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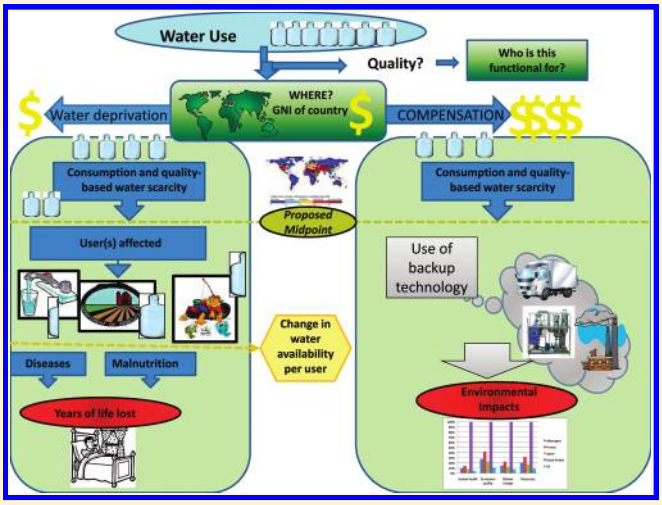
Regional Characterization of Freshwater Use in LCA: Modeling Direct Impacts on Human Health

Anne-Marie Boulay,*,† Cécile Bulle,† Jean-Baptiste Bayart,‡ Louise Deschênes,† and Manuele Margni†

†CIRAIG, Department of Chemical Engineering, École Polytechnique de Montréal (QC), P.O. Box 6079, Canada H3C 3A7
‡Veolia Environnement, Paris

Supporting Information

ABSTRACT: Life cycle assessment (LCA) is a methodology that quantifies potential environmental impacts for comparative purposes in a decision-making context. While potential environmental impacts from pollutant emissions into water are characterized in LCA, impacts from water unavailability are not yet fully quantified. Water use can make the resource unavailable to other users by displacement or quality degradation. A reduction in water availability to human users can potentially affect human health. If financial resources are available, there can be adaptations that may, in turn, shift the environmental burdens to other life cycle stages and impact categories. This paper proposes a model to evaluate these potential impacts in an LCA context. It considers the water that is withdrawn and released, its quality and scarcity in order to evaluate the loss of functionality associated with water uses. Regionalized results are presented for impacts on human health for two modeling approaches regarding affected users, including or not domestic uses, and expressed in disability-adjusted life years (DALY). A consumption and quality based scarcity indicator is also proposed as a midpoint. An illustrative example is presented for the production of corrugated board with different effluents, demonstrating the importance of considering quality, process effluents and the difference between the modeling approaches.



■ INTRODUCTION

Vital to life, water is a unique natural resource. While it cannot disappear, it can be made unavailable to specific users (ecosystems, human users, and future generations[1]) either by displacement or quality degradation. This change in availability can lead to environmental impacts. Life cycle assessment (LCA) is a methodology that quantifies potential environmental impacts for comparative purposes in a decision-making context.[2] It is used by governments and industries alike to support their impact reduction strategies. In LCA, the resources consumed and emissions generated by a product or service over its entire life cycle are compiled, characterized, and grouped into different impact categories using formal models. While potential environmental impacts from pollutant emissions are characterized in LCA, impacts from water unavailability are not yet fully quantified.

Based on a review of existing methods to characterize water use impacts in LCA, Bayart et al.[3] suggested a general framework that considers three main impact pathways leading to water deficits for human uses, ecosystems, and future generations (freshwater depletion). This paper focuses solely on human uses and proposes a method that assesses the consequences of insufficient access to water for human needs. Bayart and colleagues[3] distinguish the following human users: domestic, agriculture, industry, fisheries, hydropower, transport, and recreation. A decrease in water availability for human uses can lead to impacts on human health. If there is sufficient economic wealth in the area, users will adapt to the lack of water by compensating with a backup technology (e.g., desalination, water or goods import, etc.). The impacts of these processes can be assessed in existing impact categories through traditional LCA and included in the results by expanding the product system under assessment (i.e., the system for which water use is being studied).

In Bayart et al.'s[3] review, only one method addresses the impact pathway leading to impacts on human health. Pfister et al.[4] proposed a breakthrough by quantifying in DALY (disability-adjusted life years) the impacts of malnutrition stemming from a lack of water for agriculture and addressing spatial and temporal variations for over 10 000 watersheds. These regionalized impacts include a scarcity parameter that accounts for seasonal variations. More recently, Motoshita et al.[5] also proposed a methodology to assess the human health impacts of

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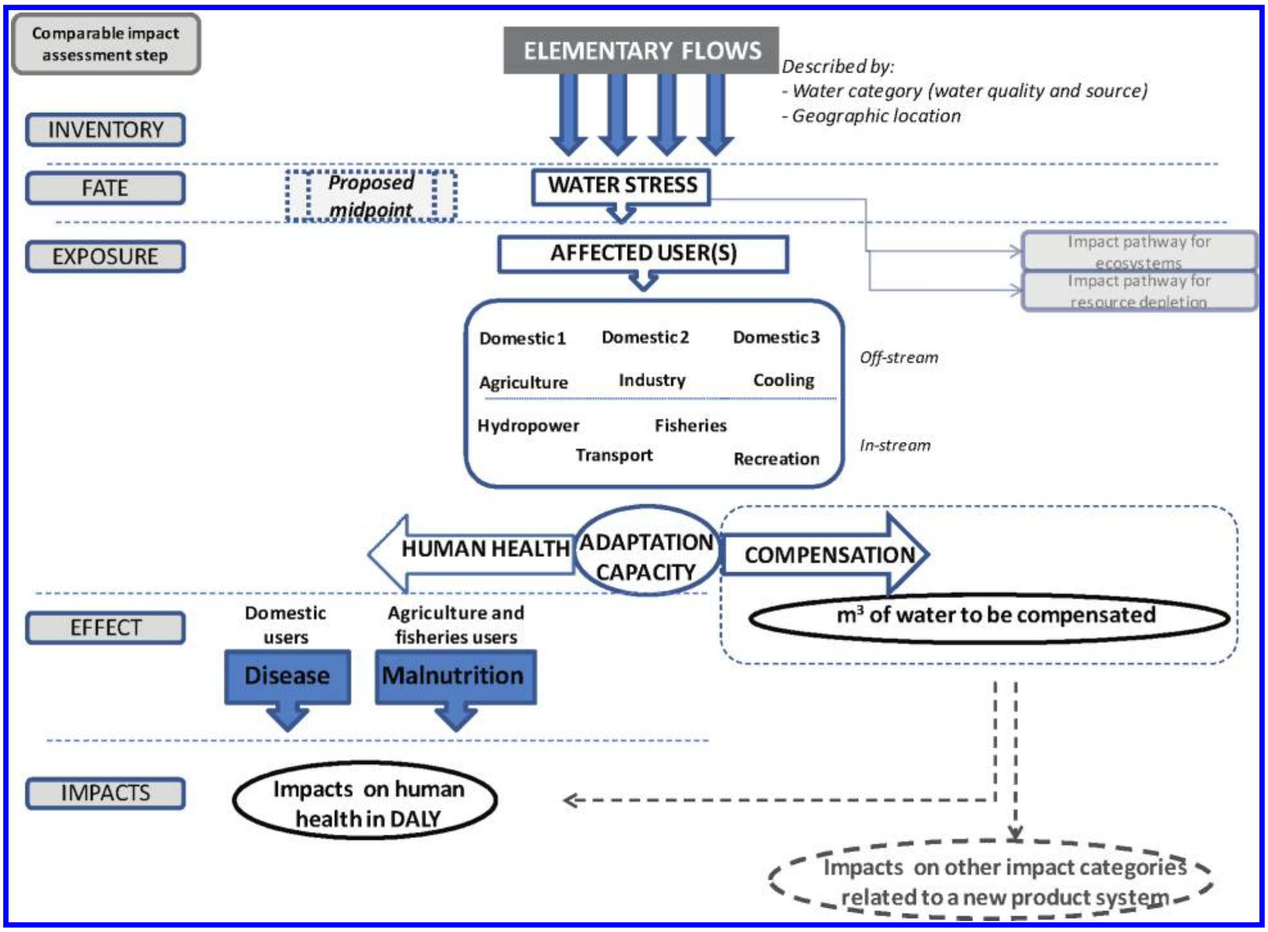

Figure 1. Water use impact pathways for human users leading to compensation or human health impacts.

water scarcity on domestic users. Outside the LCA field, Fry et al.[6] assessed the avoided health impacts from increased water availability for domestic uses. While these methods can assess potential impacts for consumptive water use, they do not consider the fact that the users' adaptation capacity may lead to compensation instead of direct human health impacts. In addition, they do not address the consequences of change in water availability due to a degradative use limiting the potential uses (i.e., functionality) of the resource. Water is considered degraded when it is returned to the body of water with a lower quality, while a consumptive use refers to evaporation, integration within a product or the return of the water to a different watershed or the sea.[7] As most industrial and domestic water uses can be considered degradative, it is important to account for the fact that returned polluted water will not provide the same function as clean water, but may still provide some in comparison to consumed water.[8] Also, none of the existing methodologies consider in-stream users, such as fisheries, nor do they distinguish between surface water and groundwater use.

The objective of this work is to develop a characterization model that assesses the potential impacts generated by a loss of water availability or functionality for human uses caused by consumptive or/and degradative use. These potential environmental impacts are modeled using two distinct and complementary impact pathways: one leading to direct human health impacts (in DALY) caused by malnutrition and disease and the other modeling compensation scenarios to overcome water shortage. This paper focuses on modeling the first impact pathways and will only discuss the second aspect within a comprehensive LCA perspective.

MATERIALS AND METHODS

General Framework Description. Figure 1 illustrates the impact pathway from a water use inventory to direct and indirect impacts generated by a deficit for human uses. Boulay et al.[8] determined two important concepts needed to identify water deficits for human uses: human users and water categories, the latter defining water of sufficient quality and adequate source to be functional for the former. Human users are identified according to domestic use, agricultural use, fisheries (here referring to catch and aquaculture), industry, cooling, transport, hydropower, and recreational use. Three domestic user categories were created in an effort to account for the different qualities of water used for domestic purposes based on local availability, each quality requiring different levels of treatment. Each user is further categorized as in-stream and off-stream according to Bayart et al.[3] and as shown in Figure 1. In this paper, off-stream hydropower was not considered. The water categories represent the 17 possible elementary flows described by source (surface, ground or rain) and water quality (see Supporting Information (SI)). Elementary flows describe the exchanges between the assessed product system and the environment. Water quality is evaluated based on a series of parameters and their thresholds, which determine the users for which a specific water category is functional (sufficient quality and adequate source). For example, groundwater is generally not functional for transport, hydropower or recreational use, and poor quality water is not functional for clean domestic water users (domestic 1) who do not treat their water before consumption.[8] Water quality ranges from 1, excellent (functional for all users) to 5, unusable (only functional for transport or hydropower). When facing water scarcity, users can adapt and compensate the loss of functionality previously provided by the water resource (water treatment, import of water or goods). Alternatively, if the socio-economic situation is not favorable enough, users will directly suffer from a reduction in available water. This could lead to disease caused by limited access to domestic water (lack of hygiene and access to safe water) or agricultural productivity losses leading to malnutrition.[9]

Model Description. The model characterizes the impacts associated with the amount of water entering and leaving the product system for a given category. Potential impacts on human health are calculated based on the difference between resource extraction and emission into the environment, as per eq 1.

$$\mathrm{HH}_{\mathrm{impact}} = \sum_{i=1}^{17}(CF_i \times V_{i,\,\mathrm{in}}) - \sum_{i=1}^{17}(\mathrm{CF}_i \times V_{i,\,\mathrm{out}}) \tag{1}$$

Where, $\mathrm{HH}_{\mathrm{impact}}$ expresses the human health impacts in DALY, $\mathrm{CF_i}$ is the characterization factor of water category i for the human health impact category (in DALY/m^3 of water category (i) and V_i (in and out) is the volume of water category i entering and leaving the process or product system, i.e. the elementary flows (in m^3).

Characterization factor CF_i includes three main components that can be compared to the three factors traditionally used to define emissions-related impact categories: (1) fate, (2) exposure, and (3) effect. As described in eq 2, they respectively represent (1) local water stress, (2) the extent to which user(s) will be affected by a change in water availability and their ability to adapt to this change, and (3) the human health impacts of a water deficit for user j.

$$CF_i = \sum_{j=1}^{10} (\underbrace{\alpha_i}_{\text{FATE}} \times \underbrace{U_{i,j}(1 - AC)}_{\text{EXPOSURE}} \times \underbrace{E_j}_{\text{EFFECT}}) \tag{2}$$

Where α_i expresses the water stress index of category i (dimensionless), $U_{i,j}$ the user(s) j that will be affected by the change in water category i availability (dimensionless), AC the adaptation capacity (dimensionless) and E_j the effect factor for user j (DALY/m^3). The following section describes these three components.

Fate: Water Stress (α_i). In eq 2, the stress index represents the level of competition among users due to the physical stress of the resource, addressing quality and seasonal variations and distinguishing surface and groundwater since these two types of resources often do not present the same scarcity in a same region and may not serve the same users. In this paper, the scarcity parameter α^*_i for surface water was first calculated based on the CU/Q90 ratio proposed by Döll.[10] A discussion on the underlying choice of this scarcity parameter is reported in the SI. The consumed water (CU) in the numerator was calculated using data from the WaterGap model (obtained from the developers).[11] While no seasonal effects were taken into account for renewable groundwater resource availability (GWR), they were considered in the denominator for surface water by the Q90 parameter. The latter, the *statistical low flow*, represents the flow that is exceeded 9 months out of 10. It is therefore a lower value than the average or median flow and allows for the exclusion of the effect of very high flows (e.g., during monsoon season), since this water is rarely fully available unless extensive storage facilities are also available.[12] However, the monthly discharge used for the Q90 assessment accounts for the presence of reservoirs.

The scarcity parameter α^*_i for surface and groundwater is described in eqs 3 and 4.

$$\alpha^*_{\mathrm{surface},\,i} = \frac{CU \times (1 - f_{\mathrm{g}})}{Q90} \times \frac{1}{P_i} \tag{3}$$

$$\alpha^*_{\mathrm{GW},\,i} = \frac{CU \times f_{\mathrm{g}}}{GWR} \times \frac{1}{P_i} \tag{4}$$

Where CU represents the consumptive use in km^3/yr, Q90 the statistical low flow in km^3/yr, f_g the fraction of usage dependent on groundwater (obtained from WaterGap), GWR the renewable groundwater resource available in km^3/yr and Pi the proportion of available water that is of category i.

It should be noted that the less functional a water category is, the more abundant it will be, since all higher quality categories will also meet the category's functionality requirements. This is a consequence of water categories being defined by upper thresholds and not by ranges. They are functionality-based, and category 3 would therefore include 2 and 1, and so on. The availability of water for a given category is considered through parameter P_i in eqs 3 and 4, which is the fraction of freshwater of category i or better available in a region. The proportion of each water category per watershed is evaluated based on data describing surface and groundwater quality from GEMStat (13). Since seawater may be considered very poor or unusable (as per water categories 4 or 5, see the SI for a detailed description), scarcity for these categories was considered to be null in regions with access to seawater, consequently considering infinite availability. When no water of a certain quality was available, no scarcity was calculated. The consumptive use was not available for each water category, which would ideally be needed to calculate the α^*_i specific to each water type. Only total water consumption CU was available. Therefore it was assumed that the best quality water is consumed first, before lower quality water, thus resulting in higher scarcity for better quality categories. Alternatively, one could have assumed that water of different quality was consumed in proportion to its availability, which would lead to discarding the parameter Pi. The first proxy was chosen and this, in some cases, may lead to an overestimation of the physical scarcity of good quality water if lower quality water is consumed first. It would be best to use the consumptive use per water category, if it ever becomes available, instead of either of the two proxies. For the assessment of rainwater use from harvesting or as green water, please refer to the SI.

The stress index (α_i) is then modeled in order to obtain an indicator ranging from 0 to 1 based on accepted water stress thresholds. Assessments of low, moderate, high and very high water stress are associated with water withdrawals of 10, 20, 40, and 80% of available water, respectively.[4,12,13] Correlations between these withdrawals-to-availability ratios and consumption-to-availability ratios were generated (see SI) and used to establish corresponding thresholds of 10, 12, 18, and 40%, respectively. Because the stress index (α_i) is meant to reflect the competition between users, the α_i is set to result in 0 for low water stress (meaning that the consumption of 1 m^3 of water will

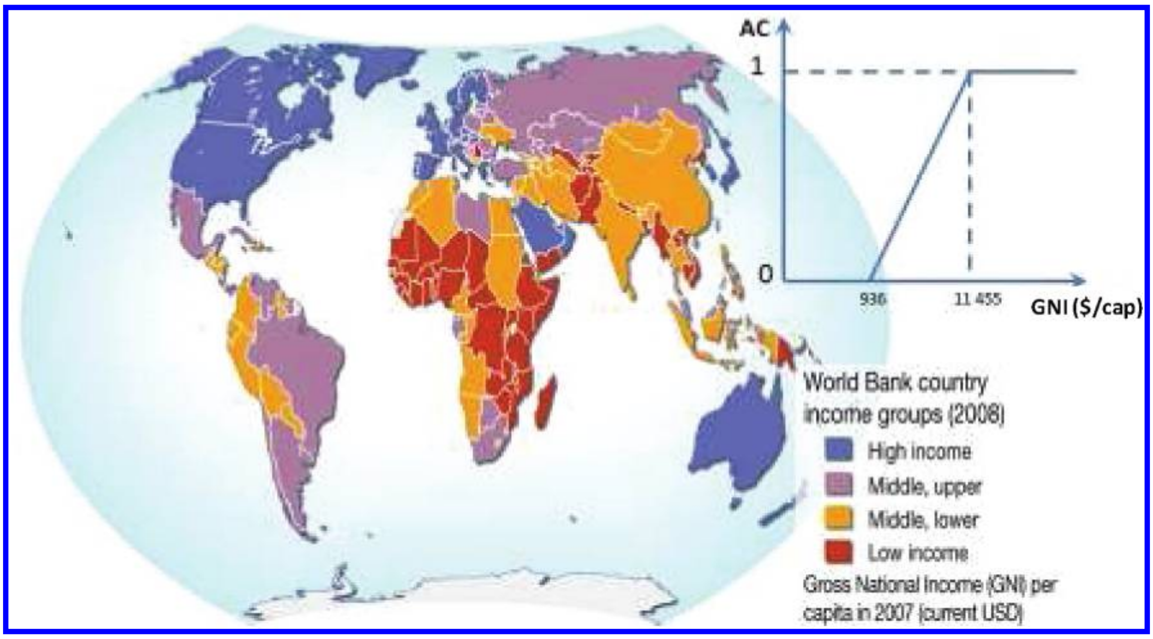

Figure 2. Adaptation capacity based on World Bank country classification:[16] No adaptation for low-income countries, complete (100%) adaptation for high-income countries and partial adaptation for middle-income countries.

not affect other users when water is abundant) and up to 1 for very high stress (meaning that each consumed 1 m^3 will deprive other competing users of 1 m^3). The in-between data were fit in an S-curve passing through 50% scarcity when the high-stress threshold is reached, as also proposed by Pfister et al.[4] and shown in SI equation S1.

Midpoint—Water Stress Indicator (WSI). The proposed midpoint uses the availability of water and differentiates source and quality by weighing the stress of each water type. The results of each flow are aggregated in eq 5 in the same way as in eq 1 for the end point, here using the water stress α_i as a midpoint CF.

$$\mathrm{WSI} = \sum_i (\alpha_i \times V_{i,\,\mathrm{in}}) - \sum_i (\alpha_i \times V_{i,\,\mathrm{out}}) \quad (5)$$

Where WSI expresses the midpoint result in m^3 equivalent of water, α_i the stress index of water category i (in m^3 of water equivalent per m^3 of water of category i withdrawn/released) and V_i (in and out) the volumes of water category i entering and leaving the process or product system (i.e., elementary flows (in m^3)). It represents the equivalent amount of water of which other competing users are deprived as a consequence of water use.

Affected User(s) ($U_{i,j}$). A change in water i availability will not affect all users to the same extent. The impacts depend on (1) the water's functionality for a specific user j, $F_{i,j}$ (based on its quality and type of water resource), and (2) the identification of the user(s) most likely to be affected by a change in water availability in the area of interest (U_j). Together, these parameters make it possible to assess the extent to which user j will be affected by a change in availability of water category i, as shown in eqs 6 and 7.

$$U_{i,j} = \frac{U_j \times F_{i,j}}{\sum_{j,\,\mathrm{offstream}} (U_j \times F_{i,j})} \text{ where } j \text{ is an offstream user} \quad (6)$$

$$U_{i,j} = U_j \times F_{i,j} \text{ where } j \text{ is an instream user} \quad (7)$$

Where $U_{i,j}$ represents the proportion in which user j is affected by a change in water availability for category i (dimensionless), U_j the proportion in which user j is affected by a change in water availability (dimensionless) and $F_{i,j}$ the functionality of water category i for user j (dimensionless).

Functionality, $F_{i,j}$. Water categories presented in Boulay et al.[8] are related to users through a binary functionality parameter (1 or 0) that reflects whether or not the water category is functional for a given user. The functionality $F_{i,j}$, is based on the potential use of water i by user j without any additional treatment.

User's Identification U_j. For offstream users, this parameter represents the user(s) that will be affected by a change in water availability (i.e., the one from which this additional water will be taken). Such users are referred to as marginal users. It is still debated which is the marginal user(s); different approaches have been suggested[4,5] and mainly differ on the inclusion or exclusion of domestic users as users potentially affected by a decrease in water availability. A UNESCO report states that "unbridled competition from richer farmers and industrial concerns for water, productive land and fisheries, often put the poor at a serious disadvantage. It is also often very difficult for the poor to assert their rights and needs so as to receive a fair entitlement to public goods and services".[9] However, there is a debate[4] as to whether an additional water use as typically assessed in LCA would indeed deprive domestic users or whether the change in water availability would be absorbed by the agricultural sector, which would be considered the sole marginal user due to its lower willingness to pay. In reality, there is not enough information to provide robust evidence of such a choice. To satisfy both ends of the debate, two approaches were chosen. The first, the distribution hypothesis, implies that all users are likely to be affected proportionally to their use. A regional distribution of water withdrawals per user was used to represent the probability of being the affected user. In the second approach, the marginal user hypothesis, agriculture is considered to be the only off-stream user that is affected. Therefore 100% of the water use will affect

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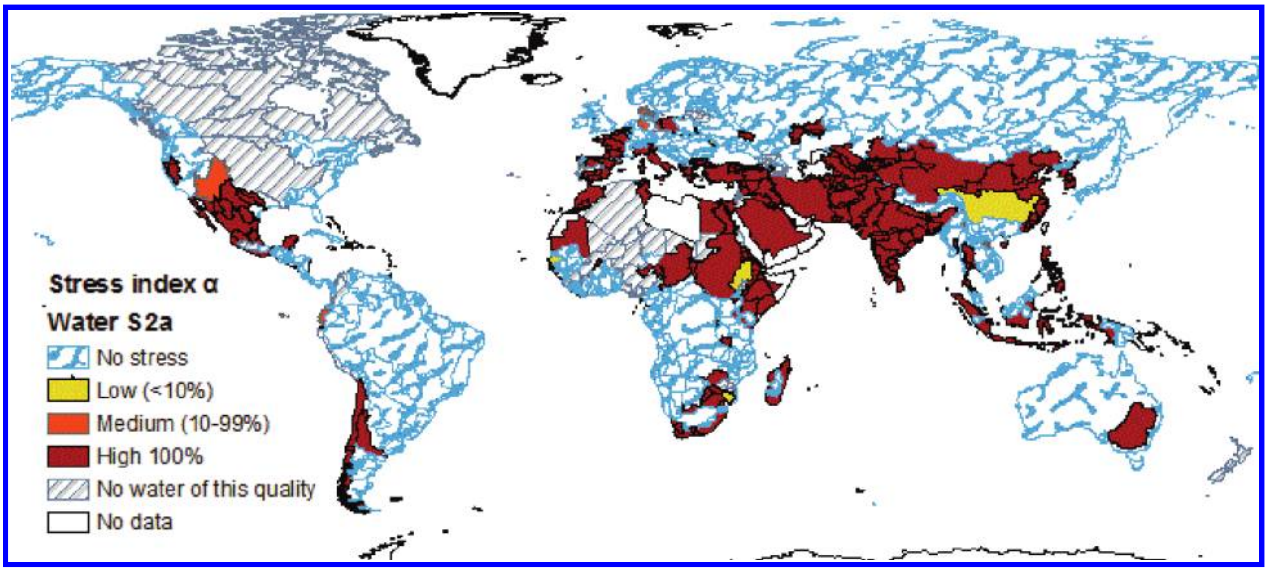

Figure 3. Regional water stress index α_{S2a}, based on the ratio of consumptive use over renewable available resource, including local water quality data and modeled based on accepted stress thresholds.

agriculture and no human health impacts will be generated from water deprivation for domestic uses. Results for both scenarios are given, leaving the final choice up to the LCA practitioner depending on the information available at the local level.

For in-stream users, a change in availability of 1 m^3 of water in a country will deprive each of the in-stream users proportionally to the intensity at which they use the surface water bodies. For human health impacts, this only concerns fisheries. The details of the calculation and hypotheses for both off-stream and in-stream users can be found in SI.

Adaptation Capacity (AC). The adaptation capacity defines whether the change in water availability will create deficit or compensation scenarios. The World Bank gross national income (GNI) classification[14] was chosen as the socioeconomic parameter to indicate a country's adaptation capacity (AC) (see Figure 2). Its correlation with access to an improved water source or improved sanitation was reported by the United Nations and reproduced in the SI.[15]

It is proposed that low-income countries (GNI< \$936/cap) will not be able to adapt to a change in water availability and will therefore suffer water deficits, whereas high-income countries (GNI \$11 455/cap) will have the means to fully compensate for this type of change. Middle-income countries (\$936/cap < GNI < 11 455/cap) are attributed an adaptation capacity proportional to their incomes, meaning that, in these countries, both compensation and deficit occur. This relation is shown in Figure 2 and described in eq 8.

$$\mathrm{AC} = (9.510^{-5} \times \mathrm{GNI}) - 8.910^{-2} \text{ for } 936\frac{\$}{\mathrm{cap}} < \mathrm{GNI} < 11455\frac{\$}{\mathrm{cap}} \quad (8)$$

Effect FactoR (E_j). Effect factor E_j assesses the importance of human health impacts caused by a water deficit for user j for 5 of the 10 users: domestic (1, 2, and 3), agriculture and fisheries. If a water deficit occurs for the remaining users (transport, hydro, industry, cooling, and recreation), impacts will only be generated through a compensation process when occurring in countries able to compensate. This is reflected by the E_j zero value for these users.

For agriculture and fisheries, it is generally accepted that a lack of water would result in malnutrition health impacts due to lower food availability.[4,17] The effect factors (DALY/m^3) were determined by first assessing the health impacts generated by malnutrition in DALY/kcal and dividing this value by the amount of water needed to produce one kcal, either from agriculture or fisheries. For domestic use, the effect factor (DALY/m^3) relates the human health impacts associated with a lack of hygiene and sanitation when water is scarce to the water deficit for domestic use. It is calculated by dividing the ratio of health burdens from water-related hygiene and sanitation issues by the actual volume of water in deficit for domestic uses (based on a value of 50 L/cap/day to ensure low health concerns and cover most basic needs).[18] The resulting effect factors are 6.53×10^{-5}, 2.02×10^{-5}, and 3.11×10^{-3} DALY/m^3 for agriculture, fisheries, and domestic, respectively. A domestic use deficit is therefore critical, since it shows health impacts that are 2 orders of magnitude greater than those for agriculture or fisheries. The details on how these parameters were obtained are presented in the SI.

■ RESULTS

Water Stress. Along with the elementary flows, the water stress indexes (α_i) are proposed to calculate the water stress indicator (WSI) at the midpoint level. Figure 3 shows the water stress index for good quality surface water (α_{2a}). Whereas high scarcity is found where expected, in addition, some major watersheds in North America do not have good quality water[19] and these quality data are also used as default for the northern watersheds when primary data is lacking. Assuming water quality data are representative of the entire region, no water of this quality would be present in that particular region, hence no assessment of its use would be needed. See the SI for all water category indexes.

Human Health Impacts. Figure 4 shows the results of the direct potential impacts on human health (in DALY/m^3) from the use of 1 m^3 of good-quality surface water (S2a). The CFs in Figure 4a are based on the hypothesis that several users are affected proportionally to their use and therefore include impacts

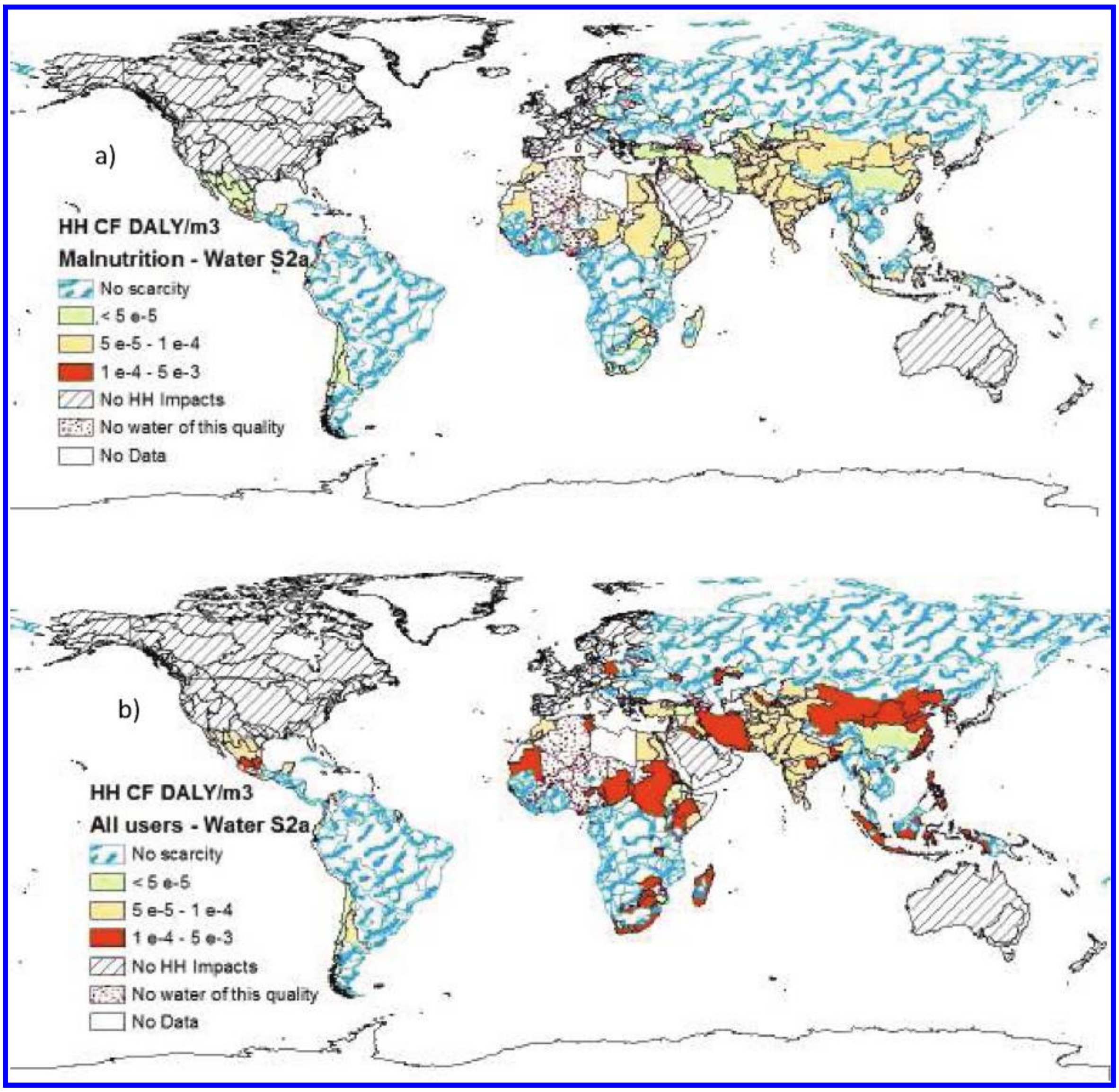

Figure 4. Human health characterization factors for good quality surface water (category S2a) in DALY/m^3 (a) considering that agriculture is the only marginal user affected (along with fisheries), leading therefore to malnutrition and (b) considering all users are affected proportionally to their use (i.e., also including domestic users and therefore considering health burdens due to lack of hygiene and sanitation in addition to malnutrition).

brought about by a lack of hygiene and sanitation related to a water deficit for domestic use and impacts generated by malnutrition from both agriculture and fisheries. The CFs in Figure 4b refer to health impacts generated only by malnutrition from both agriculture and fisheries. As expected, high-income areas such as North America, Europe, and Australia show no direct impacts on human health because they have maximum adaptation capacities. They would, however, generate potential impacts from compensation. CFs for other water types are detailed in the SI.

Illustrative Example. A paper mill producing cardboard from recycled fibres was studied as an illustrative example using the generic ecoinvent data set *Corrugated board, recycling fiber, single wall, at plant* characterized with the Impact 2002+ methodology.[20] The generic data set was adapted with available primary industry data from Cascades. For each ton of corrugated board produced, 17.4 m^3 of water are withdrawn from a nearby river and 16.4 m^3 are released into the same river (average pulp and paper plant data). The effluent is categorized as average quality water (category 2b, see Boulay et al.[8] and SI), while the influent is considered to be good quality surface water (S2a). This scenario B (average effluent S2b) is shown along with two other hypothetical variations: A. the effluent is better treated, up to the good quality surface water of the influent (well-treated effluent, S2a) and C. the effluent is considered null (i.e., 100% of the water is consumed). The purpose of this sensitivity analysis is to assess the variability of the impacts associated with the water that is consumed or used but released at different quality levels. The magnitude of the difference between both hypotheses on the marginal user affected is also illustrated by this example, as discussed below.

Impacts on human health are shown for the hypothetical production of cardboard in the Ganges Basin in India. This region was chosen because it shows a low adaptation capacity and high water scarcity. In this respect, adaptation will still occur ($AC \neq 0$), implying that both the direct impacts and impacts generated by compensation scenarios should be addressed. Only the direct

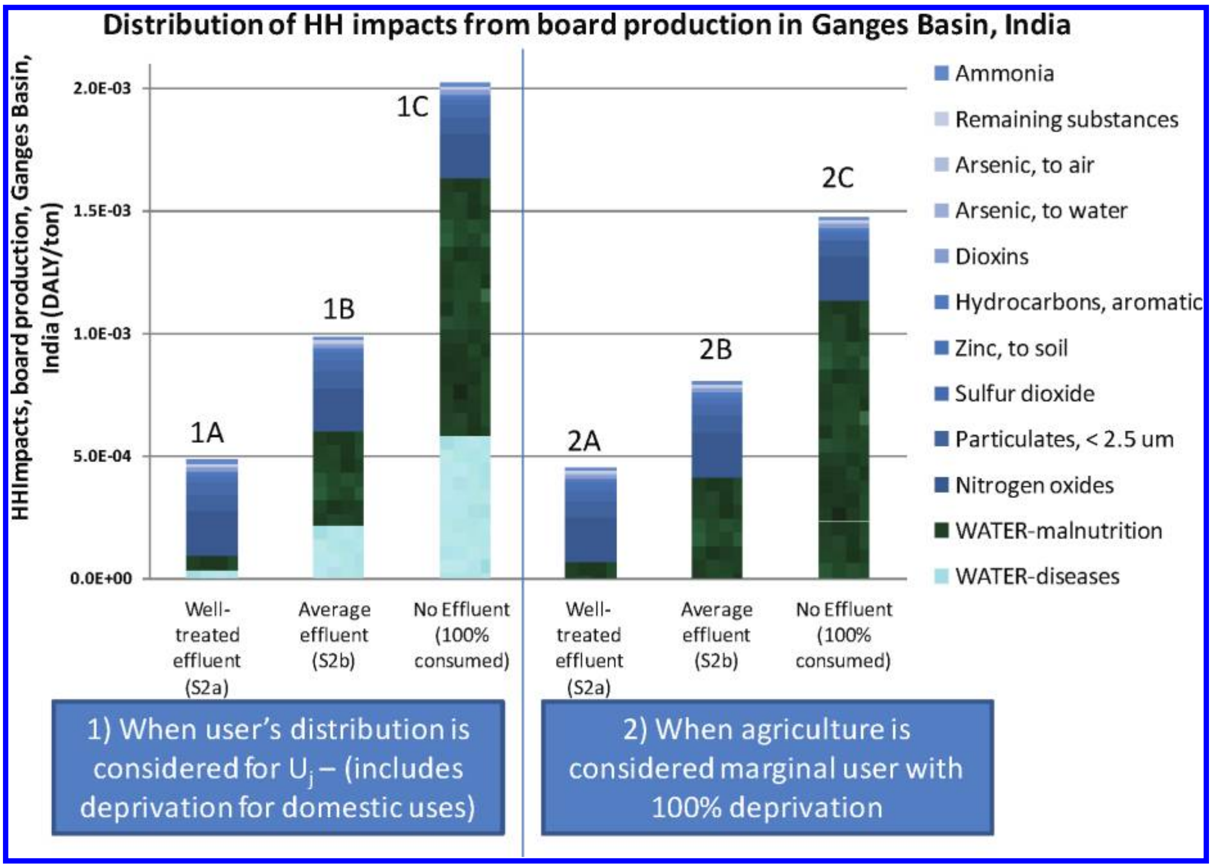

Figure 5. Human health impacts of water use for board production in comparison with other human health contributors from the production process for three different effluent scenarios and for both hypotheses on marginal use: (1) considering all users to be affected proportionally to their us (i.e., including domestic users) and (2) considering that agriculture is the only marginal user affected (along with fisheries), leading therefore to malnutrition (not including domestic use).

impacts are shown in Figure 5. The 10 main contributors (elementary flows) to human health impacts are identified, including water use, which is split into impacts generated by malnutrition and by diseases related to water deficit for domestic use. All three scenarios (A, B, and C) are presented for both hypotheses: (1) Distribution: all users are affected proportionally to their use (i.e., considering health burdens due to the lack of hygiene and sanitation and malnutrition) or (2) Marginal: reporting that only malnutrition impacts occurs. The reduced quality of the effluent in B may significantly contribute to the overall human health damages. The additional impacts from a degradative use (in 1B) are, in this case, even higher than all other human health contributors. However, considering that all water must be consumed (1C) instead of considering the polluted released flow (1B) would more than double the impacts on human health from water use. In addition to these results, compensation scenarios for each user should be modeled with a traditional LCA method to yield impacts scores that would then allow for the integration of indirect impacts into other impact categories.

DISCUSSION

This methodology modeled the impacts generated by a change in water availability for human uses in an LCA perspective. The water stress parameter α was proposed to calculate a midpoint indicator (WSI) that could be used to characterize physical inventory flows into a common metric, as suggested by Frischknecht et al.,Pfister et al. and Mila-i-Canals et al.[21,4,1] In this respect, α can be considered representative for three areas of protection, including human health, ecosystem quality and resource depletion. However, it is important to note that no ideal midpoint has been found for the impact pathway to allow for a partial characterization that could then be used directly as an input for end point modeling in all categories, as presented in Bayart et al.[3] This is due to the fact that each impact pathway involves different mechanisms. Here, the water stress parameter α corresponds to a fate factor (see eq 2). The human health impact pathway was further modeled up to the end point level by developing CFs expressed in DALY/m^3. Additionally, indirect impacts must be considered through the compensation scenario by identifying the marginal technology that is appropriate for each water type, as proposed by Weidema et al.[22] These indirect impacts could be consistently compared with the direct impacts by further modeling a new LCI (by system expansion) and assessing the related impacts on human health and other categories generated by the compensation scenario, allowing for a coherent comparison with other sources of impacts. The application of this method to a straightforward example illustrates the potential significance of considering water use impacts in an LCA carried out for a region with low adaptation capacity. However, further case studies, including higher income countries, are needed to further evaluate this approach. Moreover, regionalization was shown to be a critical issue since impacts can be dominant or nonexistent from one region to another.

While other methods have been advanced to assess water use impacts in LCA, the methodology herein differs in the following aspects:

Quality. The model does not only consider the consequences of consumptive use leading to reduced access to water. It also assesses the consequences of a loss of functionality for downstream users due to the degradative use of water. Seeing as the inventory procedure integrates the functionality of withdrawn and released water based on quality, the released water and its corresponding functionalities are considered to be returned to the environment, avoiding an overestimation of the potential impacts by considering that the water was consumed. This is especially important for heavy water users (e.g., thermal plants for cooling). Assessing the quality of the returned water would also serve as an incentive for effluent treatment. In the aforementioned example, if the plant were to treat its effluents to attain the same water quality as the influent (2a), water use impacts would be reduced by a factor of 6 as compared to the water released as 2b. Finally, including quality in the methodology also curbs the impacts of using low-quality water vs high-quality water since not all users will be affected the same way.

Stress. Unlike other widely used scarcity indicators, the one proposed here considers the ratio of consumptive use over a statistical low-flow parameter. The numerator allows for a better representation of the physical scarcity of water without considering the withdrawn water that is released in the same watershed (e.g., for cooling). The denominator takes seasonal variations into account, which is very important in countries that face monsoons and droughts. Moreover, the indicator distinguishes surface water, groundwater, rainwater, and quality, which is significant since the water categories are not available in the same quantities and not functional for all users. A more specific scarcity parameter per water type could be obtained by adjusting the CU term to reflect the actual consumption of each water quality category. However, the regional breakdown of the volume of water consumed for each specific water category is not available. The parameter therefore currently assesses the scarcity of a water category based on its availability and assumes that water of good quality will be consumed before a lower water quality.

Users. All users are considered, and some are even differentiated based on the quality of water they require. While not all suffer human health impacts, it would be especially important to consider them in a compensation perspective, since industry and the energy business in developed countries are unlikely to stop their activities due to water shortage without first considering compensation strategies.

Human Health. Although a first attempt to model human health impacts for malnutrition has already been proposed by Pfister and colleagues[4] with a statistical correlation of $R^2 = 0.26$, in this paper, a probabilistic approach was proposed instead to evaluate the health burdens associated with malnutrition and with water shortages for domestic use. Both show acceptability in terms of the distribution—log-normal, which allowed for the use of geometric averages. The p-values describing the distribution of the correlation are of 0.0839 and 0.15, respectively. A p-value higher than 0.05 reflects an acceptable distribution. Malnutrition was modeled for a water shortage affecting agriculture, fisheries and livestock (through agricultural feed). With regards to domestic use, while infrastructure plays an important role in the health burden caused by water-related diseases, this role did not need to be considered since the impacts of a change in water availability in current socioeconomic conditions were modeled. The health burden for 1 m^3 of water that is unavailable for domestic use (whether from lack of access or scarcity) was assessed from the correlation between the actual water used for domestic purposes, the water required to avoid health issues and the actual health burden of water-related issues. This rationale is based on strong epidemiological evidence that access to water is correlated with diarrheal diseases, worm infections, and malnutrition.[15] However, whether or not access to water for domestic users will be reduced from typical inventory data in LCA, and, consequently, the inclusion or exclusion of the associated impacts, are still open for debate. Pfister and colleagues[4] chose to exclude them, but Motoshita and colleagues[5] developed a model that suggests they should be included. When addressing the impact pathway, it is important to understand whether a water use in a low-income, water-stressed region would indeed lower water availability for domestic users or rather only affect other users (e.g., agricultural or industries). At this stage, the information to support the choice and determine the marginal affected user is insufficient. For this reason, we chose to present CF for two main scenarios: (1) all users are affected proportionally to their water use in a given region, implying that the burden caused by a lack of hygiene and sanitation is considered in addition to malnutrition, and (2) only agriculture is affected among the off-stream users as it would present the lowest willingness to pay. As demonstrated in the example, human health impacts from water use may be of the same order of magnitude as the human health impacts generated by toxic emissions, thus supporting the conclusion that including or excluding this impact pathway has a relevant influence in a LCA.

Compensation. Compensation accounts for the capacity of human users to adapt to a freshwater deficit through the use of technology. Model results indicate that direct human health impacts are expected to be null in developed countries, but indirect impacts may be generated by compensation scenarios. In this respect, the use of backup technologies is not only meant to alleviate depletion, as proposed by Pfister,[4] but also to compensate when local resources are not necessarily being depleted but are still used to the extent that they reduce availability for users due to competition. Marginal technology use should therefore be included as having potential impacts within LCA and not solely as a depletion metrics. The volume of water needed would be obtained through the marginal technology in place to compensate for a specific water category. Impacts from this technology should be included in the water use impact assessment by system boundary expansion. However, the assessment should be done consistently with the method proposed here. This implies that only a fraction of the volume, based on the adaptation capacity, is produced from the marginal technology for the withdrawn water category. The identification of the regional marginal technology for each water type should be performed and its impacts included in the scope of the assessment.

Limitations. Though it demonstrates spatially differentiated capabilities, the model does not predict absolute or real impacts. It addresses the potential environmental impacts used to characterize environmental interventions within an LCA with an underlying hypothesis of linearity between a change in water availability and the resulting impacts. The default characterization factors in this model may be well-suited to exploring the potential impacts of water use but the robustness of the results and required level of detail can only be evaluated once the model is used and the results are compared with those from other models. Obtaining better data on water quality per watershed or region is necessary to increase the accuracy of the methodology. Current data is not adequately distributed in time or space, and the parameters and uncertainty of the model have yet to be evaluated. Several specific limitations apply to this model. Interactions between surface and groundwater or between watersheds are not considered and the consecutive use of the water resource is not taken into account, a fact that could lead to an underestimation of potential impacts. These limitations also apply to (downstream) transboundary watersheds. However, the results could be corrected on a case-by-case basis by identifying the country in which the impacts are most likely to occur for a specific water use or by adding the potential impacts generated by water use in downstream watersheds. Also, user and water availability distribution within a watershed is considered to be homogeneous, implying that there is no difference if the water is withdrawn upstream or downstream of other users. However, it is unlikely that sufficient data would be available on the exact location of the water use to allow for such distinctions or modeling. Moreover, as a modeling choice, the quality of the effluent was taken *as is* and therefore does not account for dilution or degradation time. While this option is believed to be the best choice since dilution would require the availability of more water, thus creating a loop effect, it may become a limitation in cases in which the natural buffering capacity of the environment would assimilate some of the pollutants. Lastly, limitations associated with water categories, as described in Boulay et al.[8] may lead to either an overestimation or underestimation of the impacts by grouping different user functionality requirements into a limited set of water categories. Boulay et al. propose a more detailed functionality-based approach to overcome this.

To ensure the integration of the method within daily LCA practices, life cycle inventory databases must be expanded to account for released water volume and therefore support the calculation of water categories. The inclusion of impacts from compensation scenarios may be facilitated by adapting a life cycle inventory database to a consequential approach by including the use of the local marginal source of water, which may come from desalination, reuse, etc.

As for other regionalized impact categories, data sets should allow for region selection and appropriate CFs. To facilitate the use of these CFs, a generic data set of effluent water quality by industry type could be generated. Moreover, a water mix similar to a grid mix could be set out based on the local surface/groundwater consumption data and water quality data that could be used when actual inventory input data is not known.

ASSOCIATED CONTENT

Supporting Information. The SI is made up of PDF and Excel documents. The PDF describes the water categories and provides information on water scarcity, user distribution and effect factors, maps and a detailed example of a tailored CF. The Excel document contains all intermediate data, as well as CF for human health at the local (cell) and national scales. One of the tabs is designed to be used as a tool to calculate a tailored CF (Spec CF). A Google Earth layer and other materials are available for download at: www.ciraig.org/wateruseimpacts. This material is available free of charge via the Internet at http://pubs.acs.org.

AUTHOR INFORMATION

Corresponding Author

*E-mail: anne-marie.boulay@polymtl.ca.

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