# Freshwater consumption and domestic water deprivation in LCIA: revisiting the characterization of human health impacts

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**Authors contributions**

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Laura Debarre. The first draft of the manuscript was written by Laura Debarre and Manuele Margni and Anne-Marie Boulay reviewed and edited previous versions of the manuscript. All authors read and approved the final manuscript.

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**Abstract**

***Purpose:*** An insufficient amount of available domestic water can lead to an increase in the occurrence of water-related diseases. No LCIA consensus has been reached on how to model the potential impacts on human health resulting from water use implying domestic water deprivation. Building on Boulay et al. (2011), this research work provides an updated and revisited characterization model and factors assessing the potential impact on human health induced along this impact pathway. ***Method:*** This work consolidates the cause effect chain linking water use to domestic impacts on human health. The revised fate factor aligns current water use assessment methods and includes information not only on the physical water scarcity but also on the level of population access to water in a region. Building on Boulay et al. (2011) the global effect factor is revised. The data source is updated, and a novel approach is developed estimating the domestic water deficit. Country scale exposure factors are updated, building on Boulay et al. (2011)'s proposal to rely on the gross national income per capita as a proxy for a country's capacity to adapt to water shortages. ***Results and discussion:*** Compared to Boulay et al. (2011), the revised fate and exposure factors show lower values as a result of different methodological choices and of the overall increase of GNI per capita, respectively. The revised value of the effect factor is equal to 3.13E-3DALY/m3 which compares to the value of 3.11E-3 in Boulay et al. (2011). Revised characterization factors (CF) range from 0 DALY/m3 (the potential impact on human health due to water use is null with respect to domestic water deprivation) to 3.13E-3 DALY/m3. The distribution of the new CFs shows an order of magnitude decrease compared to the previous model. These CFs assess the consequences on human health induced by water use leading to short-term water deprivation. ***Conclusion and recommendations:*** This research work helps to better account for the impacts of water use at the endpoint level. However, it underlines significant limitations in the current calculation of the effect factor, in particular regarding current quantification of domestic water deprivation. These shortcomings prevent the model from considering a difference in vulnerability to health damages from the deprivation of 1$m^3$ of domestic water. This research work argues for additional research efforts aimed at developing an alternative calculation method for this factor.



**Keywords**

Water use; Water consumption; Human Health, Domestic water; Water quantity; LCIA; Life cycle impact assessment; Life Cycle Assessment, LCA

# I. Introduction

## i. Water use, scarcity, sanitation, hygiene and health

Domestic freshwater is essential to human wellbeing and a minimum quantity is required to meet basic needs (drinking, cooking, hygiene and sanitation) and ensure fundamental health (Gleick 1996). An insufficient amount of domestic water can lead to an increase in the occurrence of water-related diseases (Fry et al. 2010; Nyemba et al. 2010; Mahande et al. 2012; Ketema et al. 2012; Stelmach and Clasen 2015). Prüss-Ustün et al. (2019) estimate that in 2016 alone, 1.6 million deaths and 105 million DALYs were attributable to quantifiable inadequate Water Sanitation and Hygiene (WASH).

Freshwater consumption can result in a long- or short-term change of water availability at a local scale. Depending on specific conditions such as water availability and water accessibility (where availability refers to the amount of water that could be used and accessibility is linked to the level and quality of the infrastructure allowing to benefit from it), this can lead to water shortages and users' deprivation and incapacity to fulfill their basic requirements.

## ii. Water management and life cycle thinking

Sustainable Development Goal 6 calls for actions at the local level in order to promote universal access to safe water and sanitation for all (United Nations 2015). While local actions and the development of water supply infrastructures are key, there is also a need to raise awareness among all stakeholders (consumers, industries, and decision-makers) on the indirect water use and its potential impacts along the value chain of consumed products and services (Hoekstra and Hung 2005). Life Cycle Assessment (LCA) is a relevant tool to map all activities along the product life cycle, and assess the potential impact generated by their interaction with the environment in terms of resource consumption and pollutant emission (ISO14040:2006). Applying the life cycle perspective is therefore useful to shed light on the indirect potential impacts due to water use, and this all along the value chain of products or services.

## iii. Human health impact of water use in Life Cycle Assessment

During the last decade, an increased interest was devoted in the assessment of water use in LCA (Bayart et al. 2010; Kounina et al. 2013; Boulay et al. 2015; Boulay et al. 2018; Núnez et al. 2018; Pradinaud, Núñez, et al. 2019a;Mikosch et al. 2021). Consensus building and harmonization efforts have resulted in the publication of the ISO 14046 norm on water footprinting (ISO 14046:2014), designed to guide the evaluation of the potential impact of water use within the life cycle assessment framework. Since, the water use assessment framework in LCA is continuously evolving. With the consensus-based life cycle impact assessment methodology AWARE (Boulay et al. 2018), the WULCA working group provides characterization factors for water use at a midpoint level.

(Bayart et al. 2010) define water consumption as the "use of freshwater when release into the original watershed does not occur because of evaporation, product integration, or discharge into different watersheds or the sea". To date, to address the domestic water consumption' health issues in LCA, practitioners can use one of the two developed methodologies: Boulay et al. (2011) and Motoshita, Itsubo, and Inaba (2011). The two approaches' results reveal large variation, and a low rank correlation (26% (Boulay et al. 2015)). In these methods, freshwater use is assessed as a concern for the Human Health Area of Protection (AoP), without regard to the freshwater deprivation duration.

Despite regular development efforts for a better assessment of water use, still no consensus exists on how to characterize endpoint impacts on human health due to water use involving domestic water deprivation resulting in inadequate WASH practices (hygiene, hand washing behaviors, food hygiene etc.). In 2015, a consensus was built to assess human health impacts due to water use involving agricultural water deprivation, but no recommendation was provided regarding the approach or indicator to use for domestic water deprivation (Frischknecht et al. 2016). Two main issues were identified: (i) "high uncertainty in modeling the causality chain linking additional water consumption to water scarcity and human health impacts" (Frischknecht et al. 2016) and (ii) the challenge of characterizing damage on human health linked to domestic water use patterns that are not explicitly monitored worldwide and depend on local conditions, on water access infrastructures, e.g. "the distance of the population to the next well"(Pfister et al. 2009) or on cultural habits such as lifestyle, religion and education (World Health Organization 2013).

To develop a characterization factor expressing water use impacts on domestic human health issues, Motoshita, Itsubo, and Inaba (2011) combine a water scarcity index developed by Pfister, Koehler, and Hellweg (2009), a ratio of domestic over total human water use from Aquastat (FAO), and a socioeconomic and effect factor built as a multiple regression analysis describing water accessibility and damages from infectious diseases (in DALYs/m3). Despite the relevance of the socioeconomic parameters integrated in the model, the resort to statistical tools such as the multiple regression used in Motoshita, Itsubo, and Inaba (2011) raises the issue of transparency and verifiability of the mechanism at the root of the potential impact.

Boulay et al. (2011) developed two modeling alternatives. The first one, the *distribution modeling*, considers that all users are competing and impacted by an additional water use proportionally to their distribution share of water. The second one, the *marginal modeling,* assumes that only marginal users (agricultural users), less willing to pay for water (compared to domestic or industrial users), would be impacted. Potential impacts on domestic users are thus neglected in this second modeling. Therefore, the focus here is put on the first modeling alternative.

Boulay et al. (2011) assume that the *use of freshwater* implies a *change in freshwater availability when the resource is scarce*. Freshwater can serve several users: ecosystems, industrial, agricultural or domestic users. We focus on the latter here. This change in availability could cause *domestic water shortage,* i.e. the incapacity to meet basic human water needs, which, in countries where the population is not able to adapt to water shortage, would lead to *domestic water deprivation*, resulting in inadequate hygiene and sanitation practices hence increasing the potential health effects.

The **characterization factor CF** of Boulay et al. (2011)'s results from the multiplication of a regionalized **fate factor FF** (to what extent will the use of $1m^3$ of water deprive other users?), a country-scaled **exposure factor XF** (to what extent will domestic users be impacted by this decrease in water availability and is the affected population able to adapt to water shortage?), and a generic global **effect factor EF** (what are the consequences of domestic water shortages on human health?)

Boulay et al. (2011)'s **fate factor** is calculated at a watershed scale on the basis of scarcity parameters, defined as the ratio of consumed water to renewable water. These parameters are used to calculate scarcity indicators using a logistic function (S-curve) to obtain values between 0 and 1 ($m^3$deprived / $m^3$consumed). The assumption that scarcity values follow a logistic relationship is "normative choice", while "little information is available" to support it (Boulay et al. 2018). Since this factor is defined as a ratio, a single value can represent two largely different realities: a value of 0.5 means that half of the available water is used by domestic users, but gives no information on the amount of water used, that could be 10 or 100000 $m^3$ (Boulay et al. 2018). This index is one of the several indices that have been developed to define water scarcity (Hoekstra and Chapagain 2007; Pfister et al. 2009; Berger and Finkbeiner 2010; Boulay et al. 2011). Recently, the WULCA working group developed a fate factor $FF_{agri}$, quantifying the "effect of the use of 1$m^3$ of water in a watershed on the change of water availability for agricultural use" (Jolliet et al. 2018).

Boulay et al. (2011)'s **exposure factor XF** combines information on water distribution across users (the fraction of current domestic water consumption over the total human water consumption (Di)), with a factor addressing the capacity of a country to adapt to water shortage ("Adaptation Capacity", AC). XF is calculated at the country scale as XF=Di*(1-AC). It assumes that the richer a country is, the more likely its population is able to adapt to water deprivation by compensation mechanisms (such as desalination). Low-income countries are considered unable to adapt and are thus fully impacted (AC=0). Adaptation capacity of middle-income countries is assumed to be linearly proportional to Gross National Income per capita (GNI), and maximal adaptation capacity is assumed for high income countries (AC=1). That classification of countries by income per capita evolves with time and should be updated.

Boulay et al. (2011)'s **effect factor** is defined as the geometric mean of the ratio between the yearly water-related burden of disease (WRBD) (in DALYs/yr) and the yearly domestic water deficit per country (DWD) ($m^3$/yr). The WRBD is calculated as the sum of the burden of diarrheal diseases and nematode infections and 50% of the burden due to malnutrition from the World Health Organization (2009). That share of burden of malnutrition is included based on the assumption that water-related practices can trigger malnutrition issues e.g. when parasites cause low absorption of calories. The DWD is calculated as the difference between the national domestic withdrawals and the minimum human water requirements of 50 liters per capita/day (l/c/d), recommended by the World Health Organization (Gleick 1996). To quantify the amount of deprived water, Boulay et al. (2011) consider an equal sharing of water resources among the population, defining domestic water use per capita as the ratio of total domestic water use divided by the population. However, water access and use are largely unequal across a country and an equal sharing does not provide a realistic picture of individuals' water consumption. Besides, the use of a global value for the effect factor implies that all individuals are suffering equally to the deprivation of 1$m^3$ of domestic water, regardless of the country they live in (once economic adaptation has been considered in XF). Still, considering the high level of disparity between countries in terms of healthcare access and quality, this assumption could be revised.

### iv. Objective of the project

Building on Boulay et al. (2011) this research aims to revisit the characterization model and factors of human health impacts through domestic water deprivation pathways due to water use in LCA. Specific objectives are:

1- Improve the description of the cause-effect chain linking water consumption, water scarcity, water deprivation and water-related burden of diseases.
2- Revisit intermediary models and factors (FF, XF, EF) and their spatial resolution for water consumption leading to domestic water deprivation, and provide revised characterization factors.
3- Discuss the relevance of modelling the human health impacts generated by water use and domestic water deprivation and define the limits of applicability of the model.

## II. Methods

### i. Characterization model and factors

The cause-effect chain of water consumption leading to domestic water deprivation and health damages is presented in Figure 1. It can be expressed as per equation 1 according to the general life cycle impact assessment framework (Rosenbaum et al. 2008).

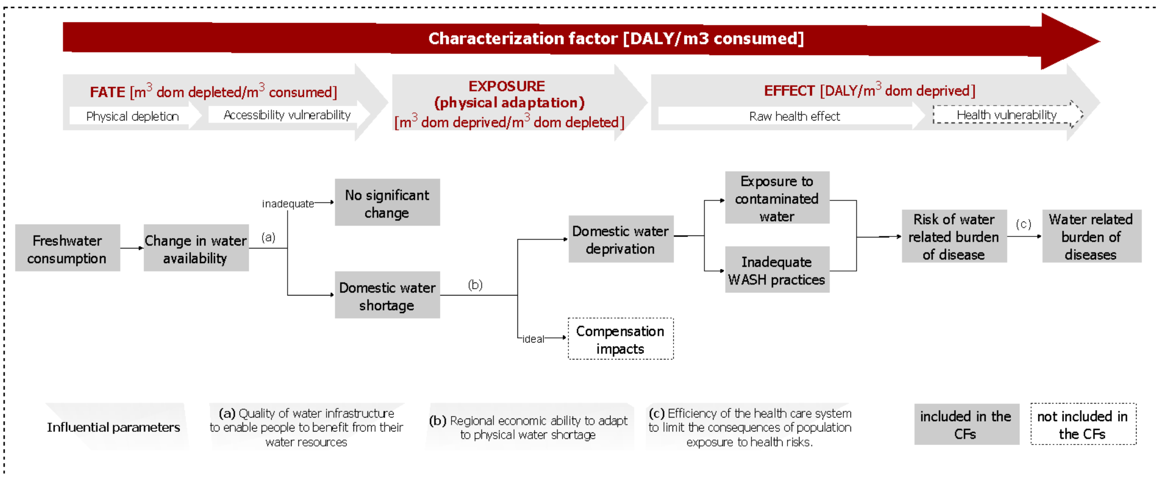


*Figure 1: Impact pathway of water-related burden of diseases from freshwater use and domestic deprivation (adapted from Boulay et al. (2011)).*

$$CF_{i,j} = FF_j \times XF_i \times EF \qquad \text{Eq1}$$

Where CF: characterization factor, FF: fate factor, XF: exposure factor, EF: effect factor. For river basin j, and country i. Below we describe how the fate and effect factors are revisited and the exposure factor is updated building on Boulay et al (2011).

A marginal freshwater water consumption can lead to a local change in water availability. Called "physical depletion", this mechanism is part of the fate factor of this model. A change in water availability is likely to induce additional domestic water shortage only if, in addition to the resource being limited (i.e. physical depletion), the level of local water infrastructure is sufficient for people to consume as much available domestic water as physically available (a., Figure 1). If a country has insufficient water infrastructure to allow its population to access its water resources, a reduced availability might not imply additional domestic water shortage. This feature is characterised as "accessibility vulnerability". When affluent, a country might be able to adapt to a physical domestic water shortage by sourcing water elsewhere or by using "back-up technologies" (Boulay et al. 2011) (b., Figure 1). At the expense of economic costs, this can limit domestic water deprivation, where the population suffers from a water consumption below the minimum needs. This situation may put populations at risk of water-related diseases, as described by the "raw health effect" of domestic water deprivation. Depending on the local "health vulnerability" defined by local features such as the quality of the health care system, the final health burden can vary (c., Figure 1).

### ii. Fate Factor

We develop a fate factor FF for domestic water scarcity in line with the WULCA working group's agricultural fate factor $FF_{agri}$ (Frischknecht et al. 2016; Jolliet et al. 2018). As per Eq2, this fate factor results from the multiplication of a generic scarcity index with the proportion of a particular user's water consumption (agricultural in $FF_{agri}$, domestic in $FF_{dom}$) compared to total human water consumption. The generic scarcity index is calculated as the ratio of human water consumption (HWC) to the remaining water after human uses, defined as the Availability Minus human water Consumption (AMC). The simplification of identical terms allows to define the FF as the ratio of domestic HWC to AMC.

$$FF_{dom} = \frac{HWC_{total}[m^3]}{AMC[m^3]} \times \frac{HWC_{dom}[m^3]}{HWC_{total}[m^3]} = \frac{HWC_{dom}[m^3]}{AMC[m^3]} \qquad \text{Eq2}$$

$$AMC[m^3] = Availability[m^3] - HWC_{total}[m^3] \qquad \text{Eq3}$$

The resulting fate factor is limited to an upper limit of 1 building on the model of Frischknecht et al. (2016). WaterGAP (Flörke et al. 2013; Müller Schmied et al. 2014) provides data for $HWC_{dom}$ and AMC at the watershed level.

**Physical depletion and accessibility vulnerability**

As described by the white arrows inside the fate factor in Figure 1, the domestic water deprivation induced by water consumption and quantified by the fate factor results from two mechanisms: *a physical depletion of water*, influenced by the quantity of available water resources, and an *accessibility vulnerability*, which determines the extent to which this physical depletion is likely to impact populations given their current level of access to water.

Human Water Consumption (HWC) represents current water use. It is calculated as the multiplication of a national or regional water use intensity (in $m^3.cap^{-1}yr^{-1}$, modeled through a sigmoid curve that increases with GDP per capita and is derived from historical data) with the population (Flörke et al. 2013). It therefore includes information on current water use quantities across different regions and on the level of water access and infrastructures.

A low fate factor can describe a situation in which the population does not suffer from water depletion since water availability and access are adequate, and water consumption is relatively low compared to water availability (low *physical depletion potential*). It can also express low water accessibility, that may lead to low water deprivation potential; if local resources are abundant but water infrastructure is insufficient to provide water to the population (*accessibility vulnerability* is low), this latter is likely to use small quantities of water. Since water accessibility is the limiting parameter for these households' water consumption, a marginal use of water may have no direct impact on them. Households would not have been able to benefit from the resource independently of this additional water use. This situation is reflected by an associated low value of $HWC_{dom}$, and possibly fate and characterization factors. The authors consider that this aspect of the fate factor can address the concerns raised and mentioned above regarding the feasibility of linking water use flows from the inventory to human health damages due to domestic water deprivation in LCIA (Frischknecht et al. 2016).

### iii. Exposure Factor

The exposure factor used in this model focuses on the ease with which a region can adapt to a physical depletion of domestic water. It follows a linear relationship with the Adaptation Capacity of a country (AC), as per Eq4. The thresholds used to classify the adaptation capacity of countries to water deprivation (previously based on UNEP (2009)) are updated according to the latest classification of GNI per capita (Atlas method current $US, (The World Bank)): low-income (GNI per capita <=1035$), middle income (1035< GNI per capita <12536$) and high-income countries (GNI per capita>=12536$). The adaptation capacity for low-income countries is zero, for high income countries 1 and for middle income countries, AC is calculated as per Eq5:

$$XF = 1 - AC \qquad \text{Eq4}$$

$$AC = (8.696 \times 10^{-5} \times GNI) - 9.009 \times 10^{-2} \qquad \text{Eq5}$$

The User's Distribution factor Di as a part of the exposure factor in Boulay et al. (2011) becomes unnecessary: the extent to which $1m^3$ use will deprive domestic users is here accounted for in the new fate factor via the ratio between human water consumption for domestic uses and the total human water consumption.

### iv. Effect Factor

As described via the arrows in figure 1, the effect of domestic water deprivation on human health stems from a *raw health effect* modulated by the *health vulnerability* of a region to this latter. This *raw health effect* is the mean of the consequences induced by human exposure to contaminated water and to inadequate WASH practices, while the *health vulnerability* adjusts this value based on socioeconomic parameters such as the quality and accessibility of the region's health care system. Although desirable, the developed EF factor does not capture this health vulnerability (see section Results). It is calculated as per Eq6, in accordance with Boulay et al. (2011).

$$EF = \frac{Water\ Related\ Burden\ of\ Disease, WRBD}{Domestic\ Water\ Deficit, DWD} \qquad \text{Eq6}$$

**Water-related Burden of diseases WRBD**

The *Subtotal drinking water, sanitation and hygiene* DALYs attributable to inadequate WAter, Sanitation and Hygiene (WASH) generated by Prüss-Ustün et al. (2019) for the year 2016 are used to quantify the Water-Related Burden of Disease (WRBD). The term "inadequate" includes unsafe water and insufficient access. The data accounts for the fraction of burden of diseases attributed to inadequate WASH for diarrhoeal diseases, soil-transmitted helminth infections, respiratory infections, protein-energy malnutrition, trachoma and schistosomiasis. Expressed in DALY per type of disease and per country, this data is in line with Verones et al. (2017)'s recommendations to "continue using DALYs in LCIA for human health". Differences are observed in the comparison between this data and the initial model: while Boulay et al. (2011) integrate 50% of the burden of disease of malnutrition, Prüss-Ustün et al. (2019) estimate that 20% is attributable to inadequate WASH. The complete comparison between the drinking water, sanitation and hygiene DALYs calculated by Prüss-Ustün et al. (2019) and the WRBD as calculated by Boulay et al. (2011) for 2016 data is presented in the Supplementary Information (SI).

**Domestic water deficit DWD**

The domestic water deficit is defined as the sum of all individual water deficits at the country scale. Individual water deficit occurs when the amount of water used (in liters per capita per day, l/c/d) is inferior to the *basic human water requirements* (BHWR), defined as 50l/c/d (Gleick, 1996). This minimum quantity is still recognized by the World Health Organization (WHO 2017).

To address the issue of water consumption inequality and quantify domestic water use -and domestic water deficit- we use the notion of access to private connection. Only a fraction of the population within a country has access to water supply on premises ($FP_i$) and their water consumption is generally higher compared to the population without access. This difference can vary between a factor 1.2 and 7, as found in the literature (Larson et al. 2006; Brown et al. 2013; Nunoo et al. 2018). A sensitivity analysis of values of p varying between 1 and 7 was carried out and the value of 6.3 was defined as the most representative of water use quantity inequality, based on Larson and Razafindralambo (2006). (see SI). Correlation is strong between the water-related DALY values per capita and the percentage of the population with access to water on premises (inversely proportional with $R^2 = 0.68$, see SI), supporting the integration of this indicator in our calculations.

Considering that the total domestic water use in a country is the sum of domestic water use (DWU) of households with and without access on premises (respectively called Population With Access on Premises, PWAP and Population without Access on Premises, PwtAP and both expressed in percentage of total population) [Eq7], and that the former uses a quantity of water greater by a factor p than the latter [Eq8], we have:

$$DWU\ [m3/cap] = PWAP\ \times DWU_{PWAP} + PWtAP \times DWU_{PWtAP} \qquad \text{Eq7}$$

$$DWU_{PWAP}[m3/cap] = p \times DWU_{PwtAP}\ [m3/cap] \qquad \text{Eq8}$$

$$DWU_{PwtAP}[m3/cap] = \frac{DWU[m3]}{p \times PWAP + PWtAP} \qquad \text{Eq9}$$

The **total domestic water deficit (DWD)** is calculated at the country scale as the sum of the domestic water deficit of the population with access to water on premises (PWAP) plus the domestic water deficit of the population without access to water on premises (PWtAP) as per Eq10:

$$DWD\left[m3_{deprived}\ \right] = \sum_{i\ =\ PWAP,\ \ PWtAP} (BHWR - DWU_i)\left[\frac{m3\ deprived}{cap}\right] \times FP_i[\emptyset]\ \times Pop[cap] \qquad \text{Eq10}$$

Where BHWR stands for Basic Human Water Requirements (50l/c/d), DWUi for Domestic Water Use of population i, FPi for Fraction of the Population i (with or without access to water on premise) and Pop for the total population in the country.

The total domestic water use (DWU) is estimated with the “municipal withdrawals” from Aquastat (FAO).

The percentages of the population with access to water on premises were provided from Prüss-Ustün et al. (2019) for the year 2016.

The results of this study are compared to a "general" version of Boulay et al. (2011)'s model. This latter differs slightly from the published model as it excludes quality and source-specific aspects, making it comparable to our model. (see SI for additional information).

## III. Results

### i. Fate Factor

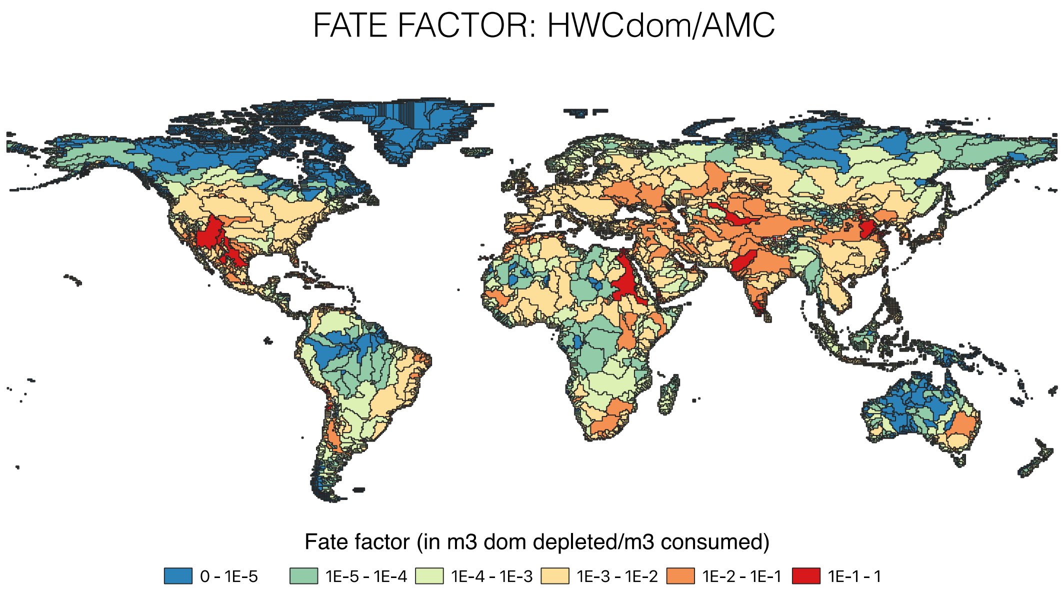


*Figure 2: Revised fate factors [m$^3$dom depleted/m$^3$ consumed]. Lower (respectively higher) values appear in blue (red). These fate factors account for areas where the potential domestic water deprivation caused by an incremental use of water from the current situation is low (respectively high).*

The revisited fate factor is calculated for 12013 cells accounting for the river basin level (with the 34 world's largest river basins being divided into sub-basins). High fate factors (red cells with FF ranging between 0.1 and 1 m$^3$ domestic depleted water per m$^3$ of water used) in Figure 2 account for high physical water depletion potential in areas such as the Nile valley, California, Nevada or Arizona. In low population areas such as central Australia, northern Canada, the Amazon rainforest, northern Russia or Saharan Africa, low fate factors can be explained by low water demand. Low fate factors can also be explained by low accessibility vulnerability. For instance, the Democratic Republic of the Congo (DRC) (where FF values are as low as 2.79E-7) is endowed with important freshwater resources, but governance choices and underinvestment in the water sector and infrastructures have seriously affected the population's water access (UNEP 2011). DRC's mean fate factor (currently equal to 9.4E-5 m3 deprived/m$^3$ consumed) would reach 7.0E-3 if the country's population could use 50lpcd, and 1.4E-2 if it could use 100lpcd. Details on the results of HWCtotal/AMC and HWCdom/HWCtot ratios are presented in the SI.

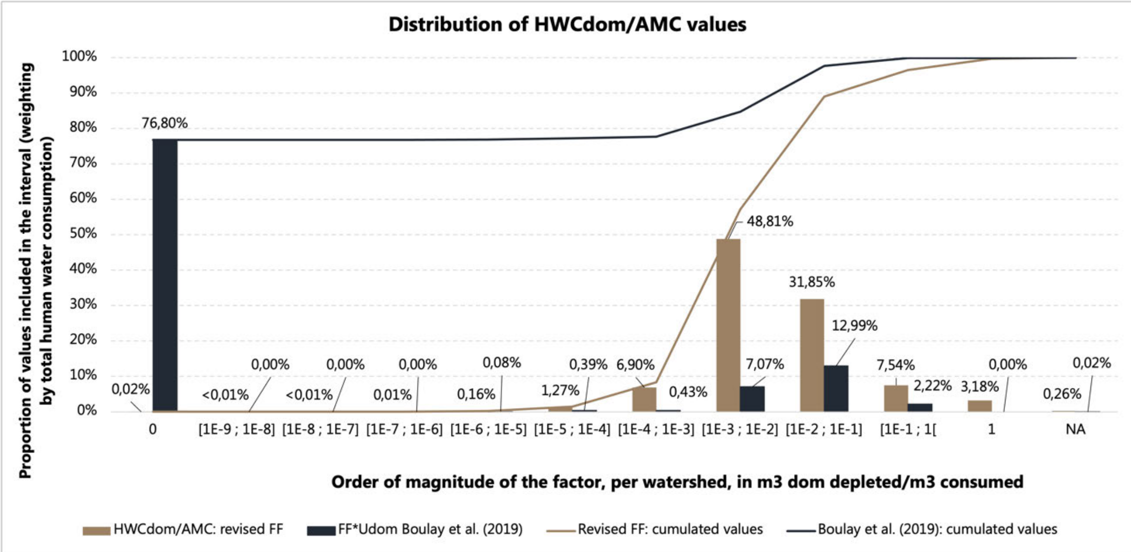


***Figure 3 : Water-use weighted distributions of fate factors in this model and in Boulay et al. (2011). The distribution is based on the factors' order of magnitude. To make the factors comparable, the revised fate factors are compared to the combination of Boulay et al. (2011)'s fate factors with the proportion of water use by domestic users (initially included in the XF in Boulay et al. (2011). For the revised (respectively Boulay et al. (2011)'s) model, brown (respectively dark blue) bars represent the percentage of total water use whose fate factors are included in corresponding intervals (expressed in m$^3$ depleted/m$^3$ consumed). Solid lines represent the cumulative distribution for each model. NA values account for missing values. The choice of a "general" version of Boulay et al. (2011)'s model as a reference for comparison can explain the large number of zero values.***

Figure 3 illustrates the water-use weighted distribution of fate factors in this model and in Boulay et al. (2019). 95% of revised fate factors are included between 1E-4 and 1 m$^3$ dom depleted/m$^3$ consumed. Respectively, 95% of Boulay et al. (2019)'s non-zero values are included between 1E-3 and 1 m$^3$ dom depleted/m$^3$ consumed. Overall, the distribution curve of non-zero factors shows a larger distribution and is shifted to the left by about one order of magnitude in the revised model compared to the previous one. Additional results are presented in the SI.

### ii. Exposure Factor

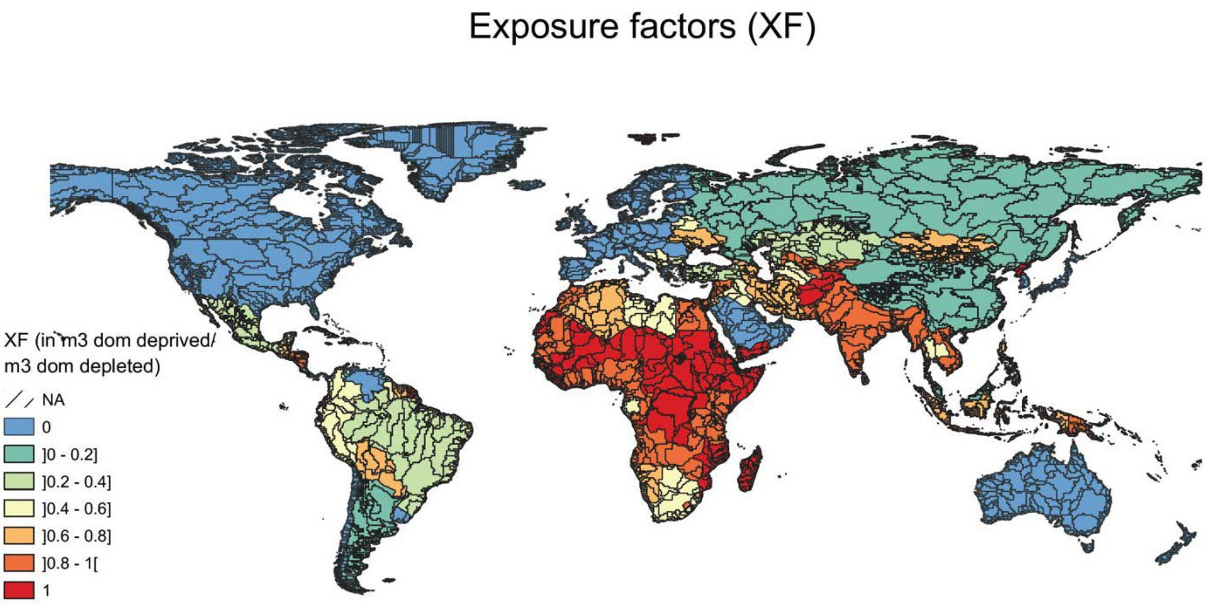


*Figure 4: Graphical distribution of the updated exposure factors (in m3 dom deprived/m3 dom depleted). Building on Boulay et al. (2011), high value exposure factors are representative of countries that encounter difficulties to adapt to water shortage*

Figure 4 provides a visual representation of the geographical distribution of exposure factors. Additional information on this distribution is presented in the SI. Blue, high-income countries can adapt to domestic water depletion (XF=0 and no domestic water deprivation) while red, low-income countries are fully impacted and 1m$^3$ domestic water depletion implies 1m$^3$ domestic water deprivation (XF=1).

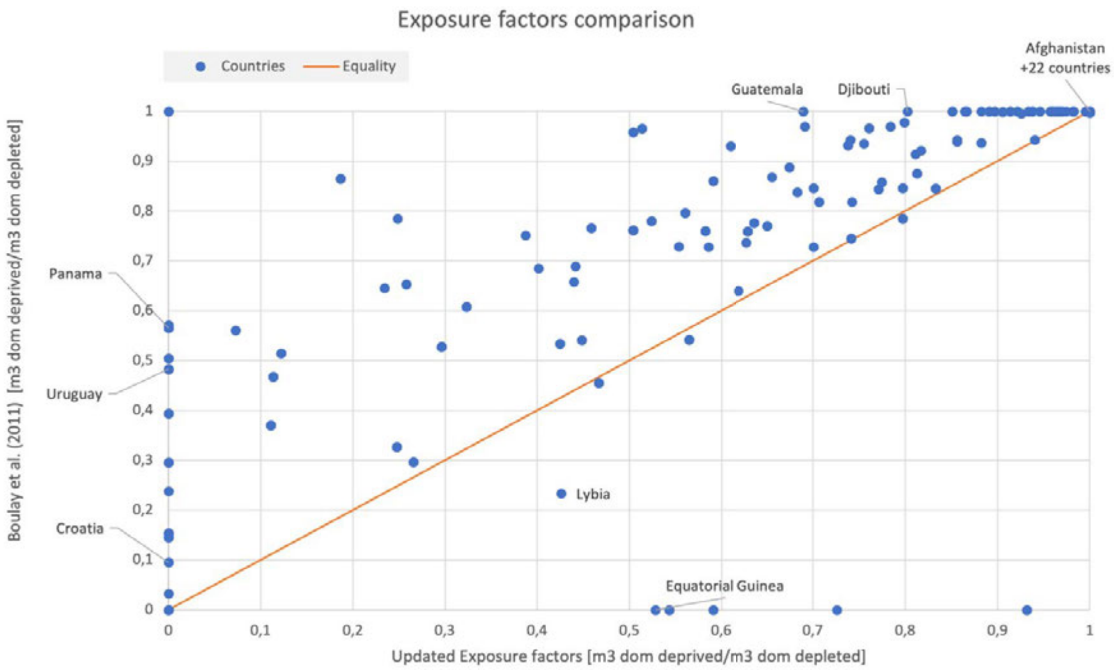

*Figure 5: Comparison of the exposure factors calculated in Boulay et al. (2011) and this revised model. For comparison compatibility purpose, the revised exposure factors are compared with Boulay et al. (2011)'s exposure factors to which the proportion of water use by domestic users has been deducted. Each point corresponds to the exposure factor of a country in the revised model (abscise) and in the original Boulay et al. (2011) model (ordinate) in m3 dom deprived/m3 dom depleted. The orange line represents equality between both models.*

Figure 5 shows the variation between Boulay et al. (2011)'s and the updated exposure factors. Of the 209 values calculated by Boulay et al. (2011), 84 remain identical (XF =0 in 61 countries, XF=1 in 23 countries). Most points are located above the line, showing a tendency of decreased exposure factors in the updated model. Accordingly, 27 countries are no longer considered unable to adapt, with exposure factors evolving from 1 to inferior values (e.g., Guatemala, Djibouti, Papua New Guinea or Vietnam). This is consistent with the reduction of low-income economies from the year 2009 (reference year of Boulay et al (2011)) to 2019 (present study), i.e countries in which the GNI per capita is below the threshold of 1035$ in 2019 (936$ in 2007) defined by the World Bank countries classification. Points on the Y-axis (updated exposure factors=0 vs. Boulay et al. (2011) ≠0) describe countries whose economic group has changed and are no longer likely to suffer from domestic water shortage (e.g., Mauritius, Panama, Romania, Uruguay or Venezuela). Libya, which has suffered instability since its civil war in 2011, is one of the 8 countries whose exposure factor has increased since the calculations of Boulay et al (2011) (from 0.23 to 0.43 $m^3$deprived/$m^3$depleted). Similarly, Equatorial Guinea's change of economic group from high to upper middle-income country between 2009 and 2019 explains the important change of its exposure factor (from 0 to 0.53).

### iii. Effect Factor

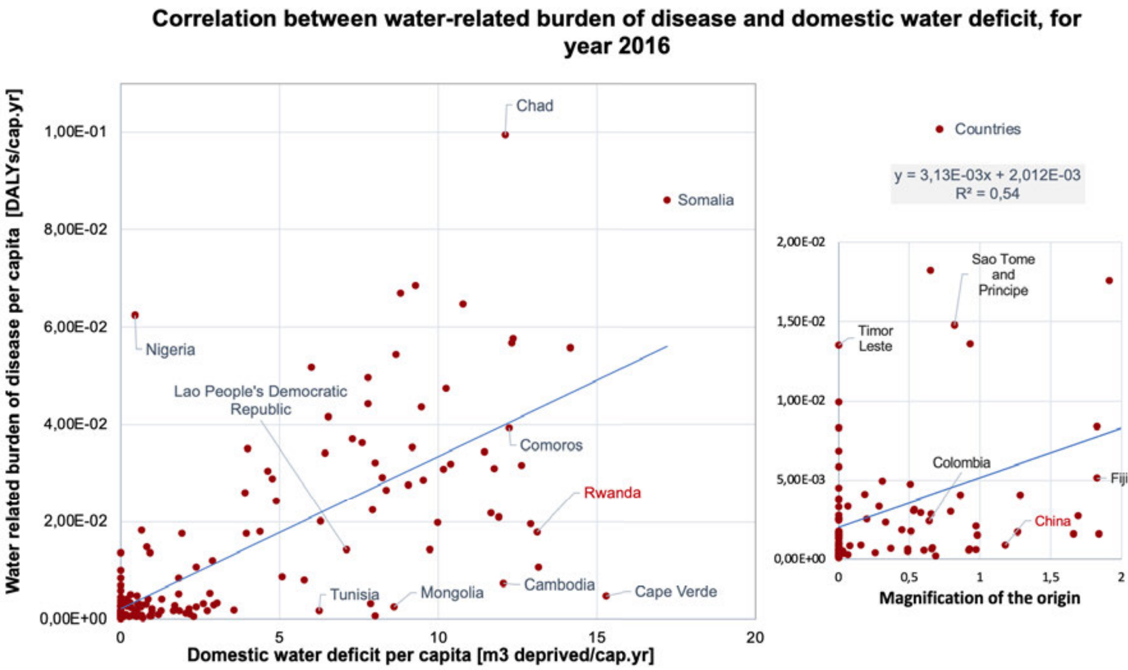


*Figure 6: Correlation between domestic water deficit (x) and water-related burden of disease (y), for the year 2016. Blue points refer to countries. The continuous blue line is the linear regression between all points. The slope of the*

*latter defines the global effect factor, expressed in DALYs/m3 deprived.*

Figure 6 shows the correlation between the domestic water deficit and the water-related burden of diseases (R2=0,59). The slope of the linear regression can be considered as the mean effect of water deprivation on human health, which has been called the “raw health effect”. Vertical distance of points to the linear regression accounts for the local “health vulnerability”, assessing the variability of health damage intensity due to water deprivation among countries.

Defining country-scale effect factors as the ratio of the WRBD and the domestic water deficit for each country would allow to capture this local health vulnerability. Different country features (health care system, education, cultural habits or climate) might influence the health consequences of an identical value of domestic water deficit. For instance, Chad and Comoros both suffer from a 1,2E+1 $m^3$ domestic water deficit per capita (Figure 6), but the amount of DALYs related to water diseases per capita is 2.5 times superior in Chad (9.93E-2 vs 3.94E-2 in Comoros). Lower Human Development index (HDI) and Gross National income (GNI) per capita, along with fewer expected years of schooling in Chad than in Comoros (United Nations Development Programme) may explain this gap. Similarly, Nigeria and the Islamic Republic of Iran suffer from a 4.5E-1 $m^3$ deficit per capita, while Nigeria’s amount of water-related DALYs is 34 times higher. The same trend between the two countries can be observed regarding the HDI, GNI and expected years of schooling (lower in Nigeria). A single value of country-scale effect factors can describe two different realities: while the ratio between the water-related burden of diseases and the domestic water deficit is the same for the Democratic Republic of Congo and Malaysia (4.67E-3), the numerators and denominators of these ratios are largely different, and so are socio-economic factors of the countries.

Important limitations in this calculation must be highlighted. Country-scale effect factors are highly sensitive to small changes of the numerator or denominator. This is especially true for small values. Although the work of Prüss-Ustün et al. (2019) has reduced uncertainty about the number of DALYs attributable to water-related diseases, the quantification of water deficit, necessary to calculate the effect factor, remains largely uncertain (See Discussion). These flaws can explain some unlikely country-wide EF values (e.g. Switzerland, EF=7.69E+2 DALY/$m^3$ deprived) and the unlikely difference between different values (up to 7 orders of magnitude).

To rule out absurd country scale effect factor values influenced by the high uncertainty of the water deficit data, it was decided not to discriminate between countries and only use a global value at this point. The effect factor is therefore defined as the slope of the linear regression and equal to 3.13E-3 DALYs/$m^3$ deprived, which compares to the value of 3.11E-3 in Boulay et al. (2011).

### iv. Characterization Factor

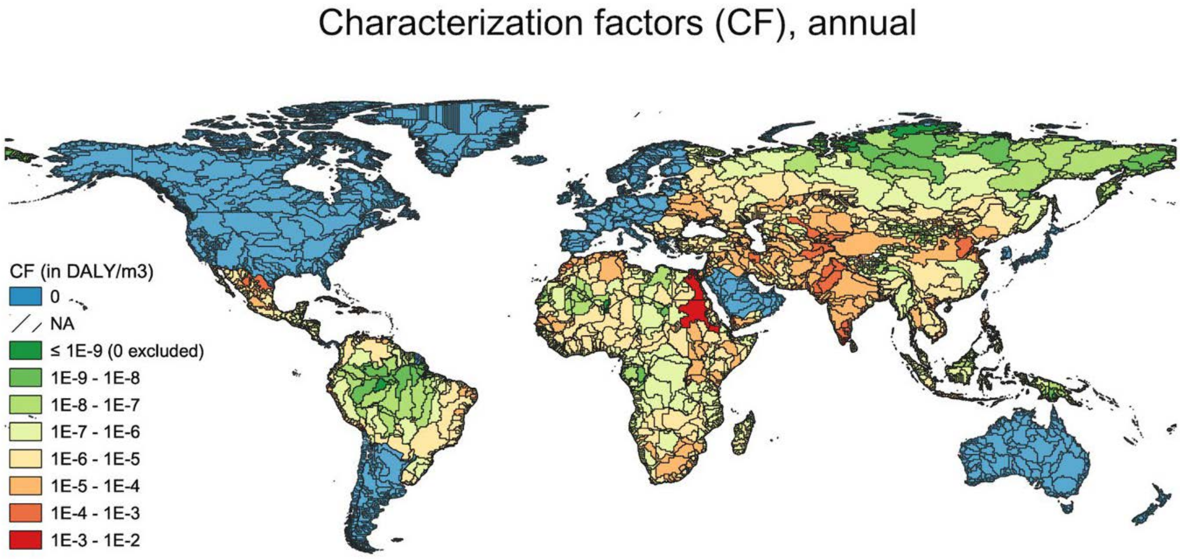


*Figure 7: Spatial distribution of the updated characterization factors (in DALY/m$^3$ consumed)*

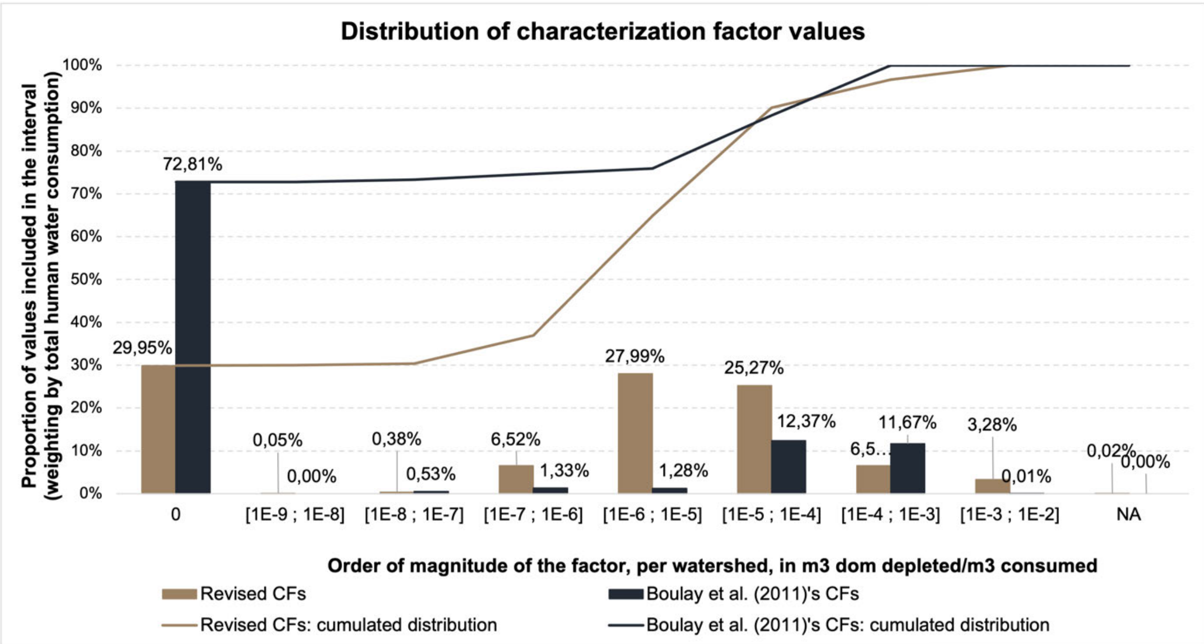


*Figure 8: Water-use weighted distributions of revised (in brown) and of Boulay et al. (2011)'s (in dark blue) CF values (annual, in DALY/m3 consumed).*

Characterization factors are calculated for 17931 cells (unavailable data for 178 cells). Water-use weighted distributions of revised (in brown) and of Boulay et al. (2011)'s CFs are represented in Figure 8. 8487 revised characterization factors are equal to zero, accounting for 29.95% of the total annual human water consumption (Figure 8). Characterization factors range from 0 DALY/m$^3$ (the potential impact on human health due to water use is null with respect to domestic water deprivation) to 3.13E-3 DALY/m$^3$. The highest values are observed in Ethiopia, Sudan and Eritrea (3.13E-3), Senegal (3.02E-3) and Egypt (2.98E-3). Maximal (=1) fate and exposure factors in Eritrea, Sudan and Ethiopia explain these high CFs. In Senegal and Egypt, exposure factors are high (>0.95) and paired with maximal fate factors (=1). Relatively low values do not necessarily express the absence of water-related health issues or of water stress but describe the lower potential health damages caused by an incremental use of water from the current situation.

For instance, Southern Algeria CFs are low (4.1E-10 to 8.6E-07 DALY/$m^3$) because of low fate factors related to low domestic water consumption. This low water consumption can be explained by a low population density, characteristic of the Saharan desert. Low CFs can also be observed in the Democratic Republic of the Congo, where the exposure factor is maximal (=1), but low fate factors driven by low water use result in low CFs. Country scale CFs were calculated by weighting the factors by water use and are presented in the SI, along with an additional comparison with Boulay et al. (2011)'s results.

## IV. Discussion

### i. Applicability limits

This impact model relies on current water use and water availability data as provided by WaterGAP (Flörke et al. 2013); it provides no insight on long-term trends. In line with Pradinaud et al (2019)'s recommendations, we consider that the CFs developed in this work assess the consequences on human health induced by water use leading to short-term water deprivation.

### ii. Revised intermediary factors

**Fate**

Domestic water use is hardly monitored worldwide and is here based on WaterGAP data. WaterGAP data was used in the calculation of the fate factor since offering consistency with current LCA water use assessment practices. It provides high geographical resolution (watershed), which presents interest since "national-level withdrawals information dilutes the usability of technical information as the country average value is not necessarily representative of any specific region in a country" (FAO 2011). Nonetheless, it does not provide an exact picture of domestic water use since it does not provide insights on how water use is unevenly distributed among the population. WaterGAP defines the *domestic water sector* as "household use, small businesses and other municipal uses, which take high quality water directly from the municipal pipelines when it is available" (Alcamo et al. 2003). Data disaggregation to focus on households' water use solely is not possible.

**Exposure**

Water access issues are complex and can not be assessed by economic parameters only. While the ISO 14044 norm describes environmental mechanisms as "systems of physical, chemical and biological processes", socioeconomic, geographical, cultural or political characteristics have to be taken into account to fully understand the mechanisms leading to potential water use impacts. Governance, political or investment choices have an important influence on the quality of water access within a country (The Lancet 2014).

**Effect**

Several limitations must be underlined in the calculation of the effect factor, whether it is about the numerator (WRBD) or denominator (DWD) of this ratio.

WRBD:

Boulay et al (2011) calculate the WRBD as the sum of the burden of diarrheal diseases and 50% of the burden due to malnutrition. Prüss-Ustün et al. (2019) provide updated estimates of the burden of diseases due to exposure to inadequate drinking-water, sanitation, and hygiene behaviours. These latter estimates are 25% lower compared to Boulay et al. (2011)'s calculations (see SI) and are used in this work to strengthen the quantification of the WRBD. Nonetheless the WRBD provided by both avenues results from the contribution of more than the sole lack of domestic water use. While sparse epidemiological works point out the links between restrictions in water quantities and water-related health issues, a majority of studies link water related diseases to flooding, heavy rainfalls or temperature (Levy et al. 2016; Wang et al. 2018). In this work we define the WRBD as the subset of water related diseases provided by Prüss-Ustün et al. (2019) linked with *drinking-water, sanitation, and hygiene*. This excludes the burden of diseases of *malaria*, which is linked to water resource management (e.g. elimination of stagnant water) rather than to water quantity. Nonetheless, additional efforts to identify the burden exclusively linked to water shortage are needed since current values are likely to still be overestimated.

Domestic Water Deficit:

The basic human water requirements and the domestic water use are both highly uncertain.

*Basic Human Water Requirement:* The value of basic human water requirements of 50l/c/d, although recommended by the World Health Organization, is still debatable. According to Chenoweth (2008), 50l/c/d allow most of hygiene requirements to be met but 100l/c/d are needed to cover them all. Accordingly, the World Health Organization (Howard and Bartram 2003) and the United Nations Development Program (Watkins 2006) recommend a range of 50 to 100l/c/d of water to be piped into households for human development and to maintain adequate health. Human basic water requirements largely depend on characteristics such as standard of living, lifestyle, physical conditions, culture and/or climate. Well-off and urban households are likely to own more water-consuming appliances (lavatories, dishwashers, washing machines etc.) and a minimum of 50l would be insufficient for these households. Therefore, global economic development and urbanization could shake the current consensus about this value. The debate is far from being closed and some consider that the "effective use of water for hygiene purposes is more important than the quantity used" (Chenoweth 2008).

A rise of the value of the minimum water requirement would increase the domestic water deficit, leading to a decrease of the effect and characterization factor (cf. sensibility analysis in the SI).

*Domestic water use:*

For country-scale effect factors, Aquastat's country scale "municipal withdrawals" data was preferred as a proxy for domestic water use since no higher geographical resolution was needed. Aquastat's "municipal withdrawals" represent water provided by public network means. They supply households but also other urban services (stores, markets, tourism centers, urban industry). The level of detail is insufficient to allow disaggregation of the values (FAO 2011). Aquastat's definition for municipal withdrawal does not clearly include or exclude informal water collection such as rainwater harvesting. Consequently, each country could either include it into its reporting or not (Gillet 2020). In practice, few countries monitor such data. This is only the result of individual initiatives that are difficult to monitor, in particular in developing countries where consumption patterns have not been well documented and investigated (Hussien et al. 2016).

In general, assumptions and estimates have to be made to fill the gap of water consumption data (Cole et al. 2018). Accessibility is often used as a proxy for quantity but the "relationship between accessibility and the quantity of water collected and available for consumption in low and middle-income settings remains as an important literature gap" (Cassivi et al. 2019).

Water access inequalities are not similar to income inequalities (Berthe 2016) and many characteristics can explain variations in terms of water use quantity: location, education, wealth, age, gender, ethnicity, electricity access, water collection time or the number of adult female members in the households (Hussien et al. 2016; Abubakar 2019). Water access and the proportion of water used by households with and without private access appeared to be the most suitable proxy for water use quantification at this stage. We introduced the concept of a factor p to account for water quantity inequalities between households with and without a private connection to water supply (p being the fraction of the domestic water use of the population within a country that has access to water supply on premises vs. the domestic water use of the population without access). However this is still insufficient to picture the extent of water use inequalities and to provide a robust enough domestic water use profile. The extent of quantity inequalities (factor p) can not be generalized among all countries and regions, and there is little evidence of the most suitable value to choose according to the studied region. Nonetheless, a change in this value showed to have no significant influence on the global value of the effect factor (see SI).

These shortcomings in the estimation of water needs and consumption lead to significant uncertainty in the calculation of the domestic water deficit. This uncertainty is reflected in the effect factor for which a country-wide distinction does not seem feasible at this stage.

## V. Conclusions and recommendations

In response to the lack of consensus on the best LCIA practice to characterize the domestic impacts on human health induced by water use, this research work provides updated and operationalizable factors to better account for the impacts of water use at the endpoint level. Building on Boulay et al. (2011), we consolidate the cause effect chain linking water consumption to domestic impacts on human health, and we provide revised characterization factors ranging from 0 to 3.11E-3 DALY/m3 consumed.

We updated and revisited intermediary factors and highlighted a need for additional refinements.

Fate factors have been adapted in line with current water assessment methods. Called *water deprivation potential,* they build on local circumstances and combine notions of *physical water depletion* potential and *accessibility vulnerability* to water shortage. Identifying the level of water infrastructures as a key parameter in populations' likelihood to suffer from water deprivation, this factor contributes to the consolidation of the cause effect chain and supports the integration of human health impacts due to domestic water deprivation into water use assessment.

The choice of the GNI per capita as a proxy to assess the capacity of a region to adapt to physical water shortage within the exposure factor could be revised by considering other socio-economical parameters such as the economic component of the Inequality-Adjusted Human Development Index. This latter indicator is used in the AC to agricultural water deprivation in Frischknecht et al. (2016).

Current modeling of the effect factor still fails to capture the share of water-related burden of diseases that can be directly linked to water shortage. Nor does it allow a realistic evaluation of domestic water deficit. This latter flaw induces a regrettable loss of information on local health vulnerability to water deprivation. We therefore argue for additional research efforts to develop an alternative method for calculating the effect factor.

## VI. Data availability

Data generated and analysed in this study are included in the article and its supplementary information files.

GIS files can be shared on request.

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## IX. Ethics declaration

The authors declare no competing interests.