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Citation

Bunsen, J., Berger, M., Ward, H., & Finkbeiner, M. (2021). Germany's global water consumption under consideration of the local safe operating spaces of watersheds worldwide. *Cleaner And Responsible Consumption*, *3*. doi:10.1016/j.clrc.2021.100034

Cleaner and Responsible Consumption 3 (2021) 100034

Contents lists available at ScienceDirect

Cleaner and Responsible Consumption

journal homepage: www.journals.elsevier.com/cleaner-and-responsible-consumption

Germany's global water consumption under consideration of the local safe operating spaces of watersheds worldwide

Jonas Bunsen [a,*], Markus Berger [a], Hauke Ward [b,c,d], Matthias Finkbeiner [a]

[a] *Chair of Sustainable Engineering, Institute for Environmental Engineering, Technische Universität Berlin, Section Z1, Straße des 17. Juni 135, 10623, Berlin, Germany*
[b] *Department of Industrial Ecology, Institute of Environmental Sciences (CML), Leiden University, Van Steenis Building, Einsteinweg 2, 2333, CC, Leiden, the Netherlands*
[c] *Mercator Research Institute on Global Commons and Climate Change (MCC), EUREF Campus 19, Torgauer Straße 12-15, 10829, Berlin, Germany*
[d] *Potsdam Institute for Climate Impact Research (PIK) e. V., Telegrafenberg A 31, 14473, Potsdam, Germany*

ARTICLE INFO

Keywords:
Water footprint
Water consumption
Environmentally extended input-output analysis
Sustainable production and consumption
Consumption externalities

ABSTRACT

Germany is one of the five largest consumer markets in the world. Given that both supply chains and water consumption in agriculture, industry and underlying resource extraction and energy generation are globally intertwined, consumption in Germany undeniably has a major impact on global water consumption.

This paper aims to determine Germany's global consumption-induced water consumption (hereinafter *water consumption*), with a particular focus on the worldwide origin of the country's *blue water* consumption at a watershed level and under consideration of the local safe operating spaces of watersheds.

First of all, an approach based on environmentally extended multi-regional input-output analysis (EE-MRIO) was used to determine the origin of national contributions to Germany's water consumption. The resulting national contributions were then allocated to 8250 watersheds worldwide, weighted by consumption, and benchmarked against their local safe operating spaces.

In this study, Germany's water consumption in 2015 was approximated to 171 km^3 (6 m^3·capita^{-1}·day^{-1}), 14.4 km^3 of which was blue water. Other countries contributed more than 80% of Germany's blue water consumption. India, Pakistan and Egypt contributed more blue water to Germany's blue water consumption than Germany itself; virtual water imports from the Indus, Nile, Ganges and Mississippi river basins alone accounted for more than a quarter of Germany's total blue water consumption. Taking into account the local safe operating spaces of watersheds worldwide, more than 15% of Germany's external blue water consumption is deemed to exceed the local safe operating spaces of the contributing watersheds.

Overall, the results are in line with previous studies of Germany's water footprint, albeit offering unprecedented spatial detail and hence new scientific substantiation for environmental policy-making. Moreover, the method applied, which can be transferred to other types of scientific analysis, shows how spatially explicit water consumption results can be derived from EE-MRIO-based analyses, even at the subnational level.

1. Introduction

Economic globalisation has now, in the 21st century, reached unprecedented levels. Since supply chains are globally interconnected, the consumption of goods, materials, energy and services in one region can cause an environmental impact in other regions throughout the world. In 2019, Germany had the world's fourth-highest gross domestic product and household final consumption expenditure (World Bank, 2020a, 2020b). Given that supply chains are globally intertwined and that there is a direct link between water consumption on the one hand and agricultural/industrial production and underlying resource extraction and energy generation on the other, consumption in Germany is likely to cause pressure on freshwater resources worldwide. In many regions of the world, freshwater resources are being depleted beyond natural regenerative capacities; as a result, social, environmental and economic risks from freshwater shortages are becoming increasingly salient (UNESCO et al., 2020; UNESCO, 2019; WEF, 2020).

To determine limits for tolerable anthropogenic freshwater appropriation, Rockström et al. (2009a, 2009b) proposed a planetary boundary for water, a concept that has further been refined by Gerten et al. (2013) into local safe operating spaces. A local safe operating space refers to the ecological carrying capacity of ecological systems such as a watershed.

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* Corresponding author.
E-mail address: jonas.bunsen@tu-berlin.de (J. Bunsen).

https://doi.org/10.1016/j.clrc.2021.100034
Received 1 March 2021; Received in revised form 18 July 2021; Accepted 15 August 2021

Rockström et al. (2009a, 2009b) claimed that if a watershed's resilience and ability to support local communities was to be sustained, its safe operating space must be respected.

A number of authors have scaled down the water planetary boundary proposed by Rockström et al. (2009a, 2009b) to a per capita allowance to benchmark against a country's national per capita water consumption (Nykvist et al., 2013; Hoff et al., 2014; O'Neill et al., 2018). With the exception of Mekonnen and Hoekstra (2020), however, no work has been published on establishing spatial links between consumption in a country and the exceedance of the local safe operating spaces of watersheds elsewhere in the world (Bunsen et al., 2021). Since Mekonnen and Hoekstra (2020) did not use input-output data, it is to our best knowledge and belief that this study is the first to link the concept of a planetary boundary for water and EE-MRIO. Apart from Lutter et al. (2016), who did not consider a planetary boundary for water, previous studies only investigated potential linkages between consumption in a country and corresponding water-related impacts in other countries but not on a watershed level. However, due to the heterogeneous pattern of exceedances of local safe operating spaces of watersheds within most countries, a national perspective can be deceiving. The assessment offers an unprecedented spatial scale and thus may aid scientifically susbtnatiated policy making. Hence, a better understanding of these links could provide guidance for countries in shaping policies to reduce consumption-induced environmental impacts related to water, with a focus on critical watersheds.

Countries' environmental impact, including water consumption, have often been determined using environmentally extended input-output (EE-MRIO) analysis (see below). EE-MRIO databases include worldwide monetary transactions between countries' sectors and consumers, supplemented by environmental indicators such as *water consumption*. In consumption-based EE-MRIO analysis, multiplying the sectors' direct externalities by the sectors' upstream requirements yields their total externalities per unit sectoral output. Subsequently multiplying the sectors' total externalities per unit output by a region's consumption (or *final demand*) yields the total externalities associated with that region's consumption (cf. Miller and Blair, 2009; Kitzes, 2013). As a result, EE-MRIO analysis enables water consumption to be assessed globally or, in other words, on a *planetary* scale. However, EE-MRIO databases usually have a national-level resolution, whereas water consumption impacts typically occur at the watershed level.

In addition, consumption-based EE-MRIO analysis disguises the regional origin of an externality. This is due to the fact that externalities along widely ramified global supply chains are aggregated and returned as the cumulated externality of the last transaction in the supply chain (cf. Section 2.1). For some externalities, e.g. greenhouse gas emissions, the origin of those externalities is of little relevance in terms of their impact on the biosphere or humans. Given that greenhouse gases mix relatively well in the atmosphere, the exact location of their emission is of little relevance, unlike in the case of water consumption, which has an impact on a highly local level, typically within a watershed. Hence, consumption-based EE-MRIO analysis has been criticised not only for falling short in disclosing the initial origin of water consumption, but also for spatially misaligning the geographic unit on which the impact of water consumption typically occurs[1] (Feng et al., 2011; Ridoutt et al., 2018; Daniels et al., 2011).

However, several authors such as Davis and Caldeira (2011), Ward et al. (2019) and Cabernard et al. (2019) have proposed and applied methods to determine the initial origin of an externality in EE-MRIO. Although someof the authors did not assess water consumption, their approaches, or parts thereof, can be transferred to the given research aim. Lutter et al. (2016) conducted an EE-MRIO-based spatially explicit subnational assessment of water embodied in European trade. However, the authors did not benchmark against the local safe operating spaces of watersheds, nor did they provide a mathematical description of the method applied. If the national origin of an externality can be determined and the national contributions of an externality can simultaneously be disaggregated to watersheds, then it would be possible to assess a country's contribution to the exceedance of safe operating spaces worldwide. The disguise of the regional origin of an externality in consumption-based EE-MRIO analysis may partly explain why previous studies analysing the regional water consumption of a country have refrained from applying EE-MRIO analysis (Hoekstra et al., 2002; Chapagain et al., 2004; Sonnenberg et al., 2009; Jiang et al., 2015; Antonelli et al., 2017; Brindha, 2017; Wagnitz et al., 2014). Yet, the alternative approach based on assessing direct trade between nations excludes the country's indirect water consumption via intermediate products (Feng et al., 2011).

Examples of studies on EE-MRIO analysis-based assessments of Germany's water consumption include Lenzen et al. (2012, 2013) and Arto et al. (2012), which refer to the year 2000 and (up to) 2008, respectively. Arto et al. (2012) calculated the cumulative water consumption of various countries, including that of Germany, but disregarded the initial origin of the water, while covering virtual water imports from *only* 33 countries. Lenzen et al. (2012, 2013) conducted a structural path analysis to map virtual water flows; however, the authors did not investigate these flows on a subnational (watershed) level, nor did they consider the local safe operating spaces of watersheds. Other authors have conducted EE-MRIO analysis-based assessments of, e.g. the domestic water footprint of England and the United Kingdom (Yu et al., 2010) and of, the European Union (Steen-Olsen et al., 2012), the domestic and provincial water footprint of China (Zhang et al., 2014), global water use (Arto et al., 2016), Italy's water footprint (Ali et al., 2018) or global grey water consumption (Zhao et al., 2019).

The aim of this study is therefore to conduct a spatial assessment of Germany's consumption-induced global water consumption (hereinafter referred to as *water consumption*). For *completeness*, results are provided for blue, green and grey water. However, the particular focus of this study is Germany's worldwide blue water consumption under consideration of the exceedance of the local safe operating spaces of watersheds worldwide. *Blue water* refers to fresh surface and groundwater in lakes, river and aquifers (Hoekstra et al., 2012). It is arguably the type of water that faces the fiercest competition. In this study, the term "*contributions to water consumption of …*" is used in place of the widely used term "virtual water imports", which refers to water embedded in goods and trade (Allan 1996, 1998, 1998). The reason for this distinction is that the term *imports* would exclude Germany's own contributions to the country's water consumption, which are included in this assessment. Depending on the context, however, the terms may be used interchangeably.

The paper is structured as follows. First, the methodology to determine the initial origin of an externality in production-based EE-MRIO analysis is introduced. Second, the results are presented, starting with Germany's total and blue water consumption. Next, the paper shows the results of allocating national contributions to Germany's blue water consumption to 8250 watersheds worldwide and of reaggregating them to the world's major river basins. Subsequently, the allocated contributions to Germany's blue water consumption are related to the exceedance of the local safe operating spaces of watersheds worldwide. Finally, the results are discussed and conclusions drawn.

2. Method

The method applied is described in detail in the following three subsections. First, the EE-MRIO-based analysis is elaborated extensively, including a comparison to consumption-based EE-MRIO analysis (Section 2.1). Sections 2.1.1 and 2.1.2 partly follow elaborations of Kitzes (2013), Ward et al. (2019) and Jakob et al. (2021). Second, the allocation to watersheds and major river basins worldwide of national contributions to Germany's blue water consumption is explained (Section 2.2). Third, the approach for assessing the exceedance of local safe operating spaces in

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[1] EE-MRIO data: nations; impacts of water consumption: watersheds.

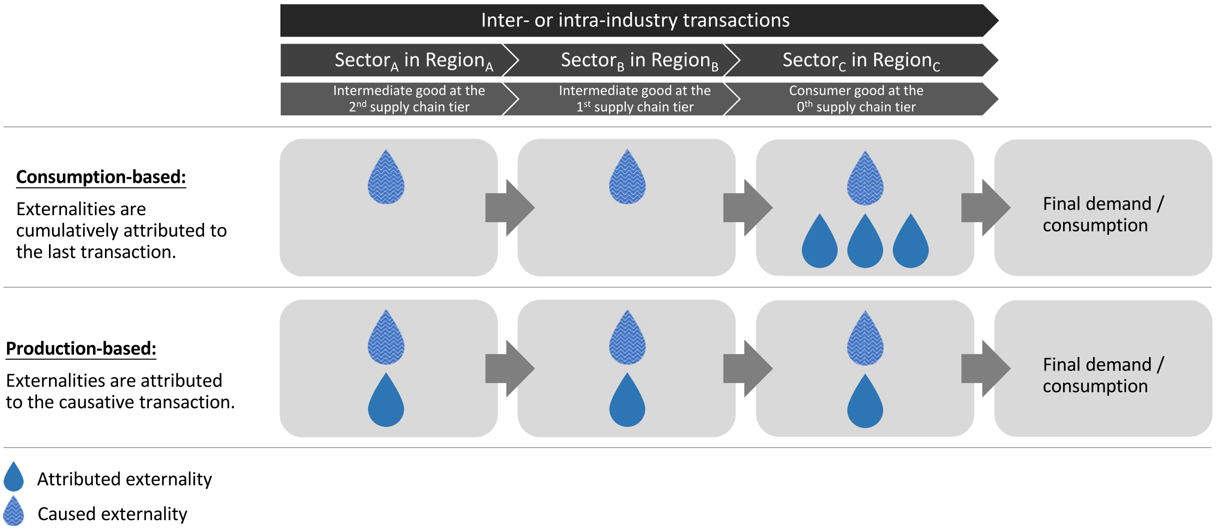

Fig. 1. Comparison of the attribution of externalities in consumption-based EE-MRIO analysis (top) and the attribution of externalities in the production-based EE-MRIO analysis approach applied (bottom). The wide arrows indicate monetary flow along with transactions and eventually into final demand. The "water drops" indicate the attribution schemes for externalities in the two approaches. Inconsumption-based EE-MRIO analysis, accruing externalities are cumulatively attributed to the last transaction in the supply chain (top). In the production-based EE-MRIO analysis approach applied, externalities are attributed to the region of the causative sector transaction in the supply chain (bottom). It should be noted that the example provided of a supply chain is simplified. Supply chains are rarely linear and one-dimensional.

watersheds worldwide is described (Section 2.3).

In the methods section, the terms *direct* and *total intensities* refer to monetary transactions between sectors, while the terms *direct* and *total externalities* refer to the virtual flow of water through the economy. The use of the terms *blue, green* and *grey water* follows the definitions provided by the Water Footprint Network (Hoekstra et al., 2012).

2.1. EE-MRIO-based analysis of contributions to Germany's water consumption

An overview of EE-MRIO databases by Pfister and Kulionis (2020) revealed that, with a coverage of 189 countries, the *Eora* global supply chain database (Lenzen et al. 2012, 2013, 2013) provides the highest national coverage among all EE-MRIO databases with environmental extensions for water consumption. Given that global national coverage was considered by the authors of the present study to be of utmost importance for the global spatial analysis of Germany's water consumption, the Eora database was chosen as the foundation for the analysis (Eora26 version 199.82 for the year 2015). Eora's native water environmental extensions for blue, green and grey water are based on Mekonnen and Hoekstra (2010a), Mekonnen and Hoekstra (2010b) and Mekonnen and Hoekstra (2011).

As described in the previous section, consumption-based EE-MRIO analysis was not applied because it determines the externalities of a sector, including that sector's supply chain (Fig. 1). Such an approach would have disguised the initial origin of water consumption along the supply chain. Instead, a production-based EE-MRIO approach by Jakob et al. (2021), which attributes an externality to the region of the causative inter-industry transaction, was adapted. As a result, the regional origin of water consumption is disclosed, enabling a spatially explicit water consumption assessment. The approach could also be adjusted to identify the sectoral origin (including the region; see the last paragraph of Section 2.1.2).

The *initial origin* of an externality is understood to be the region that contributes an externality and in which the potential impact of that externality– water consumption, in this case – materialises. This definition of the *initial origin* of an externality takes no account of whether water is embedded in intermediate products, traded between other sectors before being consumed in Germany, or contributed embedded in consumer goods directly for consumption in Germany.

2.1.1. Determining the consumption-based externalities of a region

In EE-MRIO analysis, (monetary) transactions between or within sectors are given by a T matrix with the dimension $\mathrm{R}^{(rs)\times(rs)}$. The letter r denotes the regions $r \in \{1,\ldots,m\}$ and the letter s denotes the sectors $s \in \{1\ldots n\}$ (this notation applies throughout Sections 2.1.1 and 2.1.2). The elements in T are $t_{(r,s)(r',s')}$. Each element represents the total monetary transactions between region r and sector s and region r' and sector s'. Monetary transactions between sectors and consumers are referred to as final demand, represented by a matrix Y with the dimension $\mathrm{R}^{(rs)\times r}$. The elements in Y are $y_{(r,s)r'}$ representing the transactions required from region r and sector s to meet final demand in region r'. A vector with the total output per sector is given by $x_{(r,s)} := \sum_{r'}\sum_{s'} t_{(r,s)(r',s')} + \sum_{r'} y_{(r,s)r'}$ and a vector with the total externalities per sector is given by $q_{(r,s)}$. The dimension of both x and q is $\mathrm{R}^{(rs)}$.

Dividing the total externalities per sector q by the corresponding total sector output yields the direct intensity of externalities per sector $f_{(r,s)} := q_{(r,s)} \cdot x^{-1}_{(r,s)}$. Dividing the transactions between or within sectors T by the total output per sector x yields the direct intensities or the so-called technology matrix A (the input requirements per unit sectoral output). Based on A, the supply chain of each economic sector can be traced indefinitely. For each level in a supply chain, multiplying the required direct intensities A to the power of the level in the supply chain by direct externalities f yields the *total externalities* contributed by that supply chain layer F. In theory, if this is done for all supply chain layers, it is possible to determine the total externalities associated with the generation of one unit of output in a given sector. Multiplying this result by a corresponding final demand, e.g. consumption in Germany, yields the total externality or *footprint* associated with consumption in Germany.

For practical reasons, the Leontief inverse L is applied, to yield $F = fL = f(I-A)^{-1}$, which is equal to the infinite sum of $F = fI + fA + fAA + ..$, and where I is the corresponding identity matrix. One drawback of this approach, however, is that multiplying the Leontief inverse by a vector can disguise the regional origin of externalities, except that of the last sector in the supply chain for which F is calculated.

Table 1

Domestic and foreign contributions to Germany's consumption of green, grey and blue water.

Unit	Green water consumption			Grey water consumption			Blue water consumption			Total water consumption		
	Abroad	Domestic	Total	Abroad	Domestic	Total	Abroad	Domestic	Total	Abroad	Domestic	Total
$km^3 \cdot yr^{-1}$	111,541	23,451	134,993	14,145	7108	21,253	12,985	1431	14,416	138,671	31,991	170,663

2.1.2. Determining the production-based externalities from a sector, including its region

As explained in the previous section, multiplying the total intensities L by the direct externalities f yields the total externalities per unit output F. Subsequently multiplying the total externalities F by the final demand of a country c y^c yields the total externalities associated with the final demand of that country or, in other words, that country's environmental footprint.

In this study, however, we modify the externality vector F. As in Malerba et al. (2021), a modified direct externality intensity vector $f^*_{r_1}$ is deployed for each region r_1, where the elements are given by $f_{(r,s)}$ if r belongs to region r_1, and by $f_{(r,s)} = 0$ otherwise if i does not belong to region r_1. Hence, only the externalities from region r_1 that are consumed in c are considered when calculating the total externalities $f^*_{r_1} L y^c$. The resulting vector is $\widehat{F^c_{r1}}$. If this calculation is performed for all regions, all separate total externalities associated with the final demand in region c from all other regions can be attributed step by step to their initial origin.

Moreover, if $f^*_{r_1}$ can further be modified such that only a single sector is considered (s_1, resulting in $f^*_{r_1,s_1}$), then single sectoral origins can be identified. Ultimately, if only specific sectoral final demands of y are considered, the calculation yields the externalities the externalities associated with the consumption from a specific region and sector (cf. Section 4.4).

2.2. Allocation to watersheds and major river basins of national contributions to Germany's blue water consumption

In the process of determining global national contributions to Germany's water consumption, the proportion of blue water was allocated to watersheds worldwide. Proportions were allocated based on the water consumption in a watershed as a percentage of total water consumption in the country in which the watershed is located. If, then, for example, 80% of a country's total annual water consumption occurred in a specific watershed, it was also assumed that 80% of the country's contribution to Germany's water consumption originated from that watershed. In addition, the watershed-level contributions to Germany's water consumption were reaggregated to the world's 500 major river basins, based on the GRDC (2020) dataset. To this end, the water consumption determined in each watershed was normalised per area and the watersheds intersected with the major river basins. It was possible to determine total water consumption per intersection by multiplying the area-normalised water consumption by the area of the intersection. Finally, the water consumption figures for all intersections within a major river basin were added together. The water consumption data used in the methods section and in Section 2.3 were taken from the WaterGAP3 global hydrological model (Eisner, 2016; Flörke et al., 2013).

2.3. Contributions to Germany's blue water consumption under consideration of the exceedance of the local safe operating spaces of watersheds

An approach based on safe operating spaces was used to assess whether Germany's worldwide water consumption infringes local water-use limits. In line with previous studies such as Gerten et al. (2013), Steffen et al. (2015) and Motoshita et al. (2020), the safe operating space of a watershed was defined as the natural water availability within a watershed minus a proportion of the water availability retained to ensure ecosystem well-being (also referred to as *environmental flow requirements*). The environmental flow requirements applied, based on a method by Pastor et al. (2014), vary between 30% and 60%.

The magnitude of the exceedance of the local safe operating space of a watershed and the share of water consumption in exceedance of the local safe operating space of that watershed was determined for each watershed. The magnitude of the exceedance of the local safe operating space of a watershed was determined by dividing water consumption in that watershed by its watershed's safe operating space (cf. Fig. 5). It is important to note that water consumption in a watershed comprises not only Germany's water consumption from that watershed, but also total water consumption in the watershed, regardless of which country

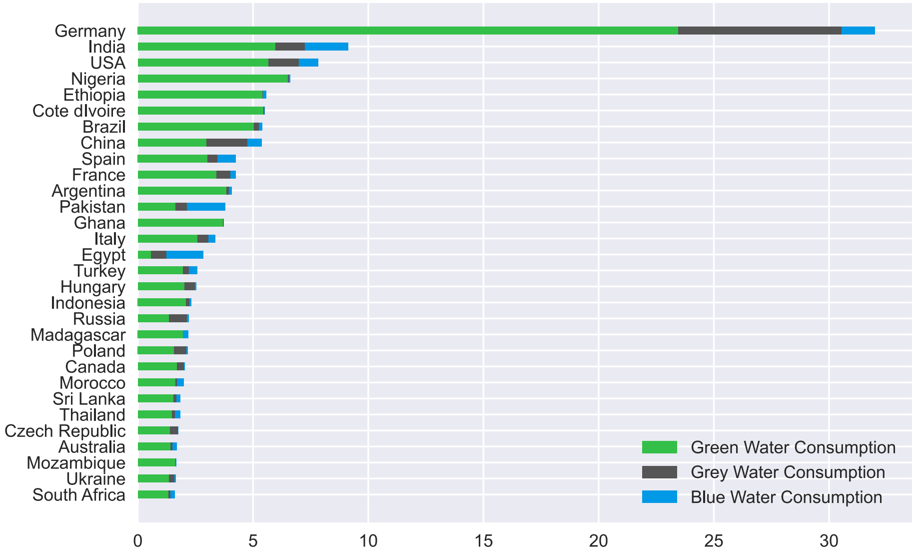

Fig. 2. The 30 highest national contributions to Germany's blue, green and grey water consumption in $km^3 \cdot year^{-1}$.

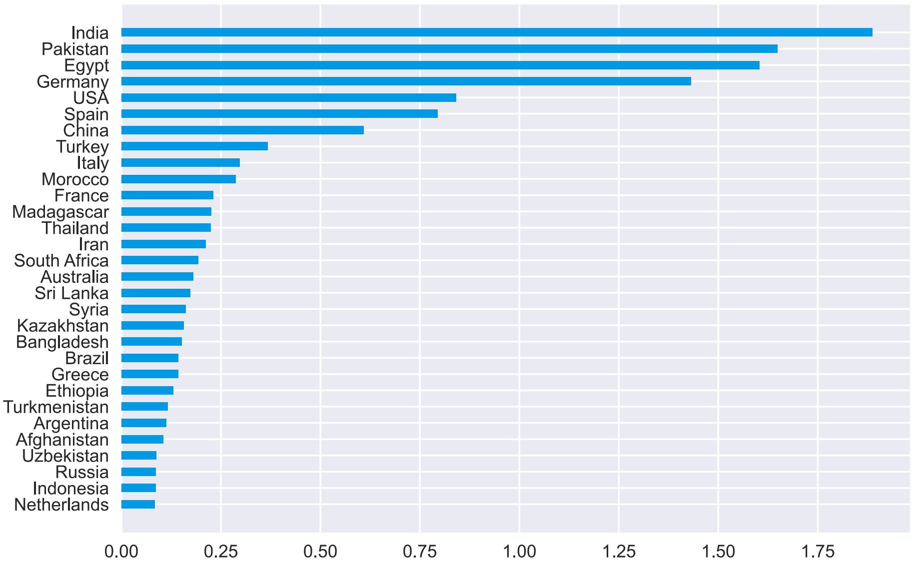

Fig. 3. The 30 highest national contributions to Germany's blue water consumption in km^3·year^{-1}.

consumed the water. To account for outliers, the maximum and minimum values for the magnitude of the exceedance of local safe operating spaces of watersheds were set to the 0.05 and 0.95 quantiles, respectively. By analogy, the share of water consumption in exceedance of the local safe operating spaces of a watershed was determined by dividing water consumption in exceedance of the local safe operating space of a watershed by its safe operating space (cf. Figs. 6, 8 and 10).

For example, if water consumption in a watershed was 0.3 km^3·year^{-1} and its safe operating space was 0.15 km^3·year^{-1}, the magnitude of exceedance would be 2 [-]. The share of water consumption in exceedance of the local safe operating space would be 0.5, or 50% (0.15 km^3·year^{-1}). The maximum possible share of water consumption in exceedance of a local safe operating space was set to 100%.

The results of determining 1) the magnitude of exceedance of the local safe operating spaces of watersheds and 2) the share of water consumption in exceedance of the local safe operating spaces of those watersheds were used to weigh the contributions to Germany's blue water consumption at the watershed level and to estimate the share of this country's water consumption in exceedance of the local safe operating spaces of watersheds worldwide. For 1), the contributions of watersheds to Germany's blue water consumption were multiplied by the characterisation factors describing the magnitude of exceedance of the local safe operating space of those watersheds. For 2), the contributions of watersheds to Germany's blue water consumption were multiplied by the relevant factors describing the share of water consumption in exceedance of the local safe operating spaces of watersheds.

3. Results

In this section, the worldwide contributions to Germany's water consumption are presented initially at different spatial scales – not only countries, but also watersheds and the world's major river basins. In addition, the exceedances of the local safe operating spaces of watersheds are shown, including the share of contributions to Germany's blue water consumption that may be considered as infringing local safe operating spaces.

3.1. Worldwide contributions to Germany's water consumption

Table 1 lists the disaggregated contributions to Germany's water

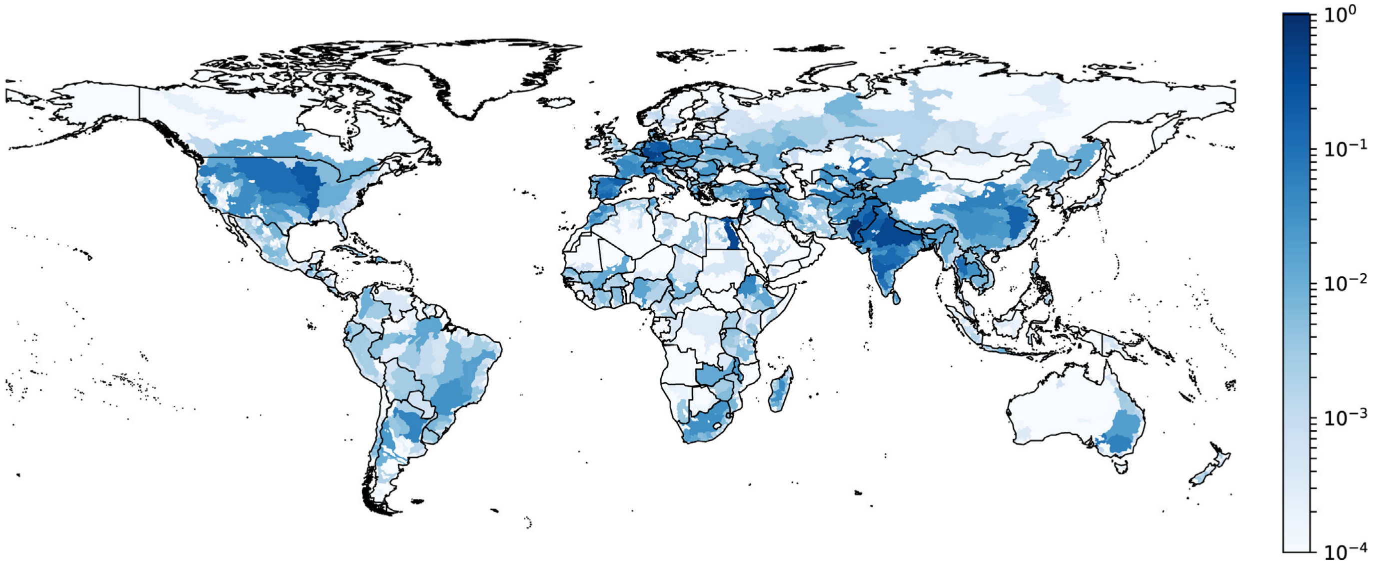

Fig. 4. Contributions of the world's watersheds to Germany's blue water consumption in km^3·year^{-1}.

Table 2
The 25 highest contributions of the world's major river basins to Germany's blue water consumption in km^3·year^{-1} (cf. SM Table 10 and SM Fig. 13).

Rank	River basin	Continent	Blue water contribution
1	Indus	Asia	1.520
2	Nile	Africa	1.360
3	Rhine	Europe	0.570
4	Ganges	Asia	0.556
5	Mississippi	North America, Central America and the Caribbean	0.418
6	Danube	Europe	0.373
7	Elbe	Europe	0.279
8	Shatt Al Arab	Asia	0.271
9	Aral Sea	Asia	0.242
10	Krishna	Asia	0.199
11	Weser	Europe	0.180
12	Yangtze	Asia	0.175
13	Ebro	Europe	0.162
14	Guadalquivir	Europe	0.154
15	Murray	South-West Pacific	0.151
16	Chao Phraya	Asia	0.142
17	Columbia	North America, Central America and the Caribbean	0.134
18	Godavari	Asia	0.128
19	Po	Europe	0.105
20	Douro (also Duero)	Europe	0.104
21	Guadiana	Europe	0.100
22	Parana	South America	0.092
23	Cauvery	Asia	0.085
24	Maas (also Meuse)	Europe	0.079
25	Meghna	Asia	0.066

consumption, which have been approximated to 170 km^3·year^{-1}. Germany's blue, green and grey water consumption accounts for 14.42, 170.66 and 21.25 km^3·year^{-1}, respectively. Around 19% of the country's water consumption originates from within Germany; approximately 81% originates from other countries.

The largest single national contribution to Germany's water consumption comes from Germany itself. Other major contributions originate from countries such as India, the USA, Nigeria, Ethiopia, Côte d'Ivoire, Brazil, China, Spain, France, Argentina and Pakistan (Fig. 2 and SM Table 4). All national contributions, particularly those of Sub-Saharan African countries, are dominated by green water.

If consideration is only given to contributions to Germany's blue water consumption, the contributions of India (1.9 km^3), Pakistan (1.6 km^3) and Egypt (1.6 km^3) exceed Germany's own domestic contribution (1.4 km^3; Fig. 3).

Based on the Natural Earth dataset 1:10 m Cultural Vectors Admin 0 – Countries (Natural Earth, 2020), the worldwide national contributions to Germany's water consumption were aggregated by world region (SM Fig. 11) and income (SM Fig. 12). The world's regions with the five highest contributions to Germany's blue water consumption are Southern Asia (4.2 km^3), Northern Africa (2 km^3), Western Europe (1.8 km^3), Southern Europe (1.3 km^3) and Northern America (0.8 km^3). Aggregated by income, lower middle-income countries (6.3 km^3) provide the highest contribution to Germany's blue water consumption, followed by high-income OECD (4.5 km^3), upper middle-income (2.8 km^3), low-income (0.8 km^3) and high-income non-OECD (0.02 km^3) countries.

Fig. 4 shows the contributions of watersheds worldwide to Germany's blue water consumption; Table 2 lists the 25 highest contributions from the world's major river basins to Germany's blue water consumption (cf. SM Fig. 13). The world's major river basins with the highest contributions to Germany's blue water consumption are located in Southern and Southeast Asia (Indus, Ganges, Chao Phraya and Krishna), Northern Africa (Nile), Central Europe (Rhine, Danube, Elbe, Weser), Southern Europe (Ebro, Guadalquivir, Po, Guadiana and Duero), the USA (Mississippi, Columbia, San Joaquin, Colorado and Sacramento) and Western Asia (Shatt Al Araband Eastern Asia (Yangtze). Together, the Indus, Nile, Ganges and Mississippi alone contribute 3.8 km^3 (~27%) of Germany's blue water consumption, followed by the Rhine (0.57 km^3), Columbia (0.41 km^3), Danube (0.37 km^3), Elbe (0.27 km^3), Shatt al-Arab (0.27 km^3) and Aral Sea (0.24 km^3) river basin.

3.2. *The exceedances of local safe operating spaces of watersheds worldwide and Germany's weighted blue water consumption*

Fig. 5 depicts the share of water consumption in the world's watersheds in exceedance of their local safe operating spaces. Based on these shares and Germany's blue water consumption allocated from these watersheds, approximately 1.98 km^3·year^{-1} of Germany's blue water consumption infringes local safe operating spaces. Given that no local safe operating spaces are exceeded in Germany, the entire volume can be attributed to Germany's external blue water consumption. As a result, 15.2% of Germany's external blue water consumption exceeds local safe operating spaces of watersheds.

The significance of Germany's domestic contribution to its blue water consumption diminishes when the country's watershed-level contributions to its blue water consumption are weighted by the exceedance of the local safe operating spaces of watersheds (Fig. 6). Aggregated to the national level, the contributions of 27 countries' watersheds to Germany's blue water consumption exceed its domestic contribution (0.21 $km^3_{weighted}$). The countries with the highest weighted contribution to Germany's blue water consumption are India (7.6 $km^3_{weighted}$), Pakistan (6.1 $km^3_{weighted}$), Spain (4.4 $km^3_{weighted}$), Egypt (4.2 $km^3_{weighted}$), Morocco (2 $km^3_{weighted}$), the USA (1.9 $km^3_{weighted}$), Turkey (1.7 $km^3_{weighted}$), Iran (1.2 $km^3_{weighted}$) and China (1 $km^3_{weighted}$). These results suggest that consumption-induced water consumption in countries such as India, Pakistan, Spain, Egypt and Morocco has a high leverage in terms of impact reduction.

If the weighted national contributions to Germany's blue water consumption are aggregated by region, the highest-contributing regions are Southern Asia (16.1 $km^3_{weighted}$), Northern Africa (7 $km^3_{weighted}$), Southern Europe (5.9 $km^3_{weighted}$), Western Asia (3.1 $km^3_{weighted}$), Northern America (1.9 $km^3_{weighted}$), Central Asia (1.2 $km^3_{weighted}$) and Eastern Asia (1.0 $km^3_{weighted}$), followed by Western Europe (0.58 $km^3_{weighted}$; SM Fig. 8). Aggregating the weighted national contributions to Germany's blue water consumption by income shows that the majority of contributions originate from lower middle-income countries (22 $km^3_{weighted}$), followed by high-income OECD countries (10 $km^3_{weighted}$), upper middle-income countries (7.3 $km^3_{weighted}$), low-income countries (1.2 $km^3_{weighted}$) and high-income non-OECD countries (0.1 $km^3_{weighted}$; SM Fig. 10).

4. Discussion

This section starts by briefly comparing the results with previous studies of Germany's water consumption. The subnational disaggregation of contributions to Germany's blue water consumption is then discussed and potential implications are reflected on. Finally, a brief proof of concept is undertaken to determine how EE-MRIO analysis can be used to further investigate drivers for the exceedance of safe operating spaces.

4.1. *Comparison with previous studies*

In this study, Germany's total (*blue*, *green* and *grey*) water consumption was approximated to 171 km^3·year^{-1}. This value is almost as high as the country's total annual water availability (188 km^3) (Örtl, 2017) or more than three times the volume of Lake Constance, Germany's largest lake (approximately 48 km^3; IGKB, 2020). Overall, the results are in line with previous approximations of Germany's total water consumption conducted by authors such as Sonnenberg et al. (2009), Arto et al. (2012) and Lenzen et al. (2013a,b), who produced estimates of 160, 186 and 234 km^3·year^{-1},

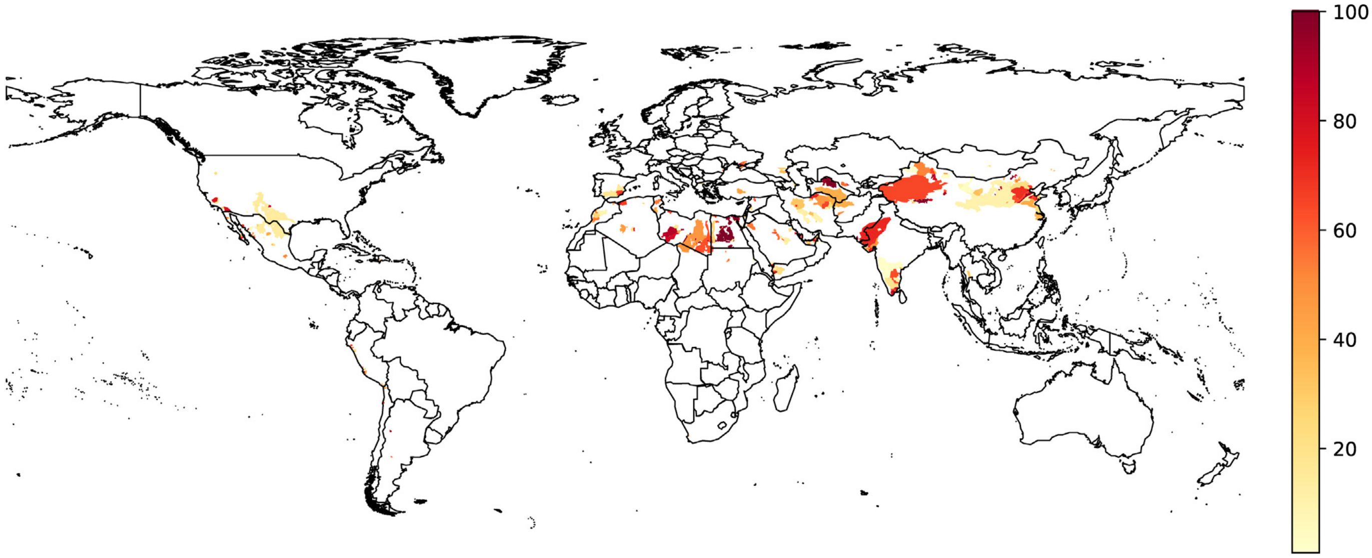

Fig. 5. The share of water consumption in the world's watersheds deemed to exceed their local safe operating spaces.

respectively. Given the differences in underlying modelling approaches, research scopes, datasets, environmental extensions and reference years, the differences between our approximations and those determined by the aforementioned studies are reasonable. Instead of taking a top-down approach, Sonnenberg et al. (2009) performed a bottom-up analysis, with an emphasis on the agricultural sector based on the PC-TAS database (a subset of the UN Comtrade database; United Nations, 2020) for the early 2000s. In contrast, Arto et al. (2012) conducted a top-down analysis using the World Input-Output Database (Timmer et al., 2015) for 1995 to 2008, omitting the regional origin of water used. Lenzen et al. (2013, 2012) used the Eora database for the year 2000, and with a different set of environmental extensions. Since the main focus of the present study was to achieve a subnational spatial disaggregation of Germany's blue water consumption in the world under consideration of the exceedance of safe operating spaces, an elaborate discussion of the differences observed compared to previous studies was considered to be beyond the scope of this paper. Nonetheless, a succinct overview is provided in SM Table 3. Section 4.3 discusses the reliability of the results, and how to interpret them, as well as a number of limitations.

4.2. Spatial disaggregation of Germany's consumption-induced blue water consumption and the exceedance of local safe operating spaces

As expected, the finding of previous studies that most of Germany's blue water consumption is contributed by foreign countries was affirmed (Finogenova et al., 2019; Sonnenberg et al., 2009; Brindha, 2020; Lenzen et al., 2013). The spatial disaggregation of global contributions to Germany's blue water consumption yields similar results to those of Lutter et al. (2016), who conducted a spatial analysis of EU27 water consumption. However, if river basin-level contributions to Germany's blue water consumption are compared to contributions to EU27 blue water consumption, Germany's large rivers (e.g. the Rhine, Danube, Elbe, Wester) gain in relevance, whereas other European river basins (e.g. Guadalquivir, Parana and Po) diminish in relevance. Beyond Europe, the same major river basins as found in previous studies are among the highest blue water contributors (e.g. Indus, Mississippi, Nile and Ganges).

The analysis of which contributions to Germany's blue water consumption possibly exceed the safe operating spaces of watersheds (cf. Section 2.3) reveals that most contributions originate from regions of the world outside Western Europe. The majority of these critical contributions originate predominantly from lower middle-income regions. Populations and governments in these regions are often seriously challenged in managing their water resources equitably and sustainably, and the exceedance of local safe operating spaces is likely to harm their communities and the local environment (UNESCO, 2019).

Weighted by the exceedance of local safe operating spaces, India and Pakistan provide the highest national contributions to Germany's blue water consumption. There are two reasons for this. First, both countries contribute large volumes of blue water to Germany's blue water consumption. Second, many watersheds in both countries, particularly along their shared border, are affected by the exceedance of local safe operating spaces. Compared to their unweighted volumetric contribution, countries such as Spain, Morocco and Greece gain in relevance, whereas the relevance of Germany's own blue water contribution diminishes. Blue water contributions from Spain mainly originate from the Guadalquivir and Guadiana river basins, which are affected by the exceedance of safe operating spaces. Egypt's weighted blue water contribution diminishes in relevance compared to its unweighted contribution. This is because most of the water is contributed from watersheds within the Nile river basin, where only coastal watersheds are deemed to be affected by the exceedance of local safe operating spaces. Other watersheds in Egypt that are seriously affected by the exceedance of local safe operating spaces contribute only minor volumes of blue water to Germany's blue water consumption.

Mekonnen and Hoekstra (2020) suggested that around 40% of Germany's total *virtual blue water consumption* exceeds worldwide local safe operating spaces. The result is significantly higher than the 15% suggested in the present study, which used EE-MRIO analysis. In contrast, Mekonnen and Hoekstra (2020) applied a bottom-up approach and used homogeneous environmental flow requirements of 80% for the entire world. In the present study, a spatially explicit environmental flow requirements dataset by Pastor et al. (2014) was applied, with environmental flow requirement values ranging from 30% to 60%. Moreover, Mekonnen and Hoekstra (2020) omitted indirect contributions to a country's water consumption, which are considered in the present study (cf. Section 2.1). In line with Mekonnen and Hoekstra (2020), the present study finds that exceedances of safe operating spaces induced by consumption in Germany occur entirely in other countries.

4.3. Implications and limitations

Feng et al. (2011) suggested that water consumption is allocated to the final sectoral transaction rather than the causative one in water consumption assessments based on EE-MRIO analysis. However, the present study has shown that water consumption in an EE-MRIO-based approach can indeed be allocated to the causative sectoral transaction, disclosing the region of origin of direct and indirect water consumption.

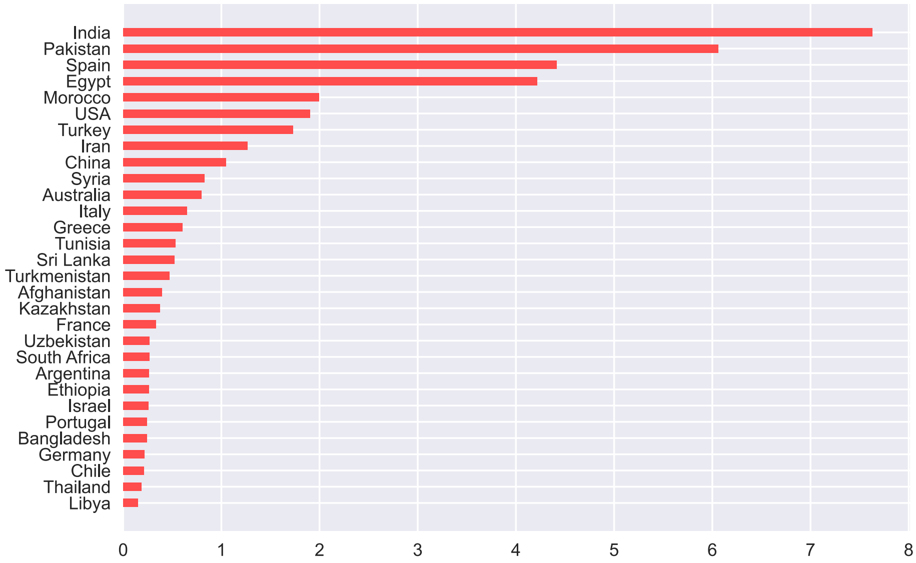

Fig. 6. The 30 highest weighted contributions to Germany's blue water consumption in $km^3_{weighted} \cdot yr^{-1}$.

The allocation of water consumption to the causative transaction in EE-MRIO has been put into practice in a case study of Germany's blue water consumption and under consideration of the safe operating spaces of watersheds worldwide. It goes without saying, however, that the method applied could equally by used for other regional foci or environmental indicators.

Nonetheless, the study was subject to a number of methodological constraints. Most importantly, Eora's native water environmental extensions for agricultural water consumption are understood to be aggregated values based on the production volume of all crops produced by a country's agricultural sector multiplied by the respective water consumption values. The resulting proportions of each product's water consumption as a percentage of total water consumption in agriculture are maintained for all transactions and across all production layers. In reality, this is not the case. Particularly in low-income countries, a small number of specific *cash crops* such as cotton, coffee, flowers and other crops often have a low share in the total production volume of an agricultural sector. At the same time, these crops may account for a large proportion in the total export value in that agricultural sector. Ethiopia, for instance, produces around 140 thousand tons of coffee and some 7 million tons of maize per year (OEC, 2021, FAO, 2019). And yet Ethiopia's coffee production accounts for approximately 25% of agricultural production value and around 30% of the country's exports in terms of value. Ethiopian coffee production requires 10.5 m^3 of green water per ton of produce, whereas maize production requires *only* 4.2 m^3 green water per ton of produce (Mekonnen and Hoekstra, 2011). It could therefore be expected that 30% or more of Ethiopia's virtually exported green water consumption is attributed to coffee production. This is not the case, however. Ethiopia produces approximately 50 times more maize than coffee, and although the green water consumption of a ton of coffee is higher than that of a ton of maize, the total green water consumption of Ethiopia's maize production exceeds the total green water consumption of the country's coffee production. As a result, the green water consumption of Ethiopia's agricultural sector is dominated by green water consumption from maize cultivation. In terms of their export value and associated virtual green water exports, however, coffee should make a bigger contribution than maize. It appears that Eora's native water environmental extensions do not account for this issue, leading to a distortion of the results.

Adverse effects of proportionality in EE-MRIO can be mitigated by

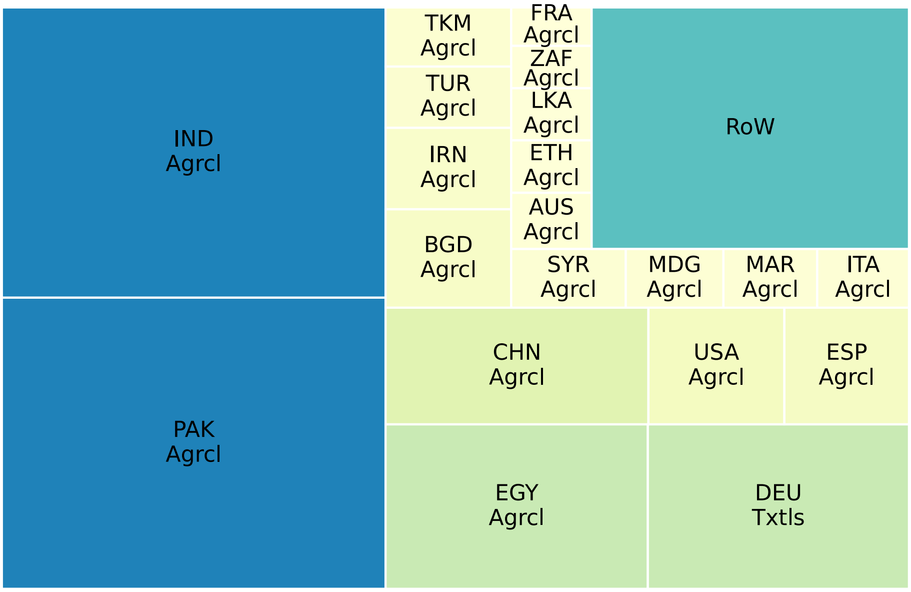

Fig. 7. Direct and indirect sectoral blue water contributions to consumption from the German “Textiles and Wearing Apparel” sector. The sectoral contributions in brackets are given in $Mm^3 \cdot year^{-1}$: PAK Agrcl: Pakistan Agriculture (34); IND Agrcl: India Agriculture (34); EGY Agrcl: Egypt Agriculture (13); DEU Txtls: Germany Textiles and Wearing Apparel (13); CHN Agrcl: China Agriculture (9); USA Agrcl: USA Agriculture (5); ESP Agrcl: Spain Agriculture (4); BGD Agrcl: Bangladesh Agriculture (4); IRN Agrcl: Iran Agriculture (3); TUR Agrcl: Turkey Agriculture (2); TKM Agrcl: Turkmenistan Agriculture (2); SYR Agrcl: Syria Agriculture (2); MDG Agrcl: Madagascar Agriculture (2); MAR Agrcl: Morocco Agriculture (2); ITA Agrcl: Italy Agriculture (2); AUS Agrcl: Australia Agriculture (1); ETH Agrcl: Ethiopia Agriculture (1); LKA Agrcl: Sri Lanka Agriculture (1); ZAF Agrcl: South Africa Agriculture (1); FRA Agrcl: France Agriculture (1); RoW: Rest of World (23).

increasing the sectoral resolution of a database. This view is shared by authors such as Feng et al. (2011), Lutter et al. (2016) and Flach et al. (2016). Exiobase 3 (Stadler et al., 2018) distinguishes between eight crop cultivation sectors, but covers fewer regions. However, global coverage was deemed crucial for the given *planetary-scale* analysis. Also, the *full* Eora database (Lenzen et al. 2012, 2013) distinguishes between more agricultural sectors for some countries, but its native water consumption environmental extensions require adjustment. Cabernard and Pfister (2021) published an EE-MRIO database with unprecedented sectoral resolution and global coverage recently, based on Eora and Exiobase; this database could potentially improve the results of the present study.

Finally, it should be noted that there are various types of limits to *sustainable* water consumption, e.g. environmental limits (e.g. volume, pollution), social limits (e.g. institutional limits to manage freshwater resources) and economic limits (e.g. costs associated with freshwater consumption or treatment). All of these limits interact which each other, and are crucial for ensuring a comprehensive assessment. However, only the consumption volume of blue water was considered in this study.

4.4. Analysing drivers for the exceedance of local safe operating spaces

Rather than investigating the drivers of the exceedance of local safe operating spaces beyond the national scale, this study focused on *where* in the world German blue water consumption is likely to contribute to the exceedance of the safe operating spaces of watersheds. However, drivers for worldwide blue water consumption could be further analysed by determining the initial origin of consumed blue water on a sectoral level induced by the final demand of a specific sector only (cf. Section 2.1.2). Fig. 7 shows the initial sectoral and regional origin of direct and indirect blue water contributions to the final demand of the sector *Germany – Textiles and Wearing Apparel*. The figure shows in which regions and from which sectors textiles and wearing apparel causes blue water consumption. Although this short example by no means provides an exhaustive analysis, it may encourage future water consumption studies.

5. Conclusions

This study had two main aims. First, it aimed to refute purported limitations for assessing the regional origin of water consumption in analyses based on EE-MRIO. Second, it sought to link the exceedance of the safe operating spaces of 8250 watersheds with Germany's consumption-induced blue water consumption.

To achieve these two key aims, Germany's worldwide consumption-induced blue water consumption was determined using EE-MRIO analysis and allocated to the world's watersheds. Subsequently, the watershed-level contributions to Germany's blue water consumption were weighted by the exceedance of local safe operating spaces of those watersheds.

The results indicate that approximately 15% of contributions to Germany's blue water footprint exceed the local safe operating space of the contributing watershed. If contributions to Germany's blue water consumption are weighted by the exceedance of local safe operating spaces, most contributions originate from countries with a low average income. These countries are often particularly challenged in terms of the sustainable management of their water resources. For future analyses, demonstration is given of an example on how the presented approach can be further refined, allocating the sectoral origin of contributions to a specific final demand.

Overall, the present study may provide guidance to policy-makers seeking to develop policies that alleviate the exceedance of safe operating spaces of watersheds and water scarcity induced by consumption in watersheds worldwide. However, the results must also be interpreted considering the limitations that are inherent in EE-MRIO and the environmental extensions for water that were applied.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Parts of this research were financed by the German Environment Agency (Umweltbundesamt) under FKZ 3719 31 201 0. The authors would like to thank Charlotte Bodenmüller from Technische Universität Berlin for her editorial remarks on the Methods section, Jan Minx from the Mercator Research Institute on Global Commons and Climate Change and Stephan Pfister from ETH Zurich for their advice on EE-MRIO analysis as well as Teresa Gehrs for proofreading of the submitted manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clrc.2021.100034.

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