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Spatially explicit assessment of water embodied in European trade: A product-level multi-regional input-output analysis

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ABSTRACT

Responsible water management in an era of globalised supply chains needs to consider both local and regional water balances and international trade. In this paper, we assess the water footprints of total final demand in the EU-27 at a very detailed product level and spatial scale—an important step towards informed water policy. We apply the multi-regional input-output (MRIO) model EXIOBASE, including water data, to track the distribution of water use along product supply chains within and across countries. This enables the first spatially-explicit MRIO analysis of water embodied in Europe's external trade for almost 11,000 watersheds world-wide, tracing indirect ("virtual") water consumption in one country back to those watersheds where the water was actually extracted. We show that the EU-27 indirectly imports large quantities of blue and green water via international trade of products, most notably processed crop products, and these imports far exceed the water used from domestic sources. The Indus, Danube and Mississippi watersheds are the largest individual contributors to the EU-27's final water consumption, which causes large environmental impacts due to water scarcity in both the Indus and Mississippi watersheds. We conclude by sketching out policy options to ensure that sustainable water management within and outside European borders is not compromised by European consumption.
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1. Introduction

Water is a renewable resource, but its availability varies in time and space. The current dense web of globalised production and consumption patterns interlinked by international trade places localized stress on water resources in many areas of the globe (Hubacek et al., 2014). Due to growing demand for agricultural and manufactured products, as well as for thermal electricity generation and domestic use, water withdrawals are projected to increase by 55% through 2050 (UN Water, 2014). Hence, in a globalised economy, local water depletion and pollution are often closely tied not only to in situ water use but also to consumption elsewhere on the planet where water is used to produce export products. As a consequence, 'embodied' or 'virtual' water flows around the globe are associated with the traded commodities (Allan 1994; also termed "indirect water flows").

Integrating economic data and environmental data on water use within a consistent accounting framework allows to quantify the potential impact of specific economic sectors as well as relative benefits of mitigation measures also in watersheds far away from final consumption. There are two main approaches to achieve this integration. "Top–down" approaches using multi-regional input-output (MRIO) models start with the overall water appropriation in a specific geographical unit and for the production of a specific sector, and allocate these water volumes to final demand via monetary information on national and international trade (for instance, Tukker and Dietzenbacher, 2013). They hence account for direct and indirect resource flows associated with the economic activity of a specific country or region, and allow linking resource use to economic activities along the complete international supply chains of all products and services delivered to final demand (Tukker et al., 2009; Dietzenbacher et al., 2013; Lenzen et al., 2013a; Tukker and Dietzenbacher, 2013). These models have been applied already in various studies for a number of environmental issues, including material use (Bruckner et al., 2012; Wiedmann et al., 2013; Giljum et al., 2015) and greenhouse gas emissions (e.g. Peters et al., 2012; Peters et al., 2011; Cranston and Hammond 2012). However, for the case of water only a limited number of

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studies are available. Some of them were carried out for specific countries like Spain (Cazcarro et al., 2013, 2012; Dietzenbacher and Velázquez, 2007), the UK (Yu et al., 2010) or China (Zhang and Anadon, 2014); others for regions such as the EU (Feng et al., 2011) or on the global level (Steen-Olsen et al., 2012; Ewing et al., 2012a). One of the most recent contributions is a study by Lenzen et al. (2013b), who incorporate water scarcity into an assessment of global virtual water flows using input-output analysis. However, all the cited MRIO studies were limited to the country level. This failure to consider local water availability and consumption levels can produce incomplete or misleading results, as certain amounts of extracted water can have different impacts in different watersheds within a country, depending on hydrological and ecosystem structures (Pfister et al., 2009).

In contrast, "bottom-up" or "coefficient-based" approaches quantify the water required for specific products, scale these products up to overall quantities needed for production in a country and allocate these water volumes via trade data to countries of final consumption. The most prominent example for the "bottom-up" approach is the "Water Footprint" developed by Hoekstra and Chapagain (2007),Hoekstra and Mekonnen (2012). "Bottom-up" approaches have been used to calculated scarcity-adjusted spatially-explicit consumption-based water footprints (Ridoutt and Pfister, 2010; Hoekstra et al., 2012). While bottom-up approaches have the advantage of a very high product detail, especially in the area of agricultural products, they lack the full and consistent coverage of global supply chains for higher processed products, which can lead to underestimations of the overall environmental effect (Hubacek and Feng 2016).

In this paper, we therefore follow the "top–down" approach through applying the MRIO database EXIOBASE (Wood et al., 2015; Tukker et al., 2013); currently the MRIO database with the highest product detail available. For the assessment, EXIOBASE was extended with comprehensive data on water withdrawal and consumption taken from the ETH dataset (Pfister and Bayer 2013; Pfister et al., 2011b) and the Water Footprint Network dataset (Mekonnen and Hoekstra 2011a) for agricultural water consumption as well as the WaterGAP model (Flörke et al., 2013) for industrial water consumption. This allows calculating the direct and indirect water consumption for a unprecedented large number of specific products and product groups and link them to the country or region of origin. The available detail of specific products and categories of water consumptions makes the EXIOBASE the most comprehensive water use extended MRIO (W-MRIO) available to date.

Lenzen et al. (2013b) characterized national footprints and trade balances in terms of scarcity-weighted water for 187 individual countries. In this paper, we move one important step further by breaking the water use and consumption induced by European final consumption down to the level of 10,936 watersheds worldwide. This level of spatial detail is unique and crucial, as water scarcity problems can vary significantly across watersheds. Hence, the watershed level is the most relevant level for water management—as has been recognised already by the European Union's Water Framework Directive (European Parliament and Council, 2000) and by widely used water scarcity assessment methods (e.g. BWSI; Hoekstra et al., 2012; EEA, 2014; Pfister et al., 2009).

With this paper we aim at illustrating the analytical capacity of the EXIOBASE W-MRIO model which combines very high levels of product and geographical detail by creating spatial extension matrices to trace the water consumption to watersheds. We use this state of the art model to identify in-depth hot spots of direct and indirect water use, analyse the contribution of various product groups to the total water footprint and assess cross-country patterns in terms of water use and international trade of embodied water, as well as scarcity levels in the source watersheds. We also discuss advantages and shortcomings of the model and available data, as it is the data quality and availability which restricts W-MRIOs in realising their full analytical potential.

2. Methodology and data

Calculations presented in this paper were carried out using EXIOBASE version 2.2 (Wood et al., 2015). The EXIOBASE system was developed in several European research projects and is especially suited for environmental applications (Tukker et al., 2013). In EXIOBASE, national IO tables were disaggregated to provide a higher detail for industries and products in environmentally-sensitive sectors, including agriculture and food processing. EXIOBASE 2.2 distinguishes 43 countries (representing around 95% of global GDP) and 5 rest-of-the-world regions and disaggregates a total of 163 industrial sectors and 200 product groups in each country/region (see list of countries and sectors in the supplementary information). The base year of EXIOBASE 2.2 is 2007, thus all analyses in this paper relate to that specific year. A detailed explanation of the construction of EXIOBASE is provided by Wood et al. (2015).

With regard to the overall sector and product disaggregation level, as well as primary resource extraction sectors, EXIOBASE 2.2 is at the research edge of global environmental-economic analyses. It is clear, however, that such a complex modelling system also contains significant sources of uncertainty. A discussion of general advantages and disadvantages of multi-regional input-output analysis, as well as a comparison with "bottom-up" approaches, can be found in the supplementary information.

2.1. Water extensions (satellite accounts)

The integration of economic data and data on water appropriation within a single framework allows illustrating the interaction between the economy and the aquatic environment and helps identifying appropriate measures for so-called "hot spots", i.e. sectors with especially high water intensity. In EXIOBASE, the environmental extension "water consumption" is a set of country and sector specific data on water consumption. Following the MRIO logic, the different water consumption quantities are allocated to the specific sectors where the actual consumption is taking place, thus creating a physical satellite account linked to the monetary MRIO database.

When defining and compiling this set of water extensions, the following aspects must be considered (for more detail see Lutter et al., 2014):

(1) Water use vs. water consumption: Water appropriation by economic activities exerts two different types of pressures on the environment. "Water use" accounts for the actual quantities of fresh water extraction where water is pumped out of e.g. a groundwater body or diverted from a river or lake. Water which is used can be returned to the same water body, although it may be shifted in time or location, and its quality may be changed. "Water consumption" accounts for the share of the extracted water which is lost for the ecosystem, either by incorporation into a product or lost through physical processes such as evapotranspiration. In the literature, "water consumption" (extraction minus return flows) is also called "consumptive use" (EEA, 2014; Pfister et al., 2009).

(2) Geographical and temporal disaggregation: The availability and use of water varies according to factors such as precipitation and temperature. Depending on the data availability, water accounts can be differentiated at various

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