A planetary boundary-based method to assess freshwater use at the global and local scales

Viktoras Kulionis and Stephan Pfister

Ecological Systems Design, Institute of Environmental Engineering, Department of Civil, Environmental and Geomatic Engineering, ETH Zürich, John-von-Neumann-Weg 9, CH-8093 Zürich, Switzerland

E-mail: viktoras.kulionis@gmail.com

Keywords: planetary boundaries, water, input output analysis, safe operating space, environmental assessment

Supplementary material for this article is available online

Abstract

Many studies have attempted to evaluate the transgression of the water planetary boundary at sub-global levels. Typically, this has been done by assessing water consumption in a country/city or sector against the assigned share of the global limit. Such an approach enables evaluating whether a sub-global unit operates within the safe global limits. However, it ignores spatial water availability and thus may provide an incomplete image of water-related environmental impacts and thus local boundaries. This study demonstrates how the water planetary boundary concept can be integrated within the Environmentally Extended Multi-Region Input-Output (EEMRIO) framework to assess global and local (watershed level) boundaries. Our results demonstrate that even though most countries operate within globally safe limits, for several countries, a large share of water comes from watersheds that have reached unsafe water consumption levels. This highlights the importance of combining local and global level assessments to design more accurate and tailored policy responses targeting specific watersheds that are most at risk.

The planetary boundaries (PB) framework defines boundaries for nine fundamental global processes that regulate the stability of the Earth system. In this respect, the PBs aim to jointly define a global ‘safe operating space’ in which human society can develop and thrive. For each PB, so-called ‘control variables’ proxies to measure whether they are transgressed globally have been defined (Rockström et al 2009, Steffen et al 2015). Climate change and biosphere integrity are considered ‘core’ boundaries based on their fundamental importance to the Earth System. Four of the nine PBs are currently transgressed due to human activity: Climate change, biosphere integrity, land system change, and biogeochemical flows (nutrients). Atmospheric aerosol loading has not been quantified yet, and discussions on including novel entities are ongoing (Persson et al 2022).

Not all Earth-system processes included in the PB framework have singular well-defined thresholds at the global level (Cornell 2012). Examples of such processes are land-system change, freshwater use, change in biosphere integrity, and changes in biogeochemical flows. For these processes (where sub-global dynamics potentially play a critical role in global dynamics), it is recommended to access a two-level set of control variables and boundaries at a global and sub-global level (Steffen et al 2015).

Previous efforts to translate planetary boundaries to local contexts have mainly adopted a fair shares approach and a local safe operating space approach (Zipper et al 2020). The fair shares approach calculates the maximum allowable local contribution to the global planetary boundary and quantifies the global responsibility (contribution) for a specific environmental pressure. The local safe operating space approach uses the principles of the planetary boundaries framework to define locally appropriate boundaries with strong local relevance but potentially weak Earth System relevance.

Global level planetary boundaries have been operationalized and accessed for countries (Nykvist et al 2013, Dao et al 2018, Lucas et al 2020), regions (EEA-FOEN 2020), cities (Hachaichi and Baouni 2020), and industries (Nathani et al 2019). Although the procedures are still evolving, common methodological elements are beginning to emerge (Häyhä et al 2018). For instance, it is common to assess the transgression of a specific global PB from...
both consumption and production perspectives using environmentally extended multi-region input-output (EEMRIO) models (e.g. Dao et al 2018, Lucas et al 2020). The production-based perspective accounts for impacts within a particular country/region. In contrast, the consumption-based perspective considers the global impacts due to the consumption of goods and services in a specific region (EEA 2013). Accounting for impacts in different countries has become particularly relevant with the recent rise of international fragmentation of production processes and the consequent explosion of trade in intermediate products (Dietzenbacher et al 2020).

The local level boundaries have received less attention, and the assessments are mainly based on the production perspective. For instance, Bjørn et al (2020a) evaluated the transgression of freshwater use concerning the local safe operating space in tomato production in 27 watersheds. Their study answers whether tomato production in 316 farms is within locally (watershed level) defined safe operating space. However, like with global boundaries, local-level impacts can be externalized via trade. For instance, a watershed in a specific country (or multiple countries) might experience severe water shortages because of tomatoes’ production destined for consumption in another country/region. In this study, we present an approach to evaluate the transgression of safe operating space (SOS) from a consumption perspective, which helps answer the question, ‘for whom are the tomatoes produced’.

A recent literature review by Bunsen et al (2021a) has shown that the application of EEMRIO within the planetary water boundary remains relatively unexplored. This is surprising given that the global EEMRIO databases typically cover the entire world economy and match the planetary boundaries framework’s spatial dimension. Bunsen et al (2021a) note that the lack of applications of the water planetary boundary concept within EEMRIO could be due to data limitations. In EEMRIO, data is typically provided on a national level rather than on a watershed level. Therefore, approaches need to scale national input-output data to a watershed level. However, it should be emphasized that while there is a lack of EEMRIO applications within the water planetary boundary framework, there is no lack of water studies within the EEMRIO framework in general. Early water studies within the input-output (IO) framework date back to Hartman (1965), who examined the usefulness of IO models for analysing regional water consumption and allocation. Duarte et al (2002) applied an IO model to assess water use in the Spanish economy, and Feng et al (2011) examined the difference between bottom-up and top-down approaches for calculating the water footprints of nations. Lenzen et al (2013) used the EEMRIO model to assess virtual water flows originating from regions of severe water scarcity. Holland et al (2015) linked the hydrological WaterGAP model with the EEMRIO model to examine pressures on freshwater resources associated with energy production across the global economy. At the same time, Lutter et al (2016) linked watershed level data to the EEMRIO model and tracked the distribution of water use along product supply chains for the European countries.

This study demonstrates how to integrate the water planetary boundary concept within the EEMRIO framework to assess global and local (watershed level) boundaries. Our study takes the approach outlined in Lutter et al (2016) and integrated by Cabernard et al (2019) as a starting point to connect EEMRIO to the water consumption at the watershed level. Several methods have identified the watershed level as a functional unit since it allows for the connection of upstream and downstream grid cells. It also has more robust global hydrological model results since calibration is often limited to discharge measurements at the river mouth or large tributaries (Zaitchik et al 2010, Scherer et al 2015). Additionally, environmental water flows are usually determined at a watershed scale (Richter et al 2012, Pastor et al 2014). Grid-cell water scarcity assessments exist (Scheve et al 2014, Scherer and Pfister 2016, Liu et al 2017). They lead to underestimation of water scarcity along with grid cells of major rivers where local water use is low compared to the river runoff (e.g. along the Nile), even if the watershed is highly water-stressed. We extend the EEMRIO analysis by deriving SOS (partially based on the work by Bjørn 2020 and Steffen et al 2015) for each watershed and calculate the share in ‘safe’ and ‘unsafe’ watersheds for all regions covered in the EXIOBASE database and provide a more detailed analysis for China, India, US, and EU27+ (+ means including UK, Norway, and Switzerland). More specifically, we aim to address the following aspects: (a) demonstrate how to link data at the sub-global unit, e.g. watershed, to economic activity; (b) assess freshwater use from different perspectives (consumption vs. production) and scales (global and local).

1. Methodology

The basic idea behind the IO analysis is that a national (or global) economy can be divided into many interlinked sectors whose relationships can be represented in a mathematical matrix (Leontief 1936). One of the key strengths of the IO framework is that it can be augmented with environmental and social accounts (usually referred to as satellite accounts or environmental extensions), which form an appropriate basis for analyzing environmental and broader sustainability impacts (Leontief 1970; Wiedmann et al 2011). Typically, environmental accounts are defined at the same sectoral and country (or sub-region, city) level as the underlying IO table. However, it is also
possible to link more detailed and spatially disaggregated data sources such as remote sensing data or satellite images, yielding what is known as spatially explicit IO analysis (Sun et al 2019).

In this study, we link spatially explicit data for water consumption at the watershed level to the EXIOBASE v3.8 data in the same way Lutter et al (2016) described: watersheds are weighted by specific water consumption within a country-sector combination to scale down country-sector water use to watersheds. This linking is motivated by the fact that the availability of water resources differs across different watersheds, and typically the watershed is considered the most appropriate level for water management measures (see, e.g. Pfister et al 2009, Bayart et al 2010). Water-related data comes from multiple sources: Pfister and Bayer (2014), Boulay et al (2018), and Pastor et al (2014) to quantify human water consumption (HWC), annual water flow (AWF), and Environmental Water Requirements (EWR) at the watershed level, respectively. The datasets provide information on water use at roughly 10 500 watersheds globally.

The general version of the EEMRIO model applied in this study can be expressed as:

\[ W^{CRA} = C \left( I - A \right)^{-1} Y + C \hat{W}_h = C \bar{S} \bar{L} + C \hat{W}_h \]  \hspace{1cm} (1)

where \( A \) is the technology matrix calculated by \( Z \bar{x}^{-1} \) (the \( \hat{\cdot} \) symbol denotes diagonalization), \( Z \) is the intermediate demand, \( \bar{x} \) is the vector of total outputs. The \( Y \) matrix represents final demands, \( L \) is the total requirement matrix (often known as the Leontief inverse) representing interdependencies between industries, \( I \) is the identity matrix, \( C \) is a mapping matrix (of appropriate dimension) that provides shares of water consumed in each watershed by region/sector combination, and \( s \) is blue water intensity (i.e. blue water consumption per C). Finally, \( \hat{W}_h \) denotes direct blue water consumption by households.

The matrix \( W^{CRA} \) denotes water consumption amounts in a given watershed due to the consumption of goods and services in a given country. In other words, it represents a blue water footprint for each country disaggregated by the watershed level. Water use from a production perspective is given by:

\[ W^{PRA} = C \bar{S} \bar{X} + C \hat{W}_h = C \bar{S} \bar{X} + C \hat{W}_h \]  \hspace{1cm} (2)

where \( W^{PRA} \) contains water consumption in a given watershed due to the production of goods and services in a given country. Note that matrix \( \bar{X} \) consist of stacked \( x \) column vectors, each contains total output for individual country with zeros elsewhere.

\( W^{CRA} \) and \( W^{PRA} \) provide information on the current environmental state (i.e. current water use for a specific country). However, they do not show if the water consumption of a given country is above or below the local and/or global limit. In order to capture these aspects, we need to compare the current water use to the assigned SOS. In the next step, we explain how we derive local and global SOS values for countries and industries (figure 1 provides more details on the procedure to derive and evaluate transgression of SOS applied in this study).

1.1. Deriving and allocating global safe operating space

There are multiple ways to allocate global SOS to the country level (e.g. Lucas et al 2020). Two commonly applied generic approaches are ‘grandfathering’ and ‘equity’ (also known as equal per capita allocation) (Bjørn et al 2020b). The grandfathering metric reflects the distribution of environmental impacts, and the equity metric reflects the population distribution. Raupach et al (2014) proposed a blended allocation approach based on a mix of more than one effort-sharing approach. In this study, we allocate global SOS under three allocation principles as follows:

\[ \text{SOS}_{r,GF}^{global} = \frac{ep_r}{EP} \times \text{SOS} \]  \hspace{1cm} (3)

where \( \text{SOS}_{r,GF}^{global} \) allocates global SOS for country \( r \) based on the grandfathering (GF) allocation principle. \( EP \) is the global population (i.e. global blue water consumption); \( ep_r \) denotes current blue water consumption for country \( r \).

\[ \text{SOS}_{r,EPC}^{global} = \frac{POP_r}{POP} \times \text{SOS} \]  \hspace{1cm} (4)

where \( \text{SOS}_{r,EPC}^{global} \) allocates allocated global SOS for country \( r \) based on the equal per capita (EPC) allocation principle; \( POP \) is the global population, and \( \text{POP}_r \) is the population for country \( r \).

\[ \text{SOS}_{r,RA}^{global} = \left( 1 - s \right) \frac{ep_r}{EP} + s \frac{POP_r}{POP} \times \text{SOS} \]  \hspace{1cm} (5)

where \( \text{SOS}_{r,RA}^{global} \) gives the safe operating space allocated to country \( r \) based on the blended approach (BA), which combines EPC and GF approaches; \( s \) is a weighting index ranging between 0 and 1. In our case, we set \( s = 0.5 \) (equal weight applied to EPC and GF). \( SOS \) in each allocation approach denotes a global boundary set to 4000 km$^2$ (Steffen et al 2015). \( \text{SOS}_{r,GF}^{global} \), \( \text{SOS}_{r,EPC}^{global} \), and \( \text{SOS}_{r,BA}^{global} \) is derived for both water consumption from a production and a consumption perspective, while for \( \text{SOS}_{r,EPC}^{global} \), both perspectives result in the same number.

1.2. Deriving safe operating space at the local (watershed) level

Global SOS does not capture the regional difference in water availability. For instance, consuming
1 m³ of water will have a different impact depending on the water availability in the region (Ridoutt and Pfister 2010). To capture these dynamics, we introduce local level SOS, which aims to capture regional differences in the water availability, enhancing recent work (e.g. Motoshita et al 2020, Bjørn et al 2020a, Bunsen et al 2021b). We express the SOS (including and excluding HWC) in relative terms as follows:

\[
SOS_{\text{local, incl HWC}}^k = \frac{(AWF_k - (HWC_k + EWR_k + e))}{AWF_k}
\]

incl. HWC

(6)

\[
SOS_{\text{local, excl HWC}}^k = \frac{(AWF_k - (EWR_k + e))}{AWF_k}
\]

excl. HWC

(7)

where \(AWF_k\) is the annual water flow at watershed \(k\), and it represents available water; HWC is human water consumption (water withdrawal that does not return into the watershed after use); \(EWR_k\) denotes annual Environmental Water Requirements, it can be understood as a fraction of water required to ensure ‘fair’ conditions of aquatic systems concerning pristine flow (i.e. flow without human intervention). We add the term \(e\) \((e = 0.15 \times AWF_k)\) to account for uncertainties associated with SOS calculations and ensure a precautionary value of SOS. The fundamental rationale for adding \(e\) is to reflect the variability in EWR estimates from different EWR methodologies (see SI material in Steffen et al (2015) for further discussions). EWR is based on Pastor et al (2014) and was taken from the AWARE methodology (Boulay et al 2018).

We classify each watershed into three categories: (a) safe, (b) increasing risk, and (c) unsafe, as shown in the table below.
The rationale for including and excluding HWC from the SOS definition is based on the idea that the safety of a watershed can be determined before and after human intervention. For instance, consider a watershed with $\text{AWF} = 100$ and $\text{EWR} = 40$. Such a watershed would be classified as 'safe' because $60\%$ of water remains available. Suppose that $\text{HWC} = 50$; this would imply that a watershed reached an unsafe limit as only $10\%$ of water remains available. Thus, including HWC provides ex-ante suggestions for reducing water use to avoid detrimental water-related impacts.

2. Results

Figure 2 displays AWF (figure 2(a)), EWR (figure 2(b)), and HWC (figure 2(c)). These components are needed to derive SOS at the watershed level. Figure 2(d) shows SOS (after environmental and human requirements have been met) at the watershed level normalized by annual water availability (i.e. AWF). Watersheds with higher water availability are shaded in blue and red, indicating watersheds where water consumption has reached unsustainable levels. Water availability is especially low in North Africa, the Middle East, India, the Mediterranean region, and the Western Coast of the United States. Figures 2(a) and (b) highlight varying hydrological regimes and characteristics in different parts of the world. For instance, the predominantly arid watersheds Tigris/Euphrates in West Asia, The Nile River basin in North-Eastern Africa display lower water availability and requirements than the rain and snowmelt-fed Rhine basin in West-Central Europe.

Figure 3 displays water consumption at the watershed level for India, China, the USA, and the EU27+ (it includes Norway, Switzerland, and the UK) from production- and consumption-based perspectives. Looking at the production-based perspective, we can identify watersheds with high/low water demand within a specific country/region. The consumption-based perspective identifies watersheds that experience high/low pressures on water resources in various regions due to consumption activities in a specific country/region (e.g. water use in China to produce rice destined for consumption in the EU27+). Water use from a production perspective is bound by region-specific borders, while the consumption perspective represents global water use.

It should be noted that high water use in a specific location is not a bad thing per se. Production of goods using water that originates from an abundant water region or a region with sound water management does little harm. However, one of the critical issues concerning water use is that it exceeds ecological thresholds in many places (Mekonnen and Hoekstra 2016), and a global boundary might be of limited
use (Ridoutt and Pfister 2010). Thus, it is essential to identify watersheds depleted due to unsustainable water use causing environmental damage from both a production and consumption-based perspective.

Bar charts in figure 3 display how much water in each watershed comes from ‘safe’ (>50% of water remaining), ‘increasing risk’ (50%–75% of water is remaining), and ‘unsafe’ watersheds (<25% of water remaining). These results indicate that the majority of water (>50%) comes from watersheds that fall under the ‘increasing risk’ category, and only a tiny fraction comes from watersheds that can be considered ‘safe’. Furthermore, for India and China, between 50%–70% of water comes from ‘unsafe’ watersheds (this applies to both consumption and production perspectives (based on the watershed classification that includes HWC). In contrast, for the EU27+ and the US, the share of water from ‘unsafe’ watersheds is between 16%–35%.

How do these results compare with the previous studies? For example, a recent report by EEA-FOEN (2020) estimated that the European freshwater use footprint amounted to 99.1 km$^3$ and the allocated share of global water limit based on the median value
of different allocation principles was 291 km$^3$ (this is equivalent to 7.3% of the yearly global limit of 4000 km$^3$). These results imply that the European water footprint is around three times under the limit and thus has not been overshot.

Our results presented in figure 4 support these findings but provide additional insights. We also find that the EU27+ footprint is roughly three times below the allocated global limit (actual footprint 99 km$^3$ vs. allocated limit 302 km$^3$, equivalent to 7.5% of the 4000 km$^3$ global limit). However, figure 4 also indicates that a large share of water comes from ‘increasing risk’ and ‘unsafe’ watersheds.

The results are also similar for other countries. One notable distinction is that there is little difference between a consumption or production perspective of water use for China, India, and the US (figure 4). On the other hand, for the EU27+, water consumption from a consumption perspective (99 km$^3$) is considerably higher than from a production perspective (42 km$^3$). Typically, differences are attributed to three factors: differences in the trade balance between countries, specialization (mix of export and import bundles), and different factor intensities (e.g. water use per unit of output) (Jakob and Marschinski 2013).

2.1. Sectoral impacts

Figure 5 displays water consumption by source sector (figures 5(a) and (b)) and sector of a final good/service (figures 5(c) and (d)). Most water is consumed for the cultivation of wheat (24% of the global total) and paddy rice (23%) and followed by the cultivation of vegetables, fruits and nuts (13%), sugar cane and beet (12%), other grains (9%) crops (8%) and seeds (6%). Overall crop production accounts for over 90% of global blue water consumption. Water consumption for wheat tends to come from watersheds reaching ‘unsafe’ water use levels (figure 5(b); bars incl. HWC).
Figure 5. Water consumption by source sector ((a) and (b) panels) and by sector of final good/service ((c) and (d) panels).

The final good perspective (presented in figures 5(c) and (d)) displays where water embodied in goods and services finally ends up. Processing of food products accounts for the largest share of impacts (15.1%), closely followed by the cultivation of wheat (13.5%) and paddy rice (12.1%). It is worth noting that the distribution of water use categories changes when we shift from the source sector perspective to the final good perspective. For instance, about 5% of water for the cultivation of wheat came from ‘safe’ watersheds (figure 5(b)), but the number drops to about 2% if we look at the final good perspective (figure 5(d)). This drop is because a large share of wheat was used as an input to further production processes in other sectors (e.g. food processing). Thus, part of the ‘safe’ water from wheat cultivation is now embodied in the food-processing sector. It also means that a higher share of unsafe water is further processed by another sector than directly consumed.

3. Discussion and conclusions

The Planetary Boundaries framework has received considerable attention in the last few years. Numerous studies have attempted to evaluate the transgression of the planetary water boundary at sub-global levels. Typically, this has been done by evaluating water use in a country or a specific sector against the assigned share of the global limit. However, such approaches often ignore spatial water availability or do not consider impacts on the entire value chain, which may lead to misguided policy suggestions.

To circumvent these issues, we use spatially explicit data on water availability and consumption in more than 10 000 watersheds, which we further classified into three ‘safety’ categories based on the water availability and consumption in each watershed. We connect this spatially explicit information to the GMRIO model, enabling us to track freshwater use through the entire value chain, from production to final consumption.

Our results demonstrate that most countries operate within the ‘safe’ limits (figures 4 and S1) when we evaluate their aggregate freshwater use, regardless of which allocations approach and accounting perspective (i.e. consumption vs. production) is applied. However, at the same time, we find that for some countries (e.g. China and India) and regions (Asia and Pacific, Middle East), a large share of
freshwater comes from watersheds that have reached ‘unsafe’ water levels. This highlights the need to combine regional and global assessments for addressing safe operation spaces for freshwater consumption since the global thresholds cannot account for the regional needs of humans and ecosystems.

These results have several important implications. First, water use in most arid and semi-arid countries/regions tends to have a more detrimental environmental impact. This can be alleviated by shifting production to more water-abundant areas within a country or replacing domestically produced goods with imports from countries in humid temperate latitudes. Second, water used for irrigation is typically lost to the industrial sector (i.e. it is not available to be used by industry). As a result, this puts water-stressed regions at a competitive disadvantage in non-agricultural production (Allan 1998).

International trade can help overcome issues associated with resource endowments (some countries are more water abundant than others) in arid and semi-arid countries by shifting food production to more water-abundant regions. However, this entails several challenges. First, labour and capital are not always easy to shift from one sector or region to another, and many water-scarce countries depend on the agricultural sector (Weinzettel and Pfister 2019). Second, orienting agricultural policy around imports and exports can displace critical national production with imports from countries in humid temperate latitudes. This may help overcome environmental issues associated with food production and mitigate some of the risks of food price volatility, extreme weather conditions, and long-term climate changes. Finally, other environmental impacts such as biodiversity loss due to land use should also be considered.

Lastly, spatially explicit methodology integrated into global supply chain assessments outlined in this paper helps design more accurate and tailored policy responses targeting specific watersheds, which helps tackle the global water planetary boundary. Policymakers and businesses can use such methodology and information to set ambitious targets and identify intervention points that require a swift response.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

We thank the Swiss Federal Office for the Environment (FOEN) for the financial support that allowed us to perform the presented research.

ORCID iDs

Viktoras Kulionis https://orcid.org/0000-0003-4908-5079
Stephan Pfister https://orcid.org/0000-0001-8984-2041

References

Allan J A 1998 Virtual water: an essential element in stabilizing the political economies of the Middle East Yale Univ. For. Environ. Stud. Bull. 103 141–9
Bayart J B, Bulle C, Deschênes L, Margni M, Pfister S, Vince F and Koehler A 2010 A framework for assessing off-stream freshwater use in LCA. The international J. Life Cycle Assess. 15 439–53
Bjørn A, Chandrakumar C, Boulay A M, Doka G, Fang K, Gondran N and McLaren S 2020b Review of life-cycle based methods for absolute environmental sustainability assessment and their applications Environ. Res. Lett. 15 083001
Bjørn A, Sim S, Boulay A M, King H, Clavreul J, Lam W Y and Margni M 2020a A planetary boundary-based method for freshwater use in life cycle assessment: development and application to a tomato production case study Ecol. Indic. 110 105865
Boulay A M, Bare J, Benini L, Berger M, Lathuilière M J, Manzardo A and Pfister S 2018 The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE) Int. J. Life Cycle Assess. 23 368–78
Bunsen J, Berger M and Finkbeiner M 2021a Planetary boundaries for water—a review Ecol. Indic. 121 107022
Bunsen J, Berger M, Ward H and Finkbeiner M 2021b Germany’s global water consumption under consideration of the local safe operating spaces of watersheds worldwide Clean. Responsible Consumption 3 100034
Cabenard L, Pfister S and Hellweg S 2019 A new method for analyzing sustainability performance of global supply chains and its application to material resources Sci. Total Environ. 684 164–77
Cornell S 2012 On the system properties of the planetary boundaries Ecol. Soc. 17
Dao H, Peduzzi P and Friot D 2018 National environmental limits and footprints based on the planetary boundaries framework: the case of Switzerland Glob. Environ. Change 52 49–57
Dietzenbacher E, Lahr M and Lenzen M 2020 Recent Developments in Input-Output Analysis (Edward Elgar Publishing) (available at: www.e-elgar.com/shop/gbp/recent-developments-in-input-output-analysis-9781786430809.html)
Duarte R, Sánchez-Chóliz J and Bielsa J 2002 Water use in the Spanish economy: an input–output approach Ecol. Econ. 43 71–85
EEA-FOEN 2020 Is Europe living within the limits of our planet? An assessment of Europe’s environmental footprints in relation to planetary boundaries Joint EEA/FOEN Report No 01/2020
EEA 2013 European Union CO2 emissions: different accounting perspectives EEA Technical Report No 20/2013
Feng K, Chapagain A, Suh S, Pfister S and Hubacek K 2011 Comparison of bottom-up and top-down approaches to calculating the water footprints of nations Ecol. Syst. Res. 23 371–85
Hachaichi M and Baouni T 2020 Downscaling the planetary boundaries (Pbs) framework to city scale-level: de-risking MENA region’s environment future Environ. Sustain. Indic. 5 100023
Hartman L M 1965 The input-output model and regional water management J. Farm Econ. 47 1583–91
