions.

Footprints for different kinds of water give additional insights into water use in the EU27. The consumption-based approach leads to an estimate of 1,540 m^3 of green water use per capita in the EU27 in 2009. Green water use represents around 68% of the aggregate WF in the EU27. It is particularly important for food production, and its use has a lower environmental impact than that of blue and gray water. Seven member states (France, Italy, Germany, Spain, Romania, Poland, and Great Britain) are responsible for 72% of the green water footprint in the EU27 (figure S4 in the supporting information on the Web). This footprint is closely linked to agriculture, the food industry, and the hotels and restaurants sector. Although a significant proportion of green water is abstracted and used domestically, there are considerable flows of green water among European countries and between them and other regions in the world.

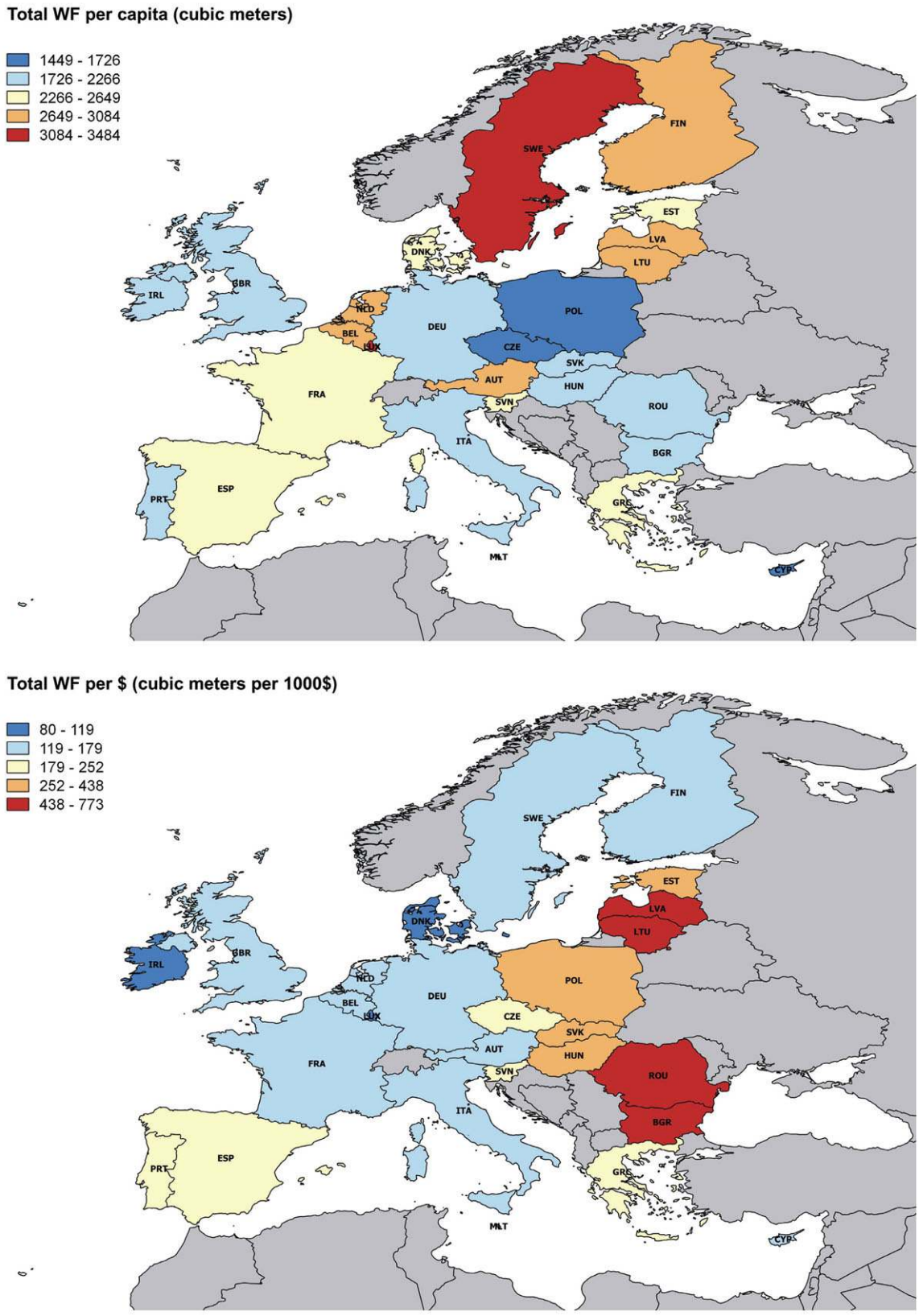

Figure 2 Per GDP and per capita total water footprint in the EU27. Upper map shows total per capita water footprint in m3/person. Lower map depicts total water footprint per unit of GDP in m3/thousand dollars. GDP = gross domestic product; EU = European Union; m^3 = cubic meters.

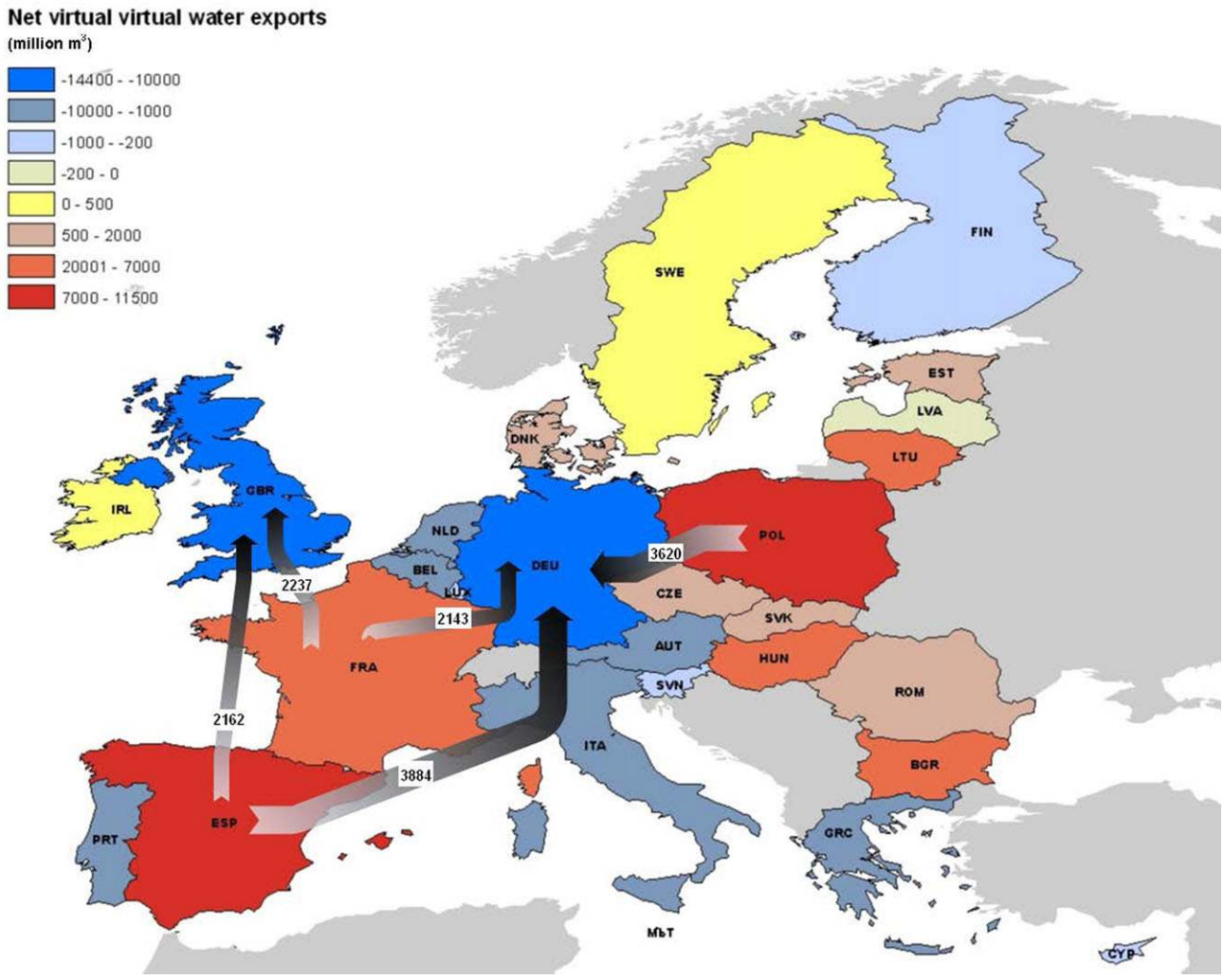

Figure 3 Net virtual water exports within the EU27 with the five most important flows. The map shows largest inter-regional fluxes (net) of water embodied in trade (million m3) among net exporting regions (red) and net importing regions (blue). Widths of arrows indicate the volume of water exchanged. Note that the net exporter (importer) position of countries is defined considering only virtual water flows within EU27. EU = European Union; m^3 = cubic meters.

Table S2 in the supporting information on the Web indicates the importance of considering virtual flows of green water. European exports of green water go chiefly to the United States, China, and Russia. Green virtual water is mainly imported from China, India, and Brazil (figure S1 in the supporting information on the Web). Spain and France account for around 30% of the total green water exports within Europe (figure S7 in the supporting information on the Web). Although being a net exporter of green water within Europe, Spain also imports green water embodied in agricultural and food products that are used as inputs in agriculture and food industry. Poland, Hungary, and Bulgaria are top green water exporters through agriculture and also have high per capita domestic green water use (table S2 in the supporting information on the Web).

Germany plays an important role in the European virtual water flows. It is the third largest exporter of green water and also its largest importer, accounting for 20% of green water imports within Europe. In fact, German consumption has a larger impact on green water resources abroad than in the country. Figure 4 shows that German consumption is associated with green water needed for producing agricultural products imported from Spain and Poland and used as inputs in the German food industry, agriculture, textile, and hotels and restaurants sectors. Great Britain and Italy are also net importers of green water in Europe. Again, agriculture, the food industry, the textile sector, and hotels and restaurants are the main final consumers of green water. (Detailed information on the sectorial water consumptive use can be found in tables S4 to S9 in the supporting information on the Web.)

We estimate that the per capita blue water footprint for the EU27 was around 397.9 m^3 per person in 2009, resonating with the estimates reported by Steen-Olsen and colleagues (2012) for 2004. Blue water represents only around 16% of the aggregate WF in the EU27. However, it is of great importance

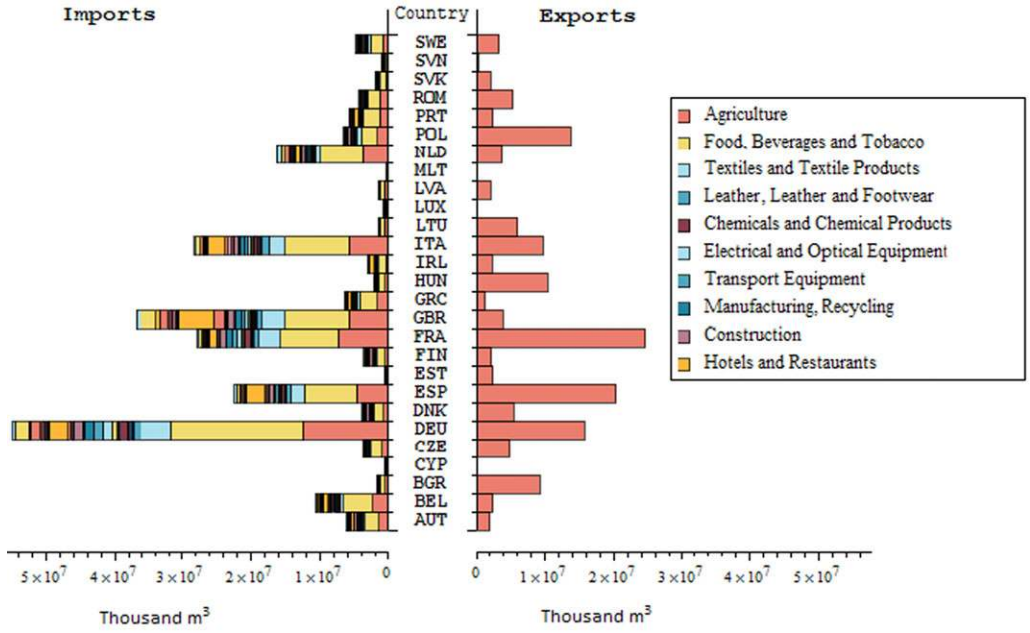

Figure 4 Country virtual green water total exports and imports by sector. Green water embodied in total trade flows (thousand m3) for the 27 European Union states. Colors distinguish the volume of water exchanged by industry sectors. The right axis represents virtual water exports whereas the left axis represents virtual water imports. *Note*: Green water exports only available for agriculture. m^3 = cubic meters.

because some semiarid and arid parts of Europe have specialized in water-intensive activities and because blue water has high opportunity costs attributed to the possibility of reallocating it to alternative uses. The management, reallocation, and use of blue water also involves long-lived and costly infrastructure, such as dams, channels, and irrigation systems, which can have substantial environmental impacts.

Germany, France, Italy, and Spain have the highest blue water footprint, together accounting for 60% of the EU27 blue water footprint. The most important blue water–consuming sectors in these countries were agriculture, food industry, and the electricity and water supply sector. Sweden stands out for its extremely large per capita water use of more than 1,613 m^3 per person attributed to their water-intensive industries (table S1 in the supporting information on the Web). Austria also has a high blue water footprint closely linked to the electricity, gas, and water sector (1,075 m^3 per person). In Austria, 787 m^3 of domestic water resources are abstracted for domestic use, 415 m^3 of domestic resources are exported, and 294 m^3 of blue water is imported from abroad per capita (table S2 in the supporting information on the Web). Greece and Portugal have also high blue water footprints of around 500 m^3 per capita (figure S5 and table S1 in the supporting information on the Web), chiefly because of domestic water use in agriculture. The economies of Cyprus and Romania are particularly blue water intensive, needing more than 60 m^3 of blue water per thousand USD of GDP (table S2 and figure S5 in the supporting information on the Web).

Blue water and its virtual flows have important environmental and economic implications for exporting countries. Globally, ROW, the United States, and China are key exporters of blue water whereas the EU27, and particularly its most developed member states, import blue water from ROW, China, India, Canada, and Russia (figure S2 in the supporting information on the Web). Within EU27, Spain, France, and Austria are the largest exporters of blue water, accounting for around 50% of all EU27 virtual blue water exports (figure S8 in the supporting information on the Web). Agriculture and food and beverage Industries are the most important sectors exporting blue water from the three countries. In Spain, agriculture accounts for around 80% of blue water export. Spain is more agriculturally oriented (it accounts for 2.7% of GDP and 16% of exports) than the other EU27 member states, but the Spanish agriculture is also more blue water intensive than agriculture in other European countries. Spain mainly exports blue water embodied in crops and livestock products to France, Portugal, Italy, Great Britain, and Germany. Austrian blue water exports originate from the power and water utilities sector and end up in Germany.

Germany is again the largest importer of blue water within the EU27 (24 billion m^3, 22% of total imports). The key importing sectors are agriculture, food and beverages industry, textile industry, electrical industry, and the utilities sector (figure 5). The German food industry imports blue water from Spain whereas the electricity sector imports blue water from Austria. The food and textile industries in France, Italy, and Great Britain also import large volumes of blue water. In Great Britain, hotels and restaurants are also large blue water importers in addition to the earlier mentioned sectors. Spain, Austria, and Sweden are the largest net blue virtual water exporters considering virtual water flows among EU27 members. Germany and Great Britain were the largest net importers of virtual water:

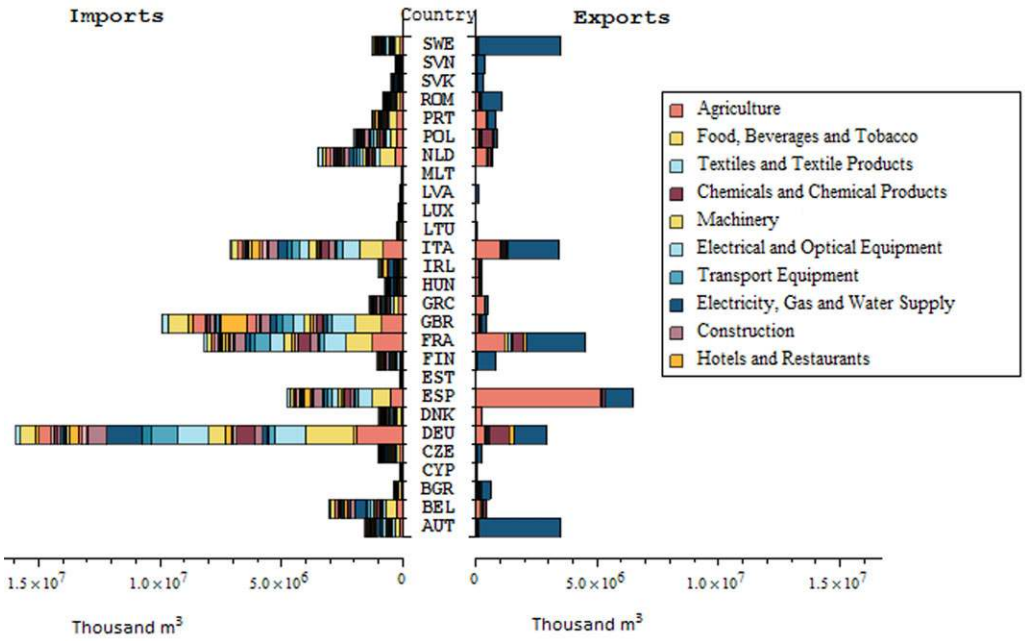

Figure 5 Country virtual blue water total exports and imports by sector. Blue water embodied in total trade flows (thousand m3) for the 27 European Union states. Colors distinguish the volume of water exchanged by industry sectors. The right axis represents virtual water exports whereas the left axis represents virtual water imports. m^3 = cubic meters.

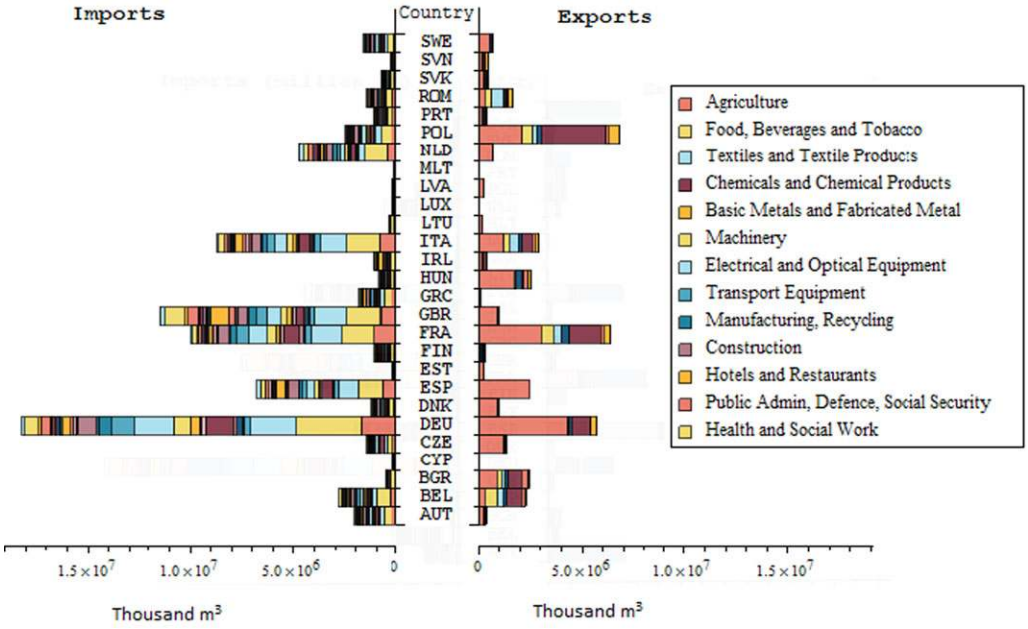

Figure 6 Country virtual gray water total exports and imports by sector. Gray water embodied in total trade flows (thousand m^3) for the 27 European Union states. Colors distinguish the volume of water exchanged by industry sectors. The right axis represents virtual water exports whereas the left axis represents virtual water imports. m^3 = cubic meters.

They use more imported than domestic blue water resources. Although France exports vast amounts of virtual blue water, its equally large imports for household consumption make the country a net importer.

We will now turn to virtual flows of gray water, which is needed to dilute pollutants to maintain acceptable in-stream water quality. The gray water footprint of the EU27 amounted to 171 billion m^3 or 340 m^3 per capita in 2009 and it accounted for 16% of the total WF in the EU27 in 2009. Germany, France, Italy, and Great Britain alone are responsible for 54% of EU27 gray water footprint (figure S6 in the supporting information on the Web). Central and Eastern Europe export gray water, which has important environmental and economic implications in the area. Looking outside Europe (figure S3 in the supporting

information on the Web), the EU27 exports gray water to the United States, China, Russia, and Japan, but it also imports gray water from China, India, and the United States. Poland exported 6.8 billion m^3 of gray water to the EU27 in 2009, which amounted to 17% of total EU27 gray water export (figure S9 in the supporting information on the Web). A key destination of Polish gray water is Germany, and it is tied to exports from agriculture and chemical industries. In per capita terms, Bulgaria and Hungary are the largest exporters of gray water, which is mostly embodied in agricultural products. Germany is the main importer of gray water (24.2 billion m^3 in 2009), accounting for 22% of all gray water export within the EU27. Agriculture and the food, textile, and electrical sectors were the key importers of gray water to Germany. But Germany also exports gray water embodied in agricultural and chemical products, particularly to France and Italy. France exports gray water embodied in agricultural and chemical products, particularly to Germany, Spain, and Great Britain (figure 6).

Conclusions

Our results shed additional light on the challenge of managing European water resources by construing the patterns of virtual water flows in Europe in 2009. Our results suggest that the total per capita WF in the EU27 was 2,280 m^3 per capita in 2009. The majority of this (68% or 1,540 m^3 per capita) is green water, which is not currently addressed by any water resources policies in the EU27. The key policy target of the Water Framework Directive (WFD) is the blue water, which only constitutes 16% or 398 m^3 of the total WF in the EU. The gray water footprint of 340 m^3 per capita, which makes 16% of the total WF, is also covered by the directive in some respects.

Our results also indicate that Europe imports more virtual water (51% of the total) from other world regions than it consumes its own water resources (49% of the total). Around 19% of the regional water directly used is exported to the other world regions, and up to 14% moves within the EU27 from one country to another as virtual water. Germany is the key net importer of green, blue, and gray water from Europe and from outside of it. German consumption puts more pressure on foreign water resources than on its domestic water resources. Green water embodied in agricultural products is exported mainly from Spain, France, and Eastern countries. Spain is the largest exporter of blue water embodied in agricultural products. Poland, in turn, is the largest supplier of gray water embodied in exports of agricultural and chemical sector products to Germany and elsewhere in Europe.

It is clear that water policy can be misguided without due attention to all types of water and virtual water flows. The WFD (2000/60/EC) is the key European policy for the management and protection of European water resources, which commits member states to attain good status of hydrological ecosystems by 2015. Although some progress has been made with regard to the quality of groundwater, around 50% of European surface waters will still have poor water quality in 2015 and a substantial proportion of water sources will suffer from water stress (EEA 2012b). Our results highlight that the WFD only targets a small proportion of the real water use in Europe, because it omits virtual water flows and the green water footprint. In a changing climate of the future, the latter omission is a particularly worrying shortcoming, given that in areas of decreasing rainfall and increased evaporation, such as in Southern and Eastern Europe, diminishing stocks of green water will need to be compensated from diminishing stocks of blue water. Doing so could intensify conflicts over water use and will demand that improved policy responses do deal with water resources use in Europe.

One possibility could be to include the price of green water into the pricing of the blue water in the EU because the two are physically interlinked. Doing so could lead to significantly increased water prices. This might not be a bad choice to make. First, these new higher water prices would better reflect the real scarcity of water and create incentives for more effective and reduced water use. Also, earlier research has shown that consumers are willing to pay more for goods produced in a sustainable way, which would make cost recovery possible (Arnot et al. 2006; Aizaki and Sato 2007; Didier and Lucie 2008). Product labeling and other measures, such as the initiatives developed by the Water Stewardship Program of the European Water Partnership, setting international standards such as the International Organization for Standardization (ISO) 14046 Water Footprint or encouraging WF reporting could help in adjusting to the new realities.

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Notes

1. Green water is said to have no economic competing uses given that it cannot be stored, but it remains in the soil or in the plants. However, the increase of natural vegetation could involve the growth of green water consumption. Also, this phenomenon could have effects regarding land use (Fader et al. 2011).
2. The work developed by Vanham and Bidoglio (2013) also estimates the WFs (green and blue water) for the EU28 for the average period 1996–2005 using the volumetric approach. Considering only green and blue water, our study estimates a larger WF.
3. Note that vectors are expressed in bold and small letters, matrixes in bold and capital letters, and scalars in italics and small letters.

References

Aizaki, H. and N. Sato. 2007. Consumers' valuation of good agricultural practice by using contingent valuation and contingent ranking methods: A case study of Miyagi Prefecture, *Japan*. *Agricultural Information Research* 16(3): 150–157.

Aldaya, M. M., A. Garrido, M. R. Llamas, C. Varela, P. Novo, and R. Rodriguez. 2008. The water footprint of Spain. *Sustainable Water Management* 3: 15–20.

Allan, T. 1997. 'Virtual water': A long term solution for water short Middle Eastern economies. Paper presented at 1997 British Association Festival of Science, Water and Development Session, Roger Stevens Lecture Theatre, 9 September, University of Leeds, Leeds, UK.

Allan, T. 1999. Productive efficiency and allocative efficiency: Why better water management may not solve the problem. *Agricultural Water Management* 40(1): 71–75.

Arnot, C., P. C. Boxall, and S. B. Cash. 2006. Do ethical consumers care about price? A revealed preference analysis of fair trade coffee purchases. *Canadian Journal of Agricultural Economics* 54(4): 555–565.

Cazcarro, I., R. Duarte, and J. Sánchez-Chóliz. 2012. Water flows in the Spanish economy: Agri-food sectors, trade and households diets in an input-output framework. *Environmental Science & Technology* 46(12): 6530–6538.

Chen, Z.-M. and G. Q. Chen. 2013. Virtual water accounting for the globalized world economy: National water footprint and international virtual water trade. *Ecological Indicators* 28: 142–149.

Davis, S. J. and K. Caldeira. 2010. Consumption-based accounting of CO_2 emissions. *Proceedings of the National Academy of Sciences of the United States of America* 107(12): 5687–5692.

Didier, T. and S. Lucie. 2008. Measuring consumer's willingness to pay for organic and Fair Trade products. *International Journal of Consumer Studies* 32(5): 479–490.

Eder, P., L. Delgado, F. Neuwahl, A. Tukker, G. Huppes, L. van Oers, and R. Heijungs. 2006. *Environmentally extended input-output tables and models for Europe*. Seville, Spain: European Commission, Joint Research Center, Institute for Prospective Technological Studies.

EEA (European Environment Agency). 2012a. *Towards efficient use of water resources in Europe*. Copenhagen: EEA.

EEA (European Environment Agency). 2012b. *European waters—Current status and future challenges—A synthesis*. EEA Report 9/2012. Copenhagen: EEA.

Ercin, A. E., M. M. Mekonnen, and A. Y. Hoekstra. 2013. Sustainability of national consumption from a water resources perspective: The case study for France. *Ecological Economics* 88: 133–147.

Fader, M., D. Gerten, M. Thammer, J. Heinke, H. Lotze-Campen, W. Lucht, and W. Cramer. 2011. Internal and external green-blue agricultural water footprints of nations, and related water and land savings through trade. *Hydrology and Earth System Sciences* 15(5): 1641–1660.

FAO (Food and Agriculture Organization of the United Nations). 2015. *AQUASTAT database*. Rome: Food and Agriculture Organization of the United Nations (FAO).

FAO (Food and Agriculture Organization of the United Nations) and UN (United Nations). 2007. *Coping with water scarcity. An action framework for agriculture and food security*. Rome; New York: FAO and UN.

Feng, K., Y. L. Siu, D. Guan, and K. Hubacek. 2012. Assessing regional virtual water flows and water footprints in the Yellow River Basin, China: A consumption based approach. *Applied Geography* 32(2): 691–701.

Feng, K., A. Chapagain, S. Suh, S. Pfister, and K. Hubacek. 2011. Comparison of bottom-up and top-down approaches to calculating the water footprints of nations. *Economic Systems Research* 23(4): 371–385.

Genty, A. (Ed.). 2012. Final database of environmental satellite accounts: technical report on their compilation. WIOD Deliverable 4.6, Documentation. www.wiod.org/publications/source_docs/Environmental_Sources.pdf. Accessed 17 April 2016.

Guan, D., X. Su, Q. Zhang, G. P. Peters, Z. Liu, Y. Lei, and K. He. 2014a. The socioeconomic drivers of China's primary PM2.5 emissions. *Environmental Research Letters* 9(2): 024010.

Guan, D., K. Hubacek, M. Tillotson, H. Zhao, W. Liu, Z. Liu, and S. Liang. 2014b. Lifting China's water spell. *Environmental Science & Technology* 48(19): 11048–11056.

Hoekstra, A. Y. and P. Q. Hung. 2005. Globalisation of water resources: International virtual water flows in relation to crop trade. *Global Environmental Change* 15(1): 45–56.

Hoekstra, A. Y. and M. M. Mekonnen. 2012. The water footprint of humanity. *Proceedings of the National Academy of Sciences of the United States of America* 109(9): 3232–3237.

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

Hubacek, K., D. Guan, J. Barrett, and T. Wiedmann. 2009. Environmental implications of urbanization and lifestyle change in China: Ecological and water footprints. *Journal of Cleaner Production* 17(14): 1241–1248.

Jiang, X., D. Guan, J. Zhang, K. Zhu, and C. Green. 2015. Firm ownership, China's export related emissions, and the responsibility issue. *Energy Economics* 51: 466–474.

Lenzen, M. and G. M. Peters. 2010. How city dwellers affect their resource hinterland. *Journal of Industrial Ecology* 14(1): 73–90.

Lenzen, M., D. Moran, A. Bhaduri, K. Kanemoto, M. Bekchanov, A. Geschke, and B. Foran. 2013. International trade of scarce water. *Ecological Economics* 94: 78–85.

Leontief, W. 1941. *The structure of American economy, 1919–1929: An empirical application of equilibrium analysis*. Cambridge, MA: Harvard University Press.

Mekonnen, M. and A. Hoekstra. 2012. A global assessment of the water footprint of farm animal products. *Ecosystems* 15(3): 401–415.

Mekonnen, M. M. and A. Y. Hoekstra. 2011. The green, blue and grey water footprint of crops and derived crop products. *Hydrology and Earth System Sciences* 15(5): 1577–1600.

Meng, B., J. Xue, K. Feng, D. Guan, and X. Fu. 2013. China's inter-regional spillover of carbon emissions and domestic supply chains. *Energy Policy* 61: 1305–1321.

Merrett, S. 2003. Virtual water and the Kyoto consensus. *Water International* 28(4): 540–542.

Miller, R. E. and P. D. Blair. 2009. *Input-output analysis: Foundations and extensions*. Cambridge, UK: Cambridge University Press.

Peters, G. P. and E. G. Hertwich. 2008. CO_2 embodied in international trade with implications for global climate policy. *Environmental Science & Technology* 42(5): 1401–1407.

Peters, G. P., R. Andrew, and J. Lennox. 2011. Constructing an environmentally-entended multi-regional input-output table using the GTAP database. *Economic Systems Research* 23(2): 131–152.

Proops, J. L. R. 1988. *Energy intensities, input-output analysis and economic development*. Staffordshire, UK: University of Keele, Department of Economics.

Shao, L. and G. Q. Chen. 2013. Water footprint assessment for wastewater treatment: Method, indicator, and application. *Environmental Science & Technology* 47(14): 7787–7794.

Sonnenberg, A., A. Chapagain, M. Geiger, and D. August. 2009. The water footprint of Germany—Where does the water incorporated in our food come from? *Frankfurt am Main: WWF Germany*.

Steen-Olsen, K., J. Weinzettel, G. Cranston, A. E. Ercin, and E. G. Hertwich. 2012. Carbon, land, and water footprint accounts for the European Union: Consumption, production, and displacements through international trade. *Environmental Science & Technology* 46(20): 10883–10891.

Tillotson, M., J. Liu, D. Guan, P. Wu, X. Zhao, G. Zhang, S. Pfister, and M. Pahlow. 2014. Water Footprint Symposium: Where next for water footprint and water assessment methodology? *The International Journal of Life Cycle Assessment* 19(8): 1561–1565.

Timmer, M. P., A. A. Erumban, R. Gouma, B. Los, U. Temurshoev, G. J. de Vries, I. Arto, et al. 2012. The World Input-Output Database (WIOD): Contents, sources and methods. WIOD Working Paper Number 10. Rotterdam, the Netherlands: Institute for International and Development Economics.

Van Oel, P. R., M. M. Mekonnen, and A. Y. Hoekstra. 2009. The external water footprint of the Netherlands: Geographically-explicit quantification and impact assessment. *Ecological Economics* 69(1): 82–92.

Vanham, D. and G. Bidoglio. 2013. A review on the indicator water footprint for the EU28. *Ecological Indicators* 26: 61–75.

WBCSD (World Business Council for Sustainable Development). 2008. *Water resources: Efficiency and conservation—Swimming in dwindling waters*. Geneva, Switzerland: WBCSD.

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

Wiedmann, T., H. C. Wilting, M. Lenzen, S. Lutter, and V. Palm. 2011. Quo Vadis MRIO? Methodological, data and institutional requirements for multi-region input-output analysis. *Ecological Economics* 70(11): 1937–1945.

WIOD (World Input-Output Database). 2012. World Input-Output Database. http://www.wiod.org/new_site/home.htm. Accessed 18 April 2016.

World Bank. 2014. World Development Indicators Online (WDI) database. Washington, DC: World Bank.

WWAP (World Water Assessment Program). 2006. The state of the resource. In *World water development report* 2. Paris: WWAP UNESCO.

Yang, H., L. Wang, and A. J. B. Zehnder. 2007. Water scarcity and food trade in the Southern and Eastern Mediterranean countries. *Food Policy* 32(5–6): 585–605.

Yu, Y., K. Hubacek, K. Feng, and D. Guan. 2010. Assessing regional and global water footprints for the UK. *Ecological Economics* 69(5): 1140–1147.

Zhao, X., H. Yang, Z. Yang, B. Chen, and Y. Qin. 2010. Applying the input-output method to account for water footprint and virtual water trade in the Haihe River Basin in China. *Environmental Science & Technology* 44(23): 9150–9156.

Zimmer, D. and D. Renault. 2003. Virtual water in food production and global trade: Review of methodological issues and preliminary results. In *Virtual water trade Proceedings of the International Expert Meeting on Virtual Water Trade*, edited by A. Y. Hoekstra. Delft, the Netherlands: UNESCO-IHEM.

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Supporting Information

Supporting information is linked to this article on the *JIE* website:

Supporting Information S1: This supporting information includes an explanation of models used to calculate consumer and producer responsibilities of water consumption in different regions. Diagrams, maps, and tables are provided to compare regions.