LCA Characterization of freshwater use on human health and through compensation

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Abstract Impacts from water unavailability are not yet fully quantified in LCA. Water displacement from the original water body (consumption) or quality degradation of released water reduces water availability to human users. This can potentially affect human health through diseases or malnutrition or, if financial resources are available, adaptation can occur, which may generate indirect environmental impacts through the use of backup technologies such as water treatment, desalination, import of water or agricultural goods, etc. This paper proposes an inventory and impact assessment model to evaluate these potential impacts in an LCA context. Results are presented in DALY for impacts on human health and/or as a quantified water inventory to be compensated by users adapting to a situation in which water is scarce or unavailable. A fictional example on board production illustrates the full applicability of the methodology.

1 Introduction

Vital to life, water is a unique natural resource. While it cannot disappear, it can be made unavailable to specific users either by displacement or quality degradation. While potential environmental impacts from pollutant emissions into water are characterized in LCA, impacts from water unavailability are not yet fully quantified. This change in availability can lead to environmental impacts. Based on a review of existing methods to characterize water use impacts in LCA, Bayart et al. [1] 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 decreased water availability for human needs, which 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, import of water or goods that can no longer be produced locally). The impacts of these compensation processes can be assessed through a traditional LCA and included in the results of the product system for which water use is being studied. This paper presents a method from inventory to midpoint and to endpoint level for the characterization of impacts from water uses on human users. This approach is based on the loss of functionality, either quantitatively or qualitatively, of the water resource resulting from a water usage.

2 Methodology

2.1 Inventory modeling by water categories

In order to assess functionality loss, the quality of the water entering and exiting the process (or product system) should be assessed along with its associated functionalities. Different water categories based on functionalities are developed for this purpose, each one representing an elementary flow, as proposed in Boulay et al. [2]. Each water category is defined by the source (i.e. its origin, being surface, ground or rain water) and its quality, based on a combination of parameter thresholds taken from national and international water quality standards. Thresholds for an extensive number of parameters (138) are proposed, including general parameters (suspended solids, fecal coliforms, pH, etc.) organics and inorganics. However, this doesn't imply that all this information needs to be collected at the inventory phase; it only ensures that maximal guidance is provided when the information is available. Seventeen (17) water categories are defined in Boulay et al. as shown in table 1 below. The category of the water entering the process is defined by its origin (surface water or groundwater) and quality. The latter is by default assumed to correspond to the average quality of surface and groundwater available in the relevant watershed. Water category data are provided by Boulay et al. [3] for most watersheds worlwide. The category of the water exiting the process is determined by its quality, which can be determined by combining the information already available in existing LCI databases (emissions to water) and the volume of discharged water (missing information in LCI databases to be collected). The categorized water influent and effluent allow the assessment of impacts from water degradation or consumption as further described below.

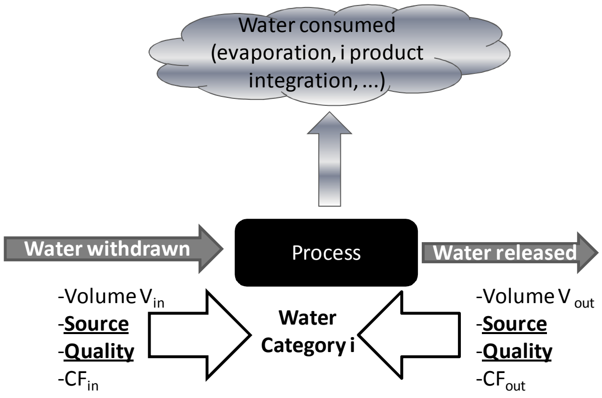
Tab.1: Water category sample (adapted from Boulay and colleagues [2])

Water	1	2 a	2b	2c	2d	3	4	5

category							
Source	Surface or ground						
Quality description	Low microbial Low tox.	Low microbial medium tox.	Medium microbial medium tox.	Low microbial high tox.	High microbial low tox.	High microbial medium tox.	High microbial high tox.	Other
Param. 1	Threshold 1	Threshold 2a	Threshold 2b	Threshold 2c	Threshold 2d	Threshold 3	Threshold 4	Threshold 5
Param. 2	Threshold 1	Threshold 2a	Threshold 2b	Threshold 2c	Threshold 2d	Threshold 3	Threshold 4	Threshold 5
…	…	…	…	…	…	…	…	…
Param. 138	Threshold 1	Threshold 2a	Threshold 2b	Threshold 2c	Threshold 2d	Threshold 3	Threshold 4	Threshold 5

2.2 Impact assessment modeling

The model proposed in the sections below includes a midpoint, endpoint and a compensation assessment. The latter is to be used as a complementary assessment in addition to the endpoint model. For the midpoint and endpoint modeling, Fig.1 below illustrates how the water categories presented above are used in the impact assessment.



$$\text{Impact} = (\text{Volume}_{in} \times CF_{in}) - (\text{Volume}_{out} \times CF_{out})$$

Note: CF= Characterization Factor

Fig.1: Impact assessment of water use - for midpoint level (c.f. equation 1) and endpoint level (c.f. equation 4)

2.2.1 Midpoint assessment modeling

At the midpoint level, impacts should be characterized considering the local water scarcity, the quality and the type of resource. The impact assessment is then performed by evaluating the difference in stress between the withdrawn and released resource. From Figure 1, it is necessary to know the volume, the source and the quality of the water entering and exiting the system or process, in order to identify the relevant water categories, each associated to a stress index. Once the water categories have been identified by their respective source and quality, the water stress indicator is calculated as per equation 1:

$$WSI = \sum_i (\alpha_i \times V_{i,in}) - \sum_i (\alpha_i \times V_{i,out}) \qquad (1)$$

Where, WSI (Water Stress Indicator) expresses the impact score at the midpoint level -representing the equivalent amount of water (m^3-eq) generating competition between users, α_i the stress index of water category i (in m^3-eq of water per m^3 of water of category i withdrawn/released) and V_i (in and out) the volumes of water category i entering and exiting the process or product system, namely elementary flows (in m^3).

Water Stress Index (α_i) – In Equation 1, the stress index α_i represents the characterization factor at the midpoint level, expressing the level of competition among users due to the physical stress of the resource. It addresses quality, seasonal variation and distinguishes between surface and groundwater, as these two types of resources often do not present the same level of scarcity in a region. First, the scarcity parameter α^*_i for surface water is calculated based on the CU/Q90 ratio proposed by Döll [4]. The consumed water (CU [m^3/yr]) in the numerator represents the volume of water consumed by human uses in a region and is calculated using data from the WaterGap model [5]. While no seasonal effects are taken into account for the renewable groundwater resource availability (GWR), they are considered in the denominator for surface water by the Q90 [m^3/yr] parameter. This parameter, called 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 the exclusion of effect from very high flows, e.g. during monsoon periods, as this water is rarely fully available unless extensive storage facilities are available [6].

The scarcity parameter α^*_i for surface and groundwater is described in Equations 2 and 3 taken from Boulay et al. [7].

$$\alpha *_{surface,i} = \frac{CU \times (1 - f_g)}{Q90} \times P_i \qquad (2)$$

$$\alpha *_{GW,i} = \frac{CU \times f_g}{GWR} \times P_i \qquad (3)$$

Where CU represents the consumptive use in km³/yr in a given watershed, Q90 the statistical low flow, in km³/yr, fg the fraction of usage dependent on groundwater (obtained from WaterGap), GWR the renewable groundwater resource available in km³/yr, P_i the inverse of the fraction of available water that is of category i.

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. There is an agreement in the literature associating different water stress levels (low, moderate, high and very high) with fractions of available water withdrawn (10%, 20%, 40% and 80%, respectively [6, 8, 9]). However, the water stress index proposed here relies on consumption-to-availability ratios, instead of withdrawal-to-availability ratios, to better capture the physical stress of the resource. Correlations were found to adapt these values for a consumptive-based water stress index [7] and the data was then fitted to an S-curve passing by a 50% scarcity when a high stress threshold is reached as proposed by Pfister and colleagues [9]. Stress indexes for all water categories were calculated and are presented in Boulay et al. [7].

2.2.2 Endpoint assessment modeling

Similarly as for the midpoint level, at the endpoint, the model characterizes potential impacts on human health based on the difference between water resource extraction and emission into the environment, as per Equation 4.

$$HH_{impact} = \sum_{i=1}^{17}(CF_i \times V_{i,in}) - \sum_{i=1}^{17}(CF_i \times V_{i,out}) \qquad (4)$$

Where, HHimpact expresses the human health impacts in DALY, CFi is the characterization factor of water category i for the human health impact category (in DALY/m³ of water category i) and V_i (in and out) is the volume of water category i entering and exiting the process or product system: the elementary flows (in m³).

Characterization Factors CF_i include three main components that can be compared to the three factors traditionally used to define emission-related impact categories [10]: 1) fate, 2) exposure and 3) effect. As described in Equation 5, they respectively represent: 1) local water stress, 2) the extent to which user(s) will be affected by a change in water availability, and 3) the human health impacts of a water deficit for user j.

$$CF_i = \sum_{j=1}^{10}(\alpha_i \times U_{i,j}(1 - AC) \times E_j) \qquad (5)$$

$$\underbrace{\qquad}_{\text{FATE}}\underbrace{\qquad\qquad\qquad}_{\text{EXPOSURE}}\underbrace{\qquad}_{\text{EFFECT}}$$

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/m³).

The parameter $U_{i,j}$ is based on the functionality of water i for the specific user, as defined by the categories, and the identification of the marginal off-stream user. This latter represents the one with the lowest willingness to pay, however in the current version of the model, the distribution of withdrawals among off-stream users in a region was used as a proxy for this parameter. For in-stream users, the intensity of the activity used is that estimated by Boulay et al. [7].

The adaptation capacity (AC) defines whether the change in water availability will create deficit or compensation scenarios. The World Bank gross national income (GNI) classification [11] was chosen as the socioeconomic parameter to indicate a country's adaptation capacity (AC). It is proposed that low-income countries (GNI< \$936/cap.yr) 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.yr) will have the means to fully compensate for this type of change. Middle-income countries (\$936/cap.yr < GNI <\$11 455/cap.yr) are attributed an adaptation capacity proportional to their incomes, meaning that, in these countries, both compensation and deficit partially occur.

The effect factor E_j assesses the importance of human health impacts caused by a water deficit for domestic, agriculture and aquaculture users. 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 aquaculture, the effect factors (DALY/m^3) were determined by first assessing the damage 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 [12]). The resulting effect factors are $6.53 \cdot 10^{-5}$, $2.02 \cdot 10^{-5}$ and $3.11 \cdot 10^{-3}$ DALY/m³ for agriculture, fisheries and domestic, respectively. A domestic use deficit is therefore critical, since it shows health impacts that are two orders of magnitude greater than those for agriculture or fisheries. The details on how these parameters were obtained are presented in Boulay et al. [7].

2.3 Water compensation volume modeling

Compensation here refers to the use of backup technologies by water-deprived human users to meet their needs. It only occurs in high- and middle-income countries (along with human health impacts). Impacts associated with these alternatives should be modeled with a traditional system expansion, but not all of the water used will be compensated, since compensation also depends on scarcity and adaptation capacity. Equation 6 serves to calculate the amount of water to be compensated by the single user j in m^3, $W_{comp,j}$.

$$W_{comp,j} = \sum_{i=1}^{13}(V_{i,in} \times U_{i,j} \times \alpha_i \times AC) - \sum_{i=1}^{13}(V_{i,out} \times U_{i,j} \times \alpha_i \times AC) \qquad (6)$$

Where, all parameters are as described in previous equations. Parameters $U_{i,j}$ and α_i must be adjusted from the ones presented above, as explained for the example below. This then becomes an inventory input in a system expansion, similarly to the mineral resource depletion assessment through the supplementary energy needed for subsequent abstraction [13, 14]. Each compensation scenario is unique and specific to each user for whom water availability is decreased (e.g. water import, desalinisation, etc. for domestic use; food import for agriculture and aquaculture) and have to be specifically modeled by a system expansion, resulting in damages that can then be added to all of the impact categories, including human health impacts.

3 Application

Using equation 1, some sample assessment of the midpoint indicator for a hypothetical process that withdraws 100 m^3 of water type S2a (low microbial, medium tox) and releases 80 m^3 of water S3 (high microbial, medium tox) is shown for several geographical locations to illustrate the variability of potential impacts due to regionalization.

For the endpoint assessment, the complete methodology was applied to a fictitious board producing plant located in the region of Cape Town in South Africa. This region was chosen as it represents a middle-income region with therefore both impacts on human health from water deprivation and on all categories from compensation scenarios. The ecoinvent process “Corrugated board base paper, kraftliner, at plant/RER” was used, along with all water data already included in the process. The volume of water released was estimated based on the hypothesis that one cubic meter of water is evaporated per ton of board produced [7]. The quality of the influent was taken to be the locally available water [2] and was thus identified to be of category 2d (high microbial, low tox). The quality of the released water was evaluated based on the emissions to water and the volume released and resulted in water category 5 (unusable) due to the high BOD content (93 mg O_2/l). Cooling water was treated separately and assumed to be both withdrawn and released at the same quality level.

Compensation was modeled based on the following hypothesis: 1) Agriculture is the off-stream user with the lowest willingness to pay and will therefore be the one affected by 100% of the change in water availability. 2) Compensation in agriculture is assumed to be achieved through wastewater reuse and was modeled with the ecoinvent process “Water, ultrapure, at plant” adapted with the South African electricity mix. 3) Hydropower compensation was modeled with the South African electricity grid mix, as it was difficult to identify whether South Africa is moving towards nuclear, as it states to be, while it is constructing new coal fired plants. 4) The aquaculture compensation would result in about 2.2 kcal to be compensated for from the loss of fish production, and was therefore neglected. 5) Transport and recreation were not modeled.

When modeling the volume of water to be compensated for each user, equation 6 was used along with the data provided by Boulay et al. [7]. However, the scarcity term was adjusted for hydro as this user is not affected by the quality of the available water, and the general surface water scarcity of the region was used.

4 Results

Results are presented i) at the midpoint level for several regional assessments to show the importance of regionalization and simplicity of the indicator and ii) at the endpoint level including impacts on human health from water deprivation as well as on all impact categories from compensation scenarios.

4.1 Regionalized midpoint assessment

Results for a regionalized midpoint assessment are presented in Tab.2. These include the stress indexes α for water flows in and out of a hypothetical process, namely water categories S2a (low microbial, medium tox) and S3 (high micrbial, medium tox). The resulting water stress indicator (WSI) in m^3 equivalent of water is calculated as per equation 1 with inventory in and out of 100 m^3 and 80 m^3 respectively. This indicator quantifies the extent to which competition will result from the assessed water use (consumption and degradation). Results show that the local stress indicator of water quality for both the influent and the effluent is important and that considering the local water quality is therefore relevant.

Tab.2: Midpoint indexes (m^3-eq./m^3 water withdrawn/released) and resulting water stress indicators (WSI, in m^3-eq) for a process withdrawing 100 m^3 of water type S2a and releasing 80 m^3 of water S3, in different regions

Country	Watershed	Stress Index S2a	Stress Index S3	WSI
France	Meuse	0.500	2.69 E-05	50
Spain	Mino	0.653	0.046	61.62
Canada	St. Lawrence	0	0	0
China	Liao	1	0.995	20.4
China	Yalu Jiang	0.272	0	27.2

4.2 Complete endpoint assessment

Results from the application of the methodology to the ecoinvent process named “Corrugated board base paper, kraftliner, at plant” are presented in this section using the four damage categories described in Impact 2002+. Detailed results for regional endpoint CF in DALY/m^3 and for the fraction of water to compensate were presented in Boulay et al. [7].

Figure 2 shows that the human health impact category is dominated by impacts from water deprivation for agriculture and domestic uses, resulting in malnutrition and diseases. A small additional impact (<3% in comparison to process) can be found in all categories from the water compensation scenarios for hydropower production and agriculture. These results are for a region with an adaptation capacity of 0.46, meaning that almost half the unavailable water will generate impacts on human health directly and the rest will be compensated. This region also presents a high stress index (0.88) for the influent water and a null index for the effluent which implies that the released water does not return a valuable functionality as this water quality is not stressed. Impacts from water use in a similar hydrological context but in a region with full adaptation capacity (1 instead of 0.46, e.g. Europe, North America, etc.), would show no impact on human health occurring from deprivation, but close to twice the compensation impacts as compared to those shown here, hence < 6%. Conversely, in a less developed region, human health impacts from compensation could almost double, becoming the largely dominating source of human health impacts from board production.

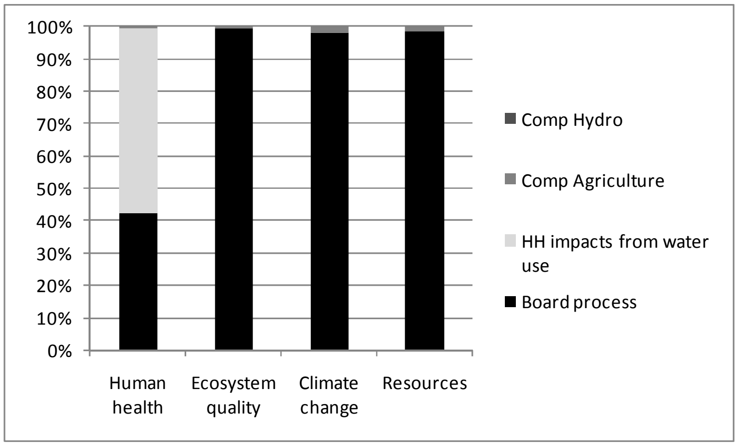


Fig. 2: Process and water use impacts from compensation and on human health from deprivation for the production of 1 ton of corrugated board in the region of Cape Town in South Africa.

5 Discussion

This methodology covers both the inventory modeling and the impact assessment of water use in a consistent framework.

The application of this method to a straightforward example illustrates the relevance of considering water use impacts in an LCA, especially from a human health perspective. This is the only method that is functionality-oriented and uses a consumptive-based scarcity ratio instead of the traditional, but misleading withdrawal-to-availability ratio. The inventory modeling takes into account the quality and the volume of water entering and exiting the process. Default water quality data are provided by this method in case no primary data on local water quality are available. To ensure the operationalization of this method within daily LCA practices, life cycle inventory databases must be expanded to account for released water volumes and therefore support the calculation of the quality of water exiting the process and thus, the water categories. To facilitate the use of these CFs, a generic dataset 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 local water quality data that could be used when actual inventory input data is not known. Still, at this point the methodology can be applied with data already available in most ecoinvent processes (volume and source of water influent and emissions to water in the effluent) and a hypothesis regarding the fraction of water evaporated.

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