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WATER USE IN LCA

A framework for assessing off-stream freshwater use in LCA

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Abstract

Purpose Freshwater scarcity is a problem in many areas of the world and will become one of the most sensitive environmental issues in coming decades. Existing life cycle assessment (LCA) methodologies generally do not provide assessment schemes or characterization factors of the potential environmental impacts of freshwater use or freshwater resource depletion. These assessments therefore do not account for the significant environmental consequences of the loss in quality and availability of freshwater. This paper aims to develop a framework to address this methodological limitation and to support further quantitative modeling of the cause–effect chain relationships of water use. The framework includes recommendations for life cycle inventory (LCI) modeling and provides a description of possible impact pathways for life cycle impact assessment (LCIA), including indicators on midpoint and endpoint levels that reflect different areas of protection (AoP).

Methodology LCI of freshwater use aims to quantify changes in freshwater availability. The key elements affected by changes in availability are sufficient freshwater supplies for contemporary human users, ecosystems, and future generations, the latter referring to the renewability of the resource. Three midpoint categories are therefore proposed and linked to common AoP as applied in LCIA.

Results and discussion We defined a set of water types, each representing an elementary flow. Water balances for each type allows the quantification of changes in freshwater availability. These values are recommended as results for the LCI of water use. Insufficient freshwater supplies for contemporary human users can mean *freshwater deficits for human uses*, which is the first midpoint impact category ultimately affecting the AoP of human life; *freshwater deficits in ecosystems* is the second proposed midpoint impact category and is linked to the AoP biotic environment. Finally, the last midpoint category is *freshwater depletion* caused by intensive overuse that exceeds the regeneration rate, which itself is ultimately linked to the AoP abiotic environment. Depending on the regional context, the development of scenarios aimed to compensate for the lack of water for specific uses by using backup technologies (e.g., saltwater treatment, the import of agricultural goods) can avoid generating direct impacts on the midpoint impact category *freshwater deficits for human uses*. Indirect impacts must be assessed through an extension of system boundaries including these backup technologies. Because freshwater is a resource with high spatial and temporal variability, the proposed framework discusses aspects of regionalization in relationship to data availability, appropriate spatial and temporal resolution, and software capacities to support calculations.

Conclusions The framework provides recommendations for the development of operational LCA methods for water

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use. It establishes the link between LCI and LCIA, water-use mechanism models, and impact pathways to environmental damages in a consistent way.

Recommendations Based on this framework, next steps consist of the development of operational methods for both inventory modeling and impact assessment.

Keywords Freshwater resources · Freshwater use · Life cycle impact assessment · Life cycle inventory

1 Introduction

1.1 Background

Freshwater is a vital resource in sustaining both ecosystem health and human survival. Freshwater scarcity has been recognized as one of the most crucial environmental concerns (UNESCO 2006). Many regions around the world are already facing this problem. In Central Asia, the diversion of rivers for irrigation purposes caused the desiccation of the Aral Sea. Ecosystems in adjacent regions have been completely disturbed, and human activities such as shipping or fishing are no longer possible. In northern China, the overuse of water resources has led to drops in water tables and river levels, and ultimately to the degradation of these resources. In the Middle East, the allocation of rivers such as the Jordan, Tigris, and Euphrates among different countries has been problematic and creates environmental as well as social and economic problems (Lasserre 2005).

Because life cycle assessment (LCA) is increasingly used by decision-makers to determine sustainable product and technology choices, it is crucial that this assessment tool be able to tackle all major environmental issues, including the consequences of freshwater use. Current life cycle inventory (LCI) data only provide information on the volume of freshwater used for product systems, with sometimes limited information about its origin (type of water resource) and none about its fate (volume, quality, and place of release). Life cycle impact assessment (LCIA) methods hardly provide assessment schemes and characterization factors for the potential environmental impacts of freshwater use and its depletion. These methods therefore generally overlook the significant environmental consequences of the decrease in freshwater quality and availability. Several method developers ((Jolliet & Müller-Wenk 2004); (Koehler 2008)) and practitioners ((Bauer & Zapp 2005); (Friedrich 2001); (Landu & Brent 2006); (Raluy et al. 2005); (Sanjuan et al. 2005); (Vince et al. 2008)) have highlighted these limitations.

Here, we present the first outcomes of the "Assessment of use and depletion of water resources within the LCA Framework" (WULCA) project, undertaken in the second phase (2007–2010) of the UNEP–SETAC Life Cycle Initiative (Koehler & Aoustin 2008).

1.2 Objectives

We aim to systematize all identified impacts of off-stream freshwater use into a conceptual framework compatible with the LCA methodology. This paper particularly aims to (1) propose a consistent terminology for assessing the use of freshwater as a resource; (2) recommend improvements to LCI methodology to better quantify and qualify the extraction of freshwater from the ecosphere into the product system; (3) suggest a consistent set of impact indicators at midpoint and endpoint levels that reflect different areas of protection; (4) define a set of possible impact pathways, including a description of the qualitative aspects of the cause–effect chain relationships; and (5) provide a scheme with which to differentiate the impacts of water use in different regional contexts.

This paper sets the methodological basis and key principles for assessing off-stream freshwater use (both degradative and consumptive water removed from the natural body, see Section 2.1), in order to support quantitative modeling in current and future research. Supplying operational assessment methods and characterization factors does not fall within the scope of this publication, but it remains the final objective of the WULCA project.

1.3 State of the art

Freshwater is commonly defined as an abiotic resource ((Finnveden 1996); (Heijungs et al. 1997); (Lindeijer et al. 2002)). Two issues pertaining to freshwater use are identified. The first one is depletion of the resource caused by an extraction rate that surpasses the regeneration rate over long periods of time. Consequently, access to the resource becomes more onerous for future generations ((Lindeijer et al. 2002); (Udo de Haes et al. 2002)). The second issue is competition for freshwater resources, which occurs when a current supply of a certain resource implies less availability for other contemporary users over a limited period. In this particular case, problems exist regarding allocating the resource among different users ((Finnveden 1996); (Lindeijer et al. 2002)).

Three types of abiotic resources are often distinguished depending on their regeneration rate ((Finnveden 1996); (Heijungs et al. 1997)): deposit or stock resources (regeneration rate ~0), fund resources (low regeneration rate), and flow resources (high regeneration rate). Although there are many methods to assess stock resources such as fossil fuels or minerals, methodological development is limited for other resource types such as freshwater.

(Owens 2001) proposes a set of indicators that allows for distinctions among different types of freshwater uses in terms of water quantity and quality. Some of these concepts are described in the present paper (see section 2.1). Although Owens' definitions establish an appropriate basis on which to assess the water balance in the LCI phase, environmental mechanisms and related impact pathways caused by freshwater use remain unaddressed.

(Brent 2004) proposed an assessment method to compare the use of different types of resources through a distance-to-target normalization approach in the South African context. However, while allowing for a comparison of freshwater use with other types of resources such as land or minerals, this method does not model the environmental mechanisms involved in freshwater use.

The Swiss Ecological Scarcity Method (Frischknecht et al. 2008) provides a set of 'eco-factors' to assess freshwater resource use. Frischknecht and colleagues used two concepts: the relationship between water scarcity and the rate of depletion (i.e., the scarcer the resource, the higher the weighting factor assigned to freshwater depletion) and the spatial variability of that rate. Their proposed eco-factors pinpoint six categories of water stress, which are calculated by comparing the current pressure on the freshwater resource (expressed by the water consumption-renewable water resource ratio) in a specific area to the critical values defined by the OECD (OECD 2004).

(Bauer & Zapp 2005) highlighted the high spatial variability of this resource. They illustrated this point with a case study on aluminum production that showed higher environmental burdens in areas exhibiting freshwater scarcity as compared with areas with a high freshwater availability.

(Chapagain & Hoekstra 2004) proposed the 'water footprint' concept, which accounts for the total volume of water used within the life cycle of products, taking into account the geographical location of withdrawals (e.g., source country). From an LCA perspective, the water footprint of a product corresponds to the output of an LCI: the quantification of the elementary flow 'freshwater' crossing the system boundary from nature to technosphere. The flow is subdivided into 'green,' 'blue,' and 'gray' water. Green water is the volume of water evaporated from soil (rainwater stored in the soil as soil moisture). Blue water denotes surface or ground water evaporated during a production process (e.g., cooling or irrigation water). Gray water is the amount of water needed to dilute pollutants released to natural waters to an accepted concentration standard.

Task Force 2 of the UNEP–SETAC Life Cycle Initiative (phase 1), which was in charge of examining issues related to resource consumption such as land and water use, made a few recommendations concerning the development of a consistent framework to assess freshwater use in LCIA in an unpublished document (Bauer et al. 2006). These recommendations can be summarized as follows: (1) the assessment method should be regionalized in reference to the hydrological context; (2) freshwater consumption (i.e., the difference between the amount of water entering and leaving the product system) is a phenomenon that creates impacts because it lowers freshwater levels and also deprives other users in the technosphere and ecosphere of the resource; (3) a set of water resource types is detailed with the constraints and limits for its use and supply; (4) resource depletion can be considered as a midpoint, while human health and reduction in biodiversity seem to be appropriate endpoints; (5) natural resource damage categories may not be considered if the cause–effect chain is modeled up to the human health and ecosystem quality categories; (6) impact pathways should be considered that highlight human health damages through the use of lower quality water for domestic purposes and reductions in food production; and (7) impacts of food-compensation production and those on biodiversity through desiccation and loss of habitat should also be addressed.

More recently, a new methodology has been proposed focusing on impacts caused by 'evaporative use' of freshwater (Milà i Canals et al. 2009). Four main impact pathways are identified: (1) changes in freshwater availability that affect human health, (2) changes in freshwater availability affecting ecosystem quality, (3) extraction of groundwater causing depletion, and (4) land use affecting the water cycle and therefore ecosystem quality. The authors propose differentiating the inventory parameters into green water (stored as soil moisture) and blue water (surface and groundwater). They also provide a set of indicators in order to generate characterization factors for freshwater ecosystems impact and for freshwater depletion. Effects on human health caused by lack of adequate water resources are not considered as a significant issue.

In parallel to the present work, (Pfister et al. 2009) developed an operational method to assess impacts of freshwater consumption. They proposed a midpoint indicator, 'water deprivation', which is calculated as a function of freshwater scarcity considering regional hydrological conditions. Seasonal variations of precipitation and freshwater storage capacities are included. This midpoint indicator is further linked to the damage category human health. The proposed damage indicator accounts for additional Disability Adjusted Life Years (DALYs) caused by malnutrition related to unavailability of freshwater for irrigation and the associated reduced crop yields. The proposed damage indicator for ecosystem quality accounts for the net primary production affected by freshwater deficits. Finally, damage to freshwater resources is modeled using the backup technology approach and with estimates of energy requirements for desalination of saltwater. The methodology is fully operational for assessing consumptive freshwater use, because it provides regionalized characterization factors on a watershed level with global coverage.

2 Key issues surrounding off-stream freshwater use

In this section we cover the key issues relevant to developing the framework for assessing freshwater off-stream use. Because harmful effects of chemicals added to the water cycle are already taken into account in other impact categories, such as aquatic ecotoxicity or eutrophication, this framework only considers that deterioration in water quality might reduce the number of uses the water can fulfill downstream. The framework also considers the net reduction of the resource due to freshwater consumptive use.

2.1 Proposed terminology

Freshwater use is a generic term that groups all types of human uses of freshwater resources. *In-stream freshwater use* is the use of water in situ (e.g., navigational transport on a river), whereas *off-stream freshwater use* is the use of water that requires human removal from a natural body of water or groundwater aquifer (e.g., pumping or diversion for municipal, agricultural, or industrial uses; (Owens 2001)). This distinction implies that different methods for LCIA are required depending on the type of use because they do not rely on the same pattern: although quality and flow regime might change, in-stream use leaves the resource available for ecosystems, whereas off-stream use does not. Building on the terminology proposed by (Owens 2001), we define *freshwater degradative use* as the withdrawal and discharge into the same watershed after the quality of the water has been altered (terminology proposed by (Pfister et al. 2009)), while *freshwater consumptive use* denotes the use of freshwater when release into the same watershed does not occur because of evaporation, product integration, or discharge into different watersheds or the sea (Table 1). Combining these definitions leads to the classification of four types of freshwater use, namely in-stream consumptive and degradative uses and off-stream consumptive and degradative uses. Illustrative examples for the water types specified are outlined in Table 2. In general, in-stream consumptive use (e.g., evaporation from dams) can be regarded as relevant when the resulting reduction in freshwater availability may cause downstream users to be deprived of freshwater.

Competition for freshwater resources arises when the current freshwater availability is too low to fulfill the requirements of all freshwater users. In such cases, the allocation of available freshwater resources among different users becomes problematic. The threshold that characterizes competition is reached when human withdrawals represent more than 10% of the total available renewable freshwater resource (OECD 2004). Then, the intensity of the competition increases with additional withdrawals and increasing reductions in availability. *Freshwater depletion* is defined as the net reduction in the availability of freshwater in a watershed for a given time period. It covers fossil aquifers and flow and fund resources exploited over their renewability rate. From a resources perspective, fossil aquifer is not equal to groundwater, but ultimately depletion can be assessed in the same way through the relationship of the resource with its renewability rate. This could be expressed as the amount of water depleted over a defined time period for a flow and infinite time for a fossil aquifer resource.

Competition for freshwater resources and freshwater depletion are strongly interconnected. Freshwater depletion also reduces freshwater availability for current users, generating competition for the freshwater resource. Therefore, both of these phenomena can appear at the same time. In addition, freshwater depletion reduces resource availability for future generations, for whom the intensity of the competition for freshwater will potentially increase.

2.2 Quantity and quality aspects of off-stream freshwater use at the life cycle inventory level

The objective of the LCI stage is to quantify changes in freshwater availability. These changes are generated by both freshwater consumptive use (a reduction of the net volume of water within the watershed) and freshwater degradative use (a reduction in the availability of freshwater of initial quality in the watershed). Current LCI concepts, however, are very rudimental in regards to water use and so far neglect such distinctions. We therefore provide a primary scheme for LCI modeling and give recommendations for improvements in LCI practice.

For this purpose, we propose that the inventory flows represent a set of water types each representing an elementary flow with its own characterization factors. Resource type (e.g., groundwater, surface water) is the first parameter that should be considered for distinguishing among water types. This distinction is already made in some LCI databases, such as in the ecoinvent database (Ecoinvent Centre (Ecoinvent 2009)). Water quality is suggested as the second parameter for water type classification. The definition of quantitative values defining water quality remains a complex challenge, which is outside the scope of this paper. However, the quality can be considered using two distinct approaches: distance-to-target or functionality. In the former, the quality of the different water types is assessed by determining the equivalent effort necessary to process each water source to the same final quality. This can be done either by assessing the volume of water required to dilute a given water type to acceptable

Table 1 Key terminology and definitions related to water use as proposed for the framework

Terminology	Definition
Freshwater use	Generic term that groups all types of human uses of freshwater resources
In-stream freshwater use	Use of water in situ (e.g., navigational transport on a river)
Off-stream freshwater use	Use of water that requires human removal from a natural body of water or groundwater aquifer (e.g., pumping or diversion of water for municipal, agricultural, or industrial purposes)
Freshwater degradative use	Withdrawal of water and discharge into the same watershed after the quality of the water has been altered (includes both quality deterioration and improvement)
Freshwater consumptive use	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
Competition for freshwater resources	Temporary reduced freshwater availability for current users
Freshwater depletion	Net reduction in the amount/availability of freshwater in a watershed or/and fossil groundwater stock. Depletion occurs when freshwater consumptive use exceeds the renewability rate of the resource over a significant time period

quality standards (e.g., drinking water quality), or by assessing the energy required to purify a resource at the same quality. In the latter, the quality is considered with a functionality approach, which assesses to which users the water withdrawn and released is functional. Water is considered functional for a particular user if its quality parameters respect accepted standards concerning this user. These standards can be taken from FAO for irrigation (Ayers and Westcot (Ayers & Wescot 1985)), and for aquaculture (Svobodová et al. 1993). Industrial standards can be used for domestic and industry.

In addition to quantifying the volume of freshwater entering the product system, LCA datasets should include the volume of water leaving it. The balance of each elementary flow makes it possible to quantify the net changes of availability for each of them. We illustrate the concept for cotton crops at a global scale: 95% of the world's irrigated cotton fields are equipped with low-cost surface irrigation that has low efficiency of about 40% (Kooistra et al. 2006). Pakistan, which is one of the biggest cotton producers with a 8.5% share of global production, consumes about 10 m3 irrigation water per kilogram cotton (Pfister et al. 2009), while the total irrigation water use amounts to 25 m^3/kg. This results in 15 m^3/kg degradative water use, which is subject to quality alteration. Assuming irrigation water withdrawn from an aquifer of good quality and drained back to a river, the elementary flows are defined as follows for the water quality inventory method: consumption of 25 m^3 of water type 'high-quality aquifer water', emission of 15 m^3 water type 'low-quality river water' (gain of this water type). With a functionality approach, this could result in the consumption of 25 m^3 of water 'functional for agriculture, domestic, and industrial', and emission of 15 m^3 water 'functional for agriculture, industrial, transport, and hydropower' for example.

All water use assessment methodologies introduced in section 1.3 have shown high spatial variability of freshwater use impacts; therefore, regionalization should be included already within the LCI phase, differentiating by geographical location (e.g., watershed; see also Section 4). This recommendation is in accordance with future evolution of LCA databases (Weidema 2009).

Table 2 Examples illustrating the terminology as proposed in Table 1

	Water use	
	In-stream use	Off-stream use
Consumptive use (depletion: use > renewability rate)	Evaporative loss of canals and water reservoirs used for, e.g., transportation and hydropower generation, respectively	Evaporation of irrigated water in agricultural production Product integration, e.g., in food products Alpine hydropower (dissipative loss of freshwater due to diversion of water from the original flow)
Degradative use	Cooling water of, e.g., a power plant: quality degradation occurs through uptake of heat and thermal releases into the aquatic environment	Water withdrawals or domestic and industrial purposes and release of effluents from wastewater plants: generally the water quality is degraded to some extent, e.g., increase in biological oxygen demand (BOD)

2.3 Impact pathways and midpoint/endpoint indicators along the cause–effect chain

2.3.1 Three elements of environmental concern

This paper identifies three general elements of environmental concern to be considered in the cause–effect chain assessment: the sufficiency of freshwater resources for contemporary human users and existing ecosystems and the sustainability of freshwater resources for future generations and the future use of present-day generations (for both humans and ecosystems). *Sufficiency of freshwater resources for contemporary human users*: past research defined resources as 'entities valued for the functionality that they deliver to human society' (Stewart & Weidema 2005). 'The concept is strongly linked to human valuation and technology. An object of nature is considered to be a natural resource only when humans show an interest in extracting and subsequently using it in an economic system' (Lindeijer et al. 2002). These concepts have been adapted here to associate the value of the freshwater resource with the functions that it delivers to the technosphere. Changes in freshwater availability affect all potential contemporary downstream human users, as these changes lead to an increasing competition for freshwater. Some users may no longer have access to freshwater at all and therefore must reduce or modify their activities, thereby changing environmental impacts.

Sufficiency of freshwater resources for existing ecosystems Freshwater is not only valuable for human needs, but it is also essential to sustain biodiversity and ecosystem functions (e.g., nutrient cycling and photosynthesis). Change in freshwater availability directly affects contemporary ecosystems (e.g., modification of biodiversity by desertification or shrinking the aquatic habitat).

Sustainable freshwater resource base for future generations and the future use of present-day generations Water is the only abiotic resource that has no substitute for certain purposes (e.g., drinking water for humans or sustaining ecosystem life). Therefore, keeping a sustainable base of freshwater resources for future generations could be considered an environmental interest for continued human and ecosystem existence.

2.3.2 General description of the cause–effect chains

An imbalance in one, two, or all of these general elements of environmental concern can potentially generate environmental impacts. Therefore, three main sets of impact pathways associated with each general element of environmental concern have been developed, linking water use to three new midpoint impact categories and ultimately to current endpoint categories (Margni et al. 2008). Figure 1 provides a description of these impact pathways in a generalized cause–effect chain framework.

The first set of impact pathways addresses the competition over freshwater resources between different contemporary human activities due to an insufficiency of the resource. This leads to freshwater deficits for human uses, or the development of compensation processes to adapt to the decrease in freshwater availability. The second set of impact pathways relates to freshwater insufficiency for existing ecosystems generally due to increased human withdrawals, which causes *freshwater deficits in ecosystems*. The third pathway addresses the reduced availability of freshwater for future generations (i.e., the reduction of long-term availability of the natural resource) and outlines *freshwater depletion*, a midpoint indicator that represents the reduction in the freshwater volume of the watershed over a long time period. The different impact pathways could be affected concurrently (for details see Section 3).

We suggest expressing these three new midpoint indicators in 'cubic meters of freshwater equivalent', calculated by weighting the physical cubic meter by parameters that differentiate the value of the resource according to water types based on indicators such as water resource type or freshwater quality (see Section 2.2). Building on the midpoint indicators proposed, impact pathways are extended to endpoint indicators within three areas of protection (AoP) commonly accepted in LCIA: human life (human health and labor), biotic environment (biodiversity and biotic productivity), and abiotic environment (abiotic natural environment, abiotic natural resources, and abiotic man-made environment). The three elements of environmental concern identified can be reflected in these three AoP, where damage to human life is only assessed for current generations. Note that the quantitative modeling and link to endpoint categories is not the primary goal of this paper, therefore it can be considered as a first proposal to be modified for further LCIA method developments, if needed.

3 Description of the three impact pathways

3.1 Impact pathways linked to freshwater resource insufficiency for contemporary human users

To assess the impacts of freshwater insufficiency for contemporary human users, we propose applying the functional approach introduced by (Stewart & Weidema 2005), which states that some abiotic resources have a functional value for humans. This impact pathway aims to

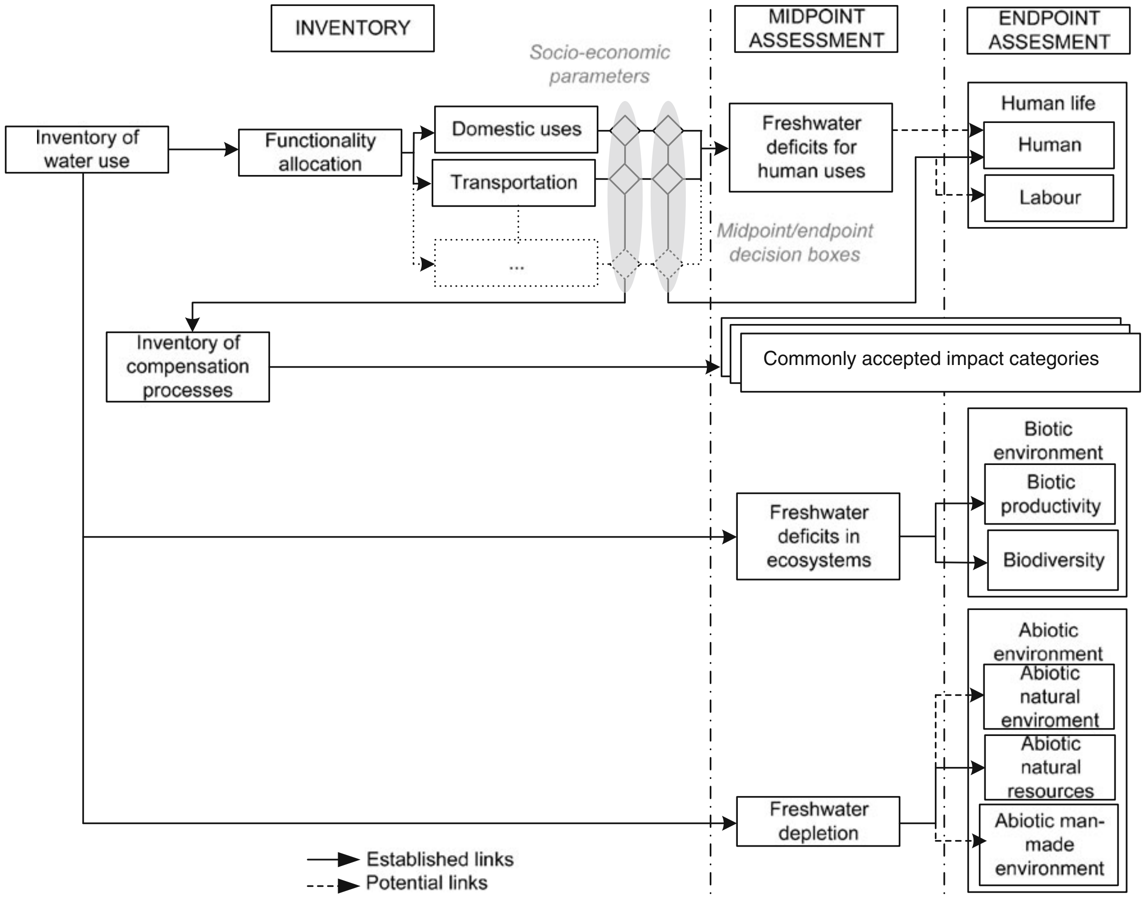

Fig. 1 Description of relevant cause–effect chains

define how the human functional value of the resource is affected by its use and how to link the resource with elements of intrinsic value such as human health.

At the most basic level, a decrease in freshwater availability affects the human activities that require freshwater. Current freshwater functions within the technosphere are well known: maintaining human and environmental health, supporting biotic production and industrial activity, carrying goods, and playing a psychological role given its esthetic or cultural value ((Lundqvist & Gleick 2000); (MEA 2005)). Freshwater is therefore used for human purposes through off-stream use (withdrawals for domestic, agricultural, and industrial purposes) and in-stream use (shipping, fisheries, and recreational uses; Table 3). Hydropower generation as an additional human use of freshwater can be both off-stream and in-stream use (see Table 3).

However, not all water types can be used for all human purposes. For example, shipping or fishing is only possible in surface waters, not in groundwater. A reduction in freshwater availability only affects the potential uses of a given water type. This principle is depicted as ‘Functionality Allocation’ in Fig. 1.

Freshwater reduction could prevent downstream users from fulfilling their needs. The yield of the activity (i.e., the quantification of the product or service delivered by the activity in a specific area) is therefore affected. For example, reducing freshwater availability in an agricultural area affects crop irrigation and thus food production; lowering canal levels when the resource is allocated to other purposes hinders barge shipping and reduces the volume of goods transported. A set of qualitative yield indicators is proposed in Table 3. When freshwater availability is reduced, two scenarios are possible: deficiency and compensation.

3.1.1 Deficiency scenario

Yield losses result in limited capabilities to provide a product or supply a service. For example, a reduction in drinking water can lead to the consumption of water of lower quality and, in turn, an increase in disease. Furthermore, water scarcity may affect agricultural yields and, consequently, food availability, which leads to an increase in cases of malnutrition and disease.

Table 3 Freshwater contemporary human users from the technosphere and impacts of reduction in water availability

Freshwater user	Yield indicator	Impact scenarios (D = deficiency; C = compensation)		LCA impact categories potentially affected		Socio-economic parameters
				Midpoint	Endpoint	
Domestic	Volume of potable water supplied	D	Lack of hygiene Use of low-quality water Thirst	Freshwater deficits for human uses	Human health	% of the population with access to safe drinking water or sanitation
		C	Water imported New water treatment processes	Generation of a new LCI assessed with a full LCIA methodology that accounts for all impacts		
Agriculture	Mass of food product	D	Undernutrition Malnutrition	Freshwater deficits for human uses	Human health; biotic production	% of the population affected by malnutrition
		C	Food imported Changes in food production	Generation of a new LCI assessed with a full LCIA methodology that accounts for all impacts		
Industry (and cooling)	GDP derived from industry	D	Lack of goods	Freshwater deficits for human uses	Human health; labor	GDP per capita
		C	Goods imported Changes in goods production processes	Generation of a new LCI assessed with a full LCIA methodology that accounts for all impacts		
Transportation	Volume or mass transported	D	Lack of goods	Freshwater deficits for human uses	Human health; labor	GDP per capita
		C	Changes in methods of transportation (e.g., truck or train)	Generation of a new LCI assessed with a full LCIA methodology that accounts for all impacts		
Hydropower	MJ produced	D	No access to electricity	Freshwater deficits for human uses	Human health; labor	% of the population with access to electricity
		C	Changes in electricity production processes	Generation of a new LCI assessed with a full LCIA methodology that accounts for all impacts		
Fisheries	Mass of fish produced	D	Malnutrition	Freshwater deficits for human uses	Human health; biotic productivity	% of the population affected by malnutrition
		C	Fish imported	Generation of a new LCI assessed with a full LCIA methodology that accounts for all impacts		
Recreation	GDP derived from aquatic recreation	D	Absence of recreational activities	Freshwater deficits for human uses	Human health	GDP per capita
		C	Changes in recreational activities Relocation of recreational activities	Generation of a new LCI assessed with a full LCIA methodology that accounts for all impacts		

Table 3 presents a proposed set of deficiency scenarios for each human activity. Each scenario may generate specific impacts related to human health. In order to aggregate the respective impacts of the scenarios suggested, we propose a new midpoint category denoted freshwater deficits for human use. This impact category represents the intensity of the competition between human users. One can argue that competition for a resource is not relevant in an LCA perspective and should be treated within the econosphere ((Lindeijer et al. 2002); (Bauer & Zapp 2005)). However, in the context of modeling environmental impacts of freshwater use, we believe that considering the competition for freshwater resources is relevant because the type and extent of environmental burdens are the direct consequence of the allocation choices with regards to human uses ((UNCSD 1997); (UNESCO 2006)). Examples are numerous and diverse: Turkish storage and withdrawal on the Euphrates River for hydropower production and irrigation of crops affect Syria and Iraq's irrigation capacity, reducing their crop yields; high extraction rates from the river supplying the Aral Sea for irrigation purposes lowered the sea level in a dramatic way, hindering fisheries and shipping (Lasserre 2005).

The associated midpoint indicator shall be expressed in cubic meters of freshwater equivalent unavailable for downstream users. Although providing operational characterization factors is outside the scope of this paper, we propose a set of principles and three related qualitative parameters that should be accounted for when calculating such midpoint characterization factors.

The first parameter is the state of freshwater scarcity in the area. As water becomes scarcer, continued water use increasingly deprives other users. This principle has already been taken into account by the Swiss Ecological Scarcity Method (Frischknecht et al. 2008) and in a more general way by all freshwater stress indexes developed (e.g., (Rijsberman 2006)). Considering this type of parameter necessarily leads to a spatially explicit modeling, i.e., to a regionalization of the midpoint assessment.

The second parameter depends on the method chosen for quality assessment within the inventory; it will either be based on distance-to-target or functionality. A distance-to-target parameter could be an index allowing the characterization of the different water types into a single indicator. The distance-to-target approaches proposed above (i.e., dilution volume or energy requirement for purification of water) represent possible solutions, but need further research to be made operational. A functionality parameter would assess for which users the water type defined in the elementary flow is functional.

The parameters encompassing scarcity and functionality or quality proposed to calculate the midpoint indicator must be viewed as suggestions to enhance the current methods based on water scarcity criteria (e.g., (Frischknecht et al. 2008); (Pfister et al. 2009)).

Apart from the midpoint assessment, the cause–effect chain can be modeled up to the damage level. A reduction in a service or a product provided to humans could result in a loss of life years or life quality and can therefore be converted for example into a DALY indicator, which is broadly applied in LCA (Murray 1996). Two phenomena predominantly affect human health in case of insufficient water availability. First, denial of access to safe drinking water implies increases in sanitation- and water-quality-related diseases. Research is under way to quantitatively determine this impact pathway (e.g., (Motoshita et al. 2009); (Pfister et al. 2009)). Second, reduced freshwater availability for irrigation can cause diminished crop yields in agricultural production, and ultimately malnutrition. Quantitative modeling of this relationship has already been integrated in the method of (Pfister et al. 2009) which employs the DALY metric for the damage factors proposed. The complex cause–effect chain model applies various socio-economic, hydrological, and environmental parameters such as the human development index, a water scarcity index, water use for agriculture, and health impact assessment information depicting the relationship between water deficiency for agricultural production and country-specific malnutrition rates.

Please note that socio-economic impacts of water scarcity are neither considered in this framework nor in the operational methods being developed. Freshwater-stress-related problems such as political tensions, social conflicts, war, or population migration, represent social consequences of freshwater use and should be rather addressed in social sustainability assessments. However, socio-economic conditions described by appropriate indicators should be integrated in the environmental damage assessment. This allows to properly evaluate the consequences of water allocation choices on human health impacts, as also demonstrated by other method developers (e.g., (Motoshita et al. 2009)).

The midpoint indicator freshwater deficits for human uses aggregates water shortage for different human activities into a single score result. Although simplifying the interpretation of this aggregated indicator is one of its advantages, relevant information is lost by the aggregation as impacts on human health differ depending on the activity affected by the lack of water (e.g., lack of water for domestic purposes may affect human health through water-related diseases, while lack of water for agriculture may cause malnutrition). Thus, subsequent meaningful midpoint/endpoint modeling is impeded. Therefore, endpoint impact categories can also directly be linked to water amounts deprived or depleted according to activity (see decision box between midpoint and endpoint in Fig. 1).

Labor could also be affected because a lack of water for industrial purposes reduces goods production. This additional link must be considered carefully to avoid double counting, as the impact on human health may already account for changes in quality of life due to restrictions regarding manufactured goods. This last link may account for social aspects rather than environmental problems (Koehler 2008). We have therefore defined this link as a potential impact pathway (dotted lines, Fig. 1), recognizing that more research is needed.

3.1.2 Compensation scenario

Compensation for the loss of yield of human activities is possible through backup technologies, which represent the additional efforts necessary to produce the goods or services generated by the human activities which are affected by the reduction in water availability (Stewart & Weidema 2005). Backup technologies can include, among others, desalination plants to offset the reduction in freshwater availability and truck transport applied when freight transport on rivers or canals is difficult or no longer possible because of low water levels. The same analysis can be extended to all human activities, as shown in Table 3.

To assess the indirect impacts generated by the compensation scenario, product system boundaries should be extended to include the environmental burdens generated by the backup technologies chosen. From an LCA standpoint, these rebound effects must be considered within the LCI, because here we are seeking to represent not the environmental mechanisms, but the technological changes induced by freshwater use ((Finnveden 2005); (Weidema et al. 2005)). The additional LCI should then further be evaluated with a standard LCIA approach. A marginal approach could be adopted if the technologies affected by the decrease in freshwater availability were exactly known, de facto turning this model into a consequential model.

A set of generic compensation scenarios could be modeled and proposed along with this method, as described in Table 3 to help practitioners. However, practitioners must ensure that the generic scenario is a relevant proxy in their specific cases. Water scarcity in the Barcelona region (Spain), for instance, is an acute problem, affecting, among other things, the drinking water supply. A default generic backup technology for water compensation could be desalination of seawater. However, while a desalinization plant is foreseen, the city of Barcelona has imported freshwater by tankers from France few times in the past, thus indicating a potential different compensation option. Water transfers by pipelines and canals such as applied in the state of California and in the South–North water transfer project in China illustrate another compensation alternative. These examples indicate the difficulties in choosing adequate marginal technologies and the need for additional research.

The choice between deficiency and compensation scenarios depends on socio-economic parameters. Wealth and economic development characterized by, e.g., gross domestic product (GDP) and the human development index strongly correlate with access to safe drinking water or improved sanitation (Sullivan 2002). This principle can be generalized to all water-using activities. Adaptability of human activities is generally based on wealth: the richer the area, the more easily it will be able to compensate for the lack of freshwater. As desalination plants, for example, represent expensive technological systems, this backup technology option is generally appropriate for wealthy countries, e.g., in the Middle East (specifically the United Arab Emirates) which can afford to operate many plants to fulfill their needs on water supply (WWF 2007). More globally, wealthy countries no longer suffer from famine due to sufficient production and imports of food products thus compensating potential food deficits (FAO 2008).

In general, GDP is a meaningful indicator of wealth and can thus be selected as decision parameter for some freshwater uses. However, we suggest to apply specific indicators for each of the freshwater functionalities because levels of socio-economic development may differ. In South Africa, for instance, less than 2.5% of the population suffered from malnutrition, while 12% of the population had no access to safe drinking water (World Resource Institute (World Resource 2004); status: 2002–2004). A selection of socio-economic parameters to assess the adaptation capacity in regards to water scarcity is presented in Table 3. Quantitative approaches have to be developed to determine the exact population share that is affected by water deficits and compensation scenarios. Generally, this compensation approach could be used for all types of resources. In the case of freshwater, without considering these compensation effects, the use of water in countries such as the United Arab Emirates would not generate any impact in LCA models.

3.2 Impact pathways linked to freshwater resource insufficiency for existing ecosystems

A decrease in freshwater availability reduces aquatic ecosystem habitats, leads to the desiccation of the land, and thus modifies the occurrence of terrestrial species ((Lundqvist & Gleick 2000); (Nixon et al. 2000); (MEA 2005)). The established impact category for ecosystem damages calculates the adverse consequences of water deficits caused by human uses in ecosystems. The midpoint indicator suggested could be expressed as cubic meters of freshwater unavailable for ecosystems and the functions they provide. Biodiversity and biotic production are damages categories that can be linked with the proposed midpoint category and measured in commonly accepted units, or alternatively directly calculated from LCI elementary flows (Fig. 1). Few examples of published and under development characterization methods are illustrated below addressing both aquatic and terrestrial ecosystems. Both the pressure of human withdrawals on the freshwater resource in a given area (expressed by the spatially explicit freshwater scarcity) and the ecological value of the resource describing the physical relation to and dependency on freshwater represent essential parameters for calculating the midpoint characterization factor. Freshwater resources in different areas exhibit a varying importance for the respective regional ecosystems. Large and long-lived lakes such as Baikal or Tanganyika, for instance, are considered to support higher species diversity than other freshwater catchments (Groombrindge and Jenkins (Groombridge & Jenkins 1998)). Therefore, further research is needed to define appropriate characterization factors which quantify potential losses in biodiversity and ecosystem functions considering regional ecosystem characteristics.

Methods that are currently under development suggest both midpoint and endpoint modeling approaches. Mila i Canals et al. (Milà i Canals et al. 2009) propose to weight consumptive water use with a water stress indicator that considers environmental water requirements as introduced by (Smakhtin et al. 2004). The category indicator describes the volume of ‘ecosystem-equivalent’ water, referring to the volume of water likely to affect freshwater ecosystems.

(Pfister et al. 2009) calculated regionalized characterization factors for water consumption by quantifying the reduction of primary production due to water limitation. The loss in primary production, which is expressed as potentially disappeared fraction, serves as a proxy for the loss of vascular plant biodiversity. The methodology applies global climate and land-use data for computing the portion of plant growth that is limited by water availability. An area–time factor (m^2*year) which is part of the characterization factor and corresponds to the water amount consumed was derived from precipitation data.

In addition to the general water-consumption methodology proposed by (Pfister et al. 2009), (Van Zelm et al. 2008) are modeling the cause–effect chain that specifically links freshwater extraction from groundwater reservoirs and the potential damages to terrestrial ecosystems. The extraction of groundwater causes a decline in groundwater levels, making it impossible for the roots of certain plants to reach the groundwater and resulting in a decline in biodiversity. The researchers suggest combining a fate factor describing the time necessary for the water table to reach its original level and an effect factor depicting the ecosystem’s sensitivity to groundwater drop. The resulting characterization factor is expressed by the potentially not occurring fraction of plant species over a given time period per cubic meters of water use (PNOF*year/m^3). Spatially resolved fate factors, expressing the change in groundwater level caused by a change in groundwater extraction rate, were calculated with the hydraulic model MODFLOW and using climatic and hydrological input data. The effect factor, expressing the change in PNOF due to change in groundwater level, was derived from the probability of occurrence of individual plant species. The method is highly data intensive and only applicable for the Netherlands. In its first version, Maendly and Humbert (Maendly and Humbert 2009) propose an empirical damage assessment model that assesses the impacts of water use for hydropower production on biodiversity. The method is based on empirical observations of the fraction of (fish) species that disappear after the construction of a dam on a given affected area (in PDF*m^2) due to a certain amount of water used per year (in m^3/year). Although they refer to in-stream freshwater use, the concepts that have been developed are interesting in that they link the reduction in the occurrence of both downstream and upstream species to river water flow modifications. These different examples show further potential quantitative development of this cause–effect chain.

3.3 Impacts for future generations linked to unsustainable use of freshwater

When consumptive use reaches the freshwater renewability rate in a specific area, further consumptive use creates freshwater depletion. This phenomenon is particularly relevant when referring to resources such as fossil aquifers, but depletion could also occur in fund or flow resources such as renewable aquifers (e.g., the High Plains Aquifer in USA (USGS 2003) and rivers, e.g., the Yellow river in northern China (Lasserre 2005)) where water is consumed at a high intensity and surpasses the natural renewability of the resource. Considering current water-use trends, this phenomenon will increase in the coming decades (UNESCO 2006) indicating the significance of depletion impacts. A new midpoint category, called water depletion, is therefore proposed that describes the volume of water that ‘disappears’ from a given watershed for a period of time and refers to both flow and stock resources. Such freshwater exhaustion implies that the resource will not be available for future generations and for future uses of existing generations. The impact indicator could be expressed in cubic meters of freshwater equivalent depleted. The renewability rate of the resource could be used to determine the time period for which depletion is occurring and thus allow a time-dependent distinction of freshwater depletion. From a practical point of view, this indicator would correspond to consumptive use of freshwater going beyond the renewability rate during a given time period, which is particularly relevant for distinct water bodies (e.g., lakes, rivers, and streams). Thus, depending on the methodological approach taken, depletion can be considered on a watershed level as well as on the level of individual water bodies (e.g., fossil aquifers and lakes). The renewability rate and the intensity of consumptive use are region-specific and a spatially differentiated approach to this midpoint impact category is therefore necessary.

Freshwater depletion can be modeled as a damage category, as we argue above, but modeling future scenarios of depletion and environmental damage due to scarcity will be complex, especially with regard to current and future human use. First of all, the choice between a deficiency or compensation scenario depends on socio-economic parameters that are extremely difficult to predict. Second, although we can reasonably identify and assess the current compensation processes used to fulfill human needs, future technological innovations are uncertain. Third, some potential freshwater uses for which water depletion would be an impediment have likely not been identified yet. For example, groundwater is essential to soil stability. Lowering the water table through withdrawal and changing particular soil properties could lead to soil surface subsidence. Human-made environments could therefore be extremely impacted (Mousavi et al. 2001). Also, in the past groundwater has been considered to be of low value for energy production. However, because of growing interest in renewable energy, increasing importance is being given to geothermal energy. Although part of the technology is limited to the energy supply mix, this freshwater function could be added to such modeling efforts in the near future.

This paper therefore proposes to link freshwater depletion with the abiotic natural resources damage category, keeping in mind that the existence of this damage category within LCIA is debatable. To quantify these impacts, we suggest using the concept of surplus energy required for future resource extraction (Müller-Wenk 1999). Future solutions to replace depleted freshwater must be identified, and the additional efforts required to replace water resources or to reduce water uses so that they fall below water resources' regeneration level must be assessed. Among the different available technologies, desalination could be the ultimate strategy for substitution of freshwater (Stewart & Weidema 2005). (Pfister et al. 2009) and Mila i Canals et al. (2009) calculated respective characterization factors for this impact category considering desalinization as the ultimate backup technology. Relocating people to reduce water stress and allow for the regeneration of freshwater resources is another scenario that could be modeled. These efforts could be translated into non-renewable primary energy needs, an indicator compatible with the energy equivalents used for the abiotic resource depletion damage category.

Additionally to the natural resources area of protection, the abiotic natural environment as such could be considered as endpoint category. The freshwater resource would then refer to elements such as waterfalls or landscapes to which one can attribute an intrinsic value (e.g., the pure existence value). Abiotic human-made environments as a third protection area could also be affected by freshwater depletion, because artificial lakes or reservoirs could disappear. However, a consistent method to assess these last two damage categories is not currently available.

4 Discussion

4.1 Geographically specific modeling—regionalization

Environmental burdens of water use are diverse in different geographical regions because many parameters involved in the impact assessment scheme depend on local and regional conditions (including water quality, water availability, socio-economic parameters, and allocation between off-stream users). Therefore, an LCI must specify the location where water has been withdrawn and eventually released.

The level of spatially explicit modeling, i.e., regionalization considered is important. A significant amount of data on hydrologic parameters (e.g., the regeneration rate of water types) and water use patterns (e.g., the intensity of the withdrawal pressure, the sectoral uses of different water types) are necessary to make this framework operational and to calculate regionalized characterization factors. Integrated water resource management recommends organizing sustainable resource management at the watershed level (UNESCO 2006). However, the national level is more relevant in regards to specifying socio-economic parameters which are pertinent for setting up backup technologies. For example, Israel and the Occupied Palestinian Territories, which are neighboring countries, have similar water availability characteristics, whereas their financial situation is very unequal. Deficiency scenarios are more adapted to the Occupied Palestinian Territories, whereas compensation scenarios rather occur in Israel. The best solution for modeling, therefore, seems to cross the watershed and national levels by applying geographic information systems, as done, e.g., by (Pfister et al. 2009). The applicability of this solution depends on detailed data availability and software capacities to perform such calculations. Grouping areas among different water resource profiles is also a solution that reduces the number of characterization factors to specific archetypes, as done in the Swiss Ecological Scarcity Method (Frischknecht et al. 2008). However, to date, data acquisition and modeling instruments are still in development, which limits adequate regionalized assessments of all freshwater-use-related environmental impacts.

4.2 Temporal modeling aspects

Water availability might also have a significant temporal variability. Water stress statistics are published on an annual basis, but variations among seasons can sometimes be significant. Depending on the data availability, we also recommend including temporal aspects when developing an operational characterization model. This could involve developing two sets of characterization factors, one for the dry season and one for the wet season, for example.

From a long-term perspective, structural changes in the socio-economic system involve changes in water use patterns and behavior over time. Climate change might also modify the state of water resources in coming decades. A set of characterization factors could also be established using prospective data. These factors could be preferable for prospective studies of possible future technological systems.

4.3 Consideration of soil moisture

The framework presented here focuses on off-stream freshwater use. As such, it currently does not consider freshwater stored in the soil as soil moisture, also denoted as ‘green water’ (FAO 2003). The transformation of natural land into agricultural fields or other human land modifications could alter the availability of freshwater in the soil because the freshwater requirements of natural vegetation differ from those of crops. An example on how to address these impact pathways is suggested by Mila i Canals et al. (Milà i Canals et al. 2009), who proposed to assess the land-use changes leading to changes in the water cycle (infiltration and runoff) and ultimately to changes in freshwater availability for ecosystems. Generally, the described types of land transformation could be viewed as changes in freshwater availability and should therefore be considered in the impact pathway modeling. However, it remains debatable whether green water alternation should be included in the water-use or land-use categories of LCIA methodologies, as human interventions changing green water budgets could also be modeled and evaluated via land-use assessment approaches. Here, further discussions are required between method developers working in the field of water use and land use and a harmonization between the respective assessment metrics needs to be achieved in order to avoid problems of double counting.

5 Conclusions

This paper provides a conceptual framework for assessing off-stream freshwater use in the context of LCA and sets the basis for the development of operational LCI schemes as well as LCIA methods and characterization factors for water use. It structures and discusses the link between LCI and LCIA and provides guidance on elements and areas of protection for impact pathway modeling. The following key elements are identified to make this framework operational:

Different freshwater types representing elementary flows in the LCI should be distinguished according to water resource types and water functionalities, with each having its own LCIA characterization factor.

- In addition to any freshwater withdrawal, freshwater release after its use should be accounted for in the LCI phase to facilitate the calculation of freshwater consumption.
- Three impact pathways are potentially affected by freshwater use, corresponding to the availability of this resource for human needs, ecosystems, and future generations.
- Specific parameters quantifying freshwater scarcity, freshwater functionality, and ecological value of the resource are required for impact characterization.
- Characterization factors should be spatially and temporally explicit. Spatial and temporal resolutions depend on data availability and software modeling capabilities.

Considering the role of the freshwater resource within socio-economic and ecological systems, we believe that the framework suggested in this paper provides an appropriate basis for method development. It facilitates the modeling of the cause–effect chain relationships up to the level of human health as well as determining technological compensation scenarios generated by changes in freshwater availability. The framework further allows for structuring the modeling of adverse impacts on both biotic production and biodiversity being the main pillars of ecosystems. Because modeling the future environmental impacts of freshwater depletion is highly uncertain, this issue remains linked to the abiotic resource impact category and is thus not included in the other damage categories of human health and ecosystem quality.

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