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WATER USE IN LCA

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Operationalisation and application of water supply mix (WSmix) at worldwide scale: how does WSmix influence the environmental profile of water supply for different users?

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Abstract

Purpose A worldwide-regionalized water supply mix (WSmix) has been developed for use in life cycle assessment (LCA) studies. The WSmix is the combination of water sources and water technologies to meet a water user need at a specific time (season, month) and location. A global database has been computed to collect information on water sources and users at country and river basin scales. However, its application to LCA case studies at different locations and for different users has not yet been fully tested and analysed. The aim of this study is to operationalise WSmix for application in LCA and to test the added value and usability of WSmix by applying it worldwide to two different systems, a service and a global product, considering different climatic and socio-economic conditions.

Methods The WSmix is applied to two main water users, the results are analysed, and the variability of the WSmix for 91 countries with different socio-economic conditions is discussed. Some examples of the variability of the water sources mix (WOmix) and the temporal variation at river basin scale are presented.

Results and discussion The results show that the WSmix has a great influence on the environmental profile of water supply for different users considering different climatic and socio-economic conditions. Moreover, the interdependence between water and energy (i.e. water-energy nexus) is clearly established, which reinforces the importance to link a regionalized WSmix with national/regionalized electricity mix.

Conclusions In conclusion, the WSmix has been operationalised and applied in LCI databases. Its added value and usability has been demonstrated by applying it at a worldwide scale for two different users. Methodological developments are still required to increase its spatiotemporal resolution, and LCIA methods need to be improved to better consider its different components (including water sources).

Keywords Life cycle assessment · WSmix application · Water footprint · Water-energy nexus · Water users · Water sources

1 Introduction

A worldwide-regionalized water supply mix (WSmix) framework and database has been developed to routinely provide life cycle inventory (LCI) data of water use in life cycle assessment (LCA) studies (Leão et al. 2018). The WSmix is the combination of water sources (surface, groundwater, seawater, etc.) and water technologies (including water withdrawal, treatment, and distribution) to meet a water user need in terms of quantity and quality (public water, agriculture, etc.) at a specific time (season, month) and location.

A first application was the environmental assessment of the supply of potable public water in two developed, climate-contrasted countries (i.e. Spain and France) and highlighted important differences between both (Leão et al. 2018).

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However, its application to LCA case studies at different locations and for different users has not yet been comprehensively tested and analysed. The WSmix may vary greatly between locations at worldwide scale in terms of composition and associated environmental impacts. In particular, the type of water use (domestic, agriculture, industry), the application perspective (e.g. providing a service versus producing a product), the economic situation (e.g. developed versus developing country) or the geographic location (coastal versus inland country) are some of the factors with major influence. For instance, in many places in the world, public water services do not exist or do not provide potable water (i.e. safe drinking water) which affects the WSmix because of lacking water treatment or the use of basic technologies and low associated energy consumption. This is essentially due to socio-economic conditions that may limit proper water treatment, resulting in illnesses and damage to human health (WHO 2017) directly via water consumption rather than indirectly through water technologies. On the other hand, many places in the world have limited access to freshwater sources (e.g. arid and semi-arid countries), but can rely on good technological and socio-economic conditions to find alternatives for supplying potable water to households (e.g. desalinated sea-water or inter-basin-transferred water). In these cases, a higher potential impact on energy resources (water-energy nexus (IEA 2016)) or land use, rather than on freshwater deprivation, can be expected due to the required technologies embedded in WSmix.

It is important to note that current LCI databases include only few datasets of water supply mix (e.g. market for tap water) for some users, with a country-based resolution or specific regional validity. Although some water users are distinguished (tap water, irrigation and cooling), overall information is incomplete, both in terms of water origin and specific water production technologies. Besides, as demonstrated by Leão et al. (2018), when comparing regionalized WSmix with current practice in LCA (European or global averages), substantial differences in the associated environmental impacts are observed.

Another perspective of WSmix application is the life cycle of global products, commonly evaluated in LCA. For instance, the life cycle of an industrial product may have large impacts associated to water treatment technologies, potentially larger than to water deprivation, because most of the water withdrawal for industrial manufacturing is released to the local environment after treatment and thus limiting water consumption (UN-Water 2017) (i.e. evaporation, evapotranspiration, or chemical transformation of water). On the contrary, for the production of an agricultural product, water treatment requirements are usually low but the volume of water evapotranspired by plants may be very high, resulting in a potentially high impact on water deprivation for the production stage (although the subsequent processing stage has important requirements for both water volume and quality).

In this context, the variability of the WSmix, the water uses, and their effects (e.g. on water deprivation, primary energy resources, and materials used for water technologies) on the environmental profile of different users and applications need to be analysed at a worldwide scale.

The aim of this study is to operationalise WSmix for application in LCA and to test its added value and usability by applying it worldwide to two different systems, a service and a global product. The goal is to evaluate the influence of the WSmix on the environmental profile of water supply to two different water users in different parts of the world, considering different climatic and socio-economic conditions among 91 countries. To this end, we explain first the technical requirements and steps to integrate WSmix into an LCI database. Then, WSmix is applied and the results are analysed including the variability of the WSmix for different spatial and temporal scales and socio-economic conditions, as well as its influence on the results compared to current LCA practice. The contribution of the WSmix to the assessment of environmental impacts related to water sources (surface, groundwater, etc.), as well as the influence of including spatial and temporal resolution beyond country scale in water supply assessment is illustrated using a river basin in one country and two river basins within another country as examples. Finally, conclusions and perspectives on the contribution of WSmix to an adequate evaluation of the environmental impacts associated with water use in LCA are drawn.

2 Methods

In this section, we describe the steps followed to operationalise (Section 2.1) and apply WSmix in LCA for two main water users, i.e. public water supply (Section 2.2.1) and irrigation for maize production (Section 2.2.2), respectively at country scale for both water users. Two countries have been assessed at river basin scale and with temporal resolution, also for both users.

2.1 Implementation of WSmix into LCI databases

For the creation of the technological WSmix components, water elementary flows were associated to water treatment technologies using the "Allocation at the point of substitution" system model from ecoinvent 3.2 (Wernet et al. 2016). The water input elementary flow "water, river" was used for surface water (i.e. river, lake), "water, well, in ground" for groundwater (i.e. "alluvial", "deep", "fossil", and "spring-water" groundwater) and "water, salt ocean" for non-freshwater (i.e. "sea water" and "brackish water"). No water input elementary flow has been associated to domestic

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Table 1 Data modelled in Simapro 8 for public water supply using WSmix

Assumptions for treatment technologies based on the country's GDP	Developed countries (High income)	Developing countries (Lower to upper middle income)	Developing countries (Low income)
	100% treated (surface and groundwater undergoes 100% conventional treatment). Sea water and domestic waste water treated with advanced technologies	**100% treated** (surface and groundwater undergoes 50% conventional treatment and 50% conventional basic treatment) Sea water and domestic waste water treated with advanced technologies	**50% treated** (surface and groundwater undergoes 50% of conventional treatment and 50% is not treated)[4]

Country-specific WSmix components

Water sources: Water sources withdrawal from WOmix database	Water sources: Environmental input flows used	Associated treatment technologies	Water treatment: Adapted processes used from ecoinvent v3.2[5]		
Surface water[1]	Water, river	→	Tap water production, conventional treatment	Tap water production, conventional treatment	Tap water production, surface water without treatment[3]
				Tap water production, direct filtration treatment	Tap water production, direct filtration treatment
Groundwater[2]	Water, well, in ground	→	Tap water production, underground with disinfection	Tap water production, underground with disinfection	Tap water production, underground without treatment[3]
				Tap water production, underground without treatment[3]	
Sea water	Water, salt ocean	→	Tap water production, seawater reverse osmosis, conventional treatment, baseline module, single stage	Tap water production, seawater reverse osmosis, conventional treatment, baseline module, single stage	*n.a*
Domestic waste water	*n.a*	→	Tap water production, ultrafiltration treatment	Tap water production, ultrafiltration treatment	*n.a*

Proportion of different water treatment technologies for each country

+

Customized network distribution and local water losses

Local WSmix
(Regional market activity)

Comments

[1] Includes river, lake, reservoir and inter-basin water transfer specified for each country. Since the origin of water from reservoir and inter-basin water transfer is unknown, we assume that is surface water. Pipes transfer and dam infrastructures were not accounted due to lack of data

[2] Includes spring, alluvial, fossil and deep groundwater, assuming that all sources receive the same treatment as groundwater

[3] It includes only energy for pumping water and for distribution to the plant gate

[4] Sea water and domestic waste water are not applicable

[5] The processes used were adapted to the specificities of each country, i.e., water flows, the proportion of technologies, the electricity mix and the water released unpolluted by the water treatment process.

n.a not applicable

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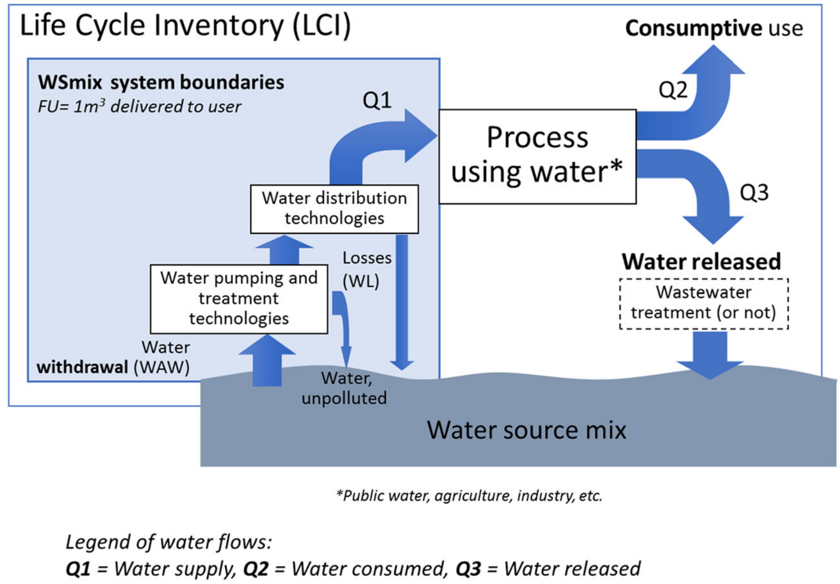

Fig. 1 Simplified representation of WSmix system boundaries

wastewater, as it is a water flow within the technosphere (i.e. economic flow). Finally, "water, sub-compartment groundwater" was the output elementary flow used for water losses during distribution in the WSmix. Table 1 illustrates the assumptions made and the water flows and processes for the user type "public water supply" (case 1) and Table S3 in the Electronic Supplementary Material (ESM) for the user type "irrigation" (case 2). Irrigation distribution networks and associated water losses were not implemented due to lack of data at worldwide scale as well as the great variability of water transportation distances and infrastructures used. The water treatment technologies used are given in Table S3 in the ESM.

In order to link water sources and users to a treatment technology in a given place, the technological matrix developed by Leão et al. (2018) was used. An update of that matrix with minor improvements is given in Table S2 in the ESM.

A distinction of water treatment technologies between three economic income groups of countries (World Bank 2017) was made, i.e. (a) low-income, (b) lower-to-upper middle–income, and (c) high-income countries (see Table 1). In high-income countries (49 analysed in this study), public water is considered to be fully potable (WHO 2017); therefore, conventional treatments for surface and groundwater as well as advanced treatments for seawater and domestic wastewater were associated (see details in Table S2 in the ESM). On the other hand, as lower-to-upper middle–income countries do not always have access to potable water (WHO 2017), it is estimated that in these countries, ~ 50% of surface and ~ 50% of groundwater are treated with conventional technologies while the respective other ~ 50% undergo a conventional, basic treatment (Table S2 in the ESM). This proportion of treatment technologies has been calculated, based on the population of the 17 lower-middle income countries (to which we associated basic treatment technologies) and the 19 upper middle–income countries studied (to which we associated conventional treatment technologies). It is assumed that in these countries, alternative sources such as seawater and domestic wastewater are treated with advanced technologies (Table S2 in ESM). Finally, in the six low-income countries under study, it is assumed that 50% of the surface water is treated with basic treatment technologies and 50% is untreated. Groundwater is generally of a higher quality than surface water and therefore is considered 100% untreated in these countries. The use of alternative sources in low-income countries under study is not applicable (Leão et al. 2018).

2.2 Application cases

While case study 1 analyses the environmental impacts of public water supply service (based on WSmix boundaries given in Fig. 1) as foreground, most LCA practitioners may use WSmix as a component of their LCI, including in the background system. This means that, in addition to the needed volume of WSmix (Q1), they will also have to quantify the consumptive (Q2) and released (Q3) use of water as shown in Fig. 1. Case study 2 illustrates this situation with the production of maize.

2.2.1 Case 1: public water supply service

The objective was to assess the impact of the regionalized WSmix on the assessment of public water supply in different parts of the world, both in terms of impacts directly related to water use and all other impacts associated with infrastructure, operation and treatment technologies. The functional unit is the supply of 1 m^3 of public water to households.

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Table 2 Indicators used for impact assessment

Set of indicators	Attribute or aspects to be included	Indicators used: LCIA indicators at midpoint level	Indicators used: LCIA indicators at endpoint Level
Comprehensive water footprint (ISO 14046)—water availability	Water consumption during all life cycle stages (called water scarcity in ISO14046) or water consumption damage in ReCiPe 2016 Endpoint (H) V1.00	AWARE (available water remaining) (Boulay et al. 2017) Spatial scale: country, river basin Temporal scale: monthly, annual	/
		WSI (water stress index) (Pfister et al. 2009) Spatial scale: country, river basin Temporal scale: monthly, annual WSI with surface-ground water differentiation[5] (Scherer et al. 2015) Spatial scale: river basin Temporal scale: monthly, annual	Area of protection (AoP) (LCIA methods) Human health, Ecosystem quality: ReCiPe 2016 Endpoint (H) V1.00 (Huijbregts et al. 2016)[3] Natural resources: Pfister et al. 2010 Endpoint V1.02[4] (Pfister et al. 2011)
Full LCA	Water degradation during all life cycle stages (freshwater eutrophication, freshwater ecotoxicity) All impacts during all life cycle stages (infrastructures, technologies, operation, energy, water use, etc.)[1]	ILCD 2011 Midpoint+ V1.08/EU27 2010, equal weighting, (EC-JRC 2011)[2]	ReCiPe 2016 Endpoint (H) V1.00 (Huijbregts et al. 2016)[3]

[1] Includes also indirect water degradation linked to infrastructure

[2] Excludes the water depletion indicator which was replaced in this study by the AWARE water availability indicator

[3] Endpoint characterisation factors for water consumption impacts on human health and terrestrial vegetation (ecosystem quality) are based on Pfister et al. (2009) and De Schryver et al. (2013) while those for the endpoint aquatic ecosystems are based on Hanafiah et al. (2013)

[4] Used for endpoint impacts on water depletion resources from water deprivation

[5] Developed only for Mississippi river basin (USA)

Although the WSmix developed by Leão et al. (2018) is available for different temporal scales (seasons or months), due to the lack of data on a worldwide scale, the WSmix has been applied in this study as an annual average. However, in order to show the value of considering the temporally differentiated WSmix, an illustrative example for the monthly supply of public water in the Duero river basin in Spain was calculated. Duero has been chosen since it is one of the most important river basins of Spain with a great affluence of tourism in certain months of the year. Figure 1 displays the system under study and its boundaries. The WSmix system boundaries were defined by Leão et al. (2018) and used as such here.

2.2.2 Case 2: irrigation for maize production

The goal was to evaluate the contribution of WSmix compared to all other environmental impacts of the farming system (fertilisers, farming exploitation, etc.) for four contrasting countries. To this end, WSmix was applied to different farming practices of maize in different locations. Maize was chosen due to its relevance as one of the main sources of human food worldwide (FAO 2017). The countries chosen for production were Spain, Pakistan, China, and the United States of America (USA), some of the world's most important producers with contrasted climatic and economic conditions. The functional unit is the production of 1 t of maize, with the system boundaries defined from cradle to farm gate.

In order to demonstrate the added value of WOmix, the driving component of WSmix, in assessing the environmental impact related to different water sources, we did a comparison using scarcity indicators to assess the quantitative effects of water deprivation. For that purpose, a comparison between applying current practices, i.e. constant characterisation factors to all water sources (Pfister et al. 2009) and specific characterisation factors differentiating water sources (Scherer et al. 2015),

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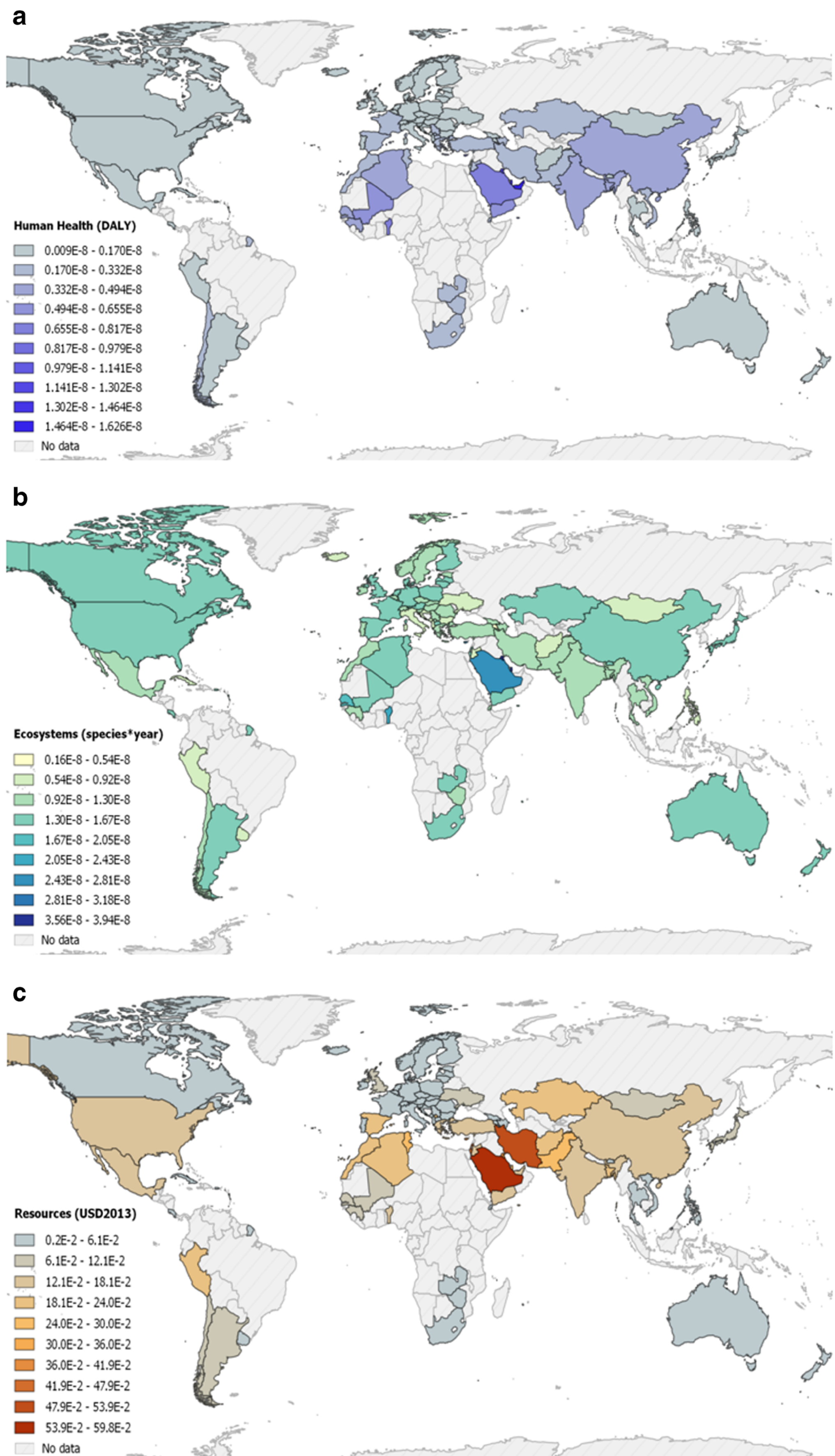

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◀ **Fig. 2** Endpoint results for supplying 1 m^3 of public water in 91 countries for three AoP: **a** human health, **b** ecosystem quality, and **c** resources; it should be noted that the colours do not represent impact levels in the respective country, but the total of global impacts, independently of where they are taking place, due to all processes needed to supply water in this country

has been done. An illustrative example for the production of maize using WOmix in the Mississippi river basin was implemented with (a) water scarcity index (WSI) (Pfister et al. 2009) of 1 m^3 of irrigated maize using current practice in LCA (i.e. the same characterisation factors for all types of water sources), and (b) WSI of 1 m^3 of irrigated maize using the specific characterisation factors for surface and groundwater from Scherer et al. (2015). The impact assessment method developed by Scherer et al. (2015) uses a hydrological model of the Mississippi river basin to calculate water stress differentiating between surface water and groundwater. More details of data used and calculations are given in Table S4 in the ESM.

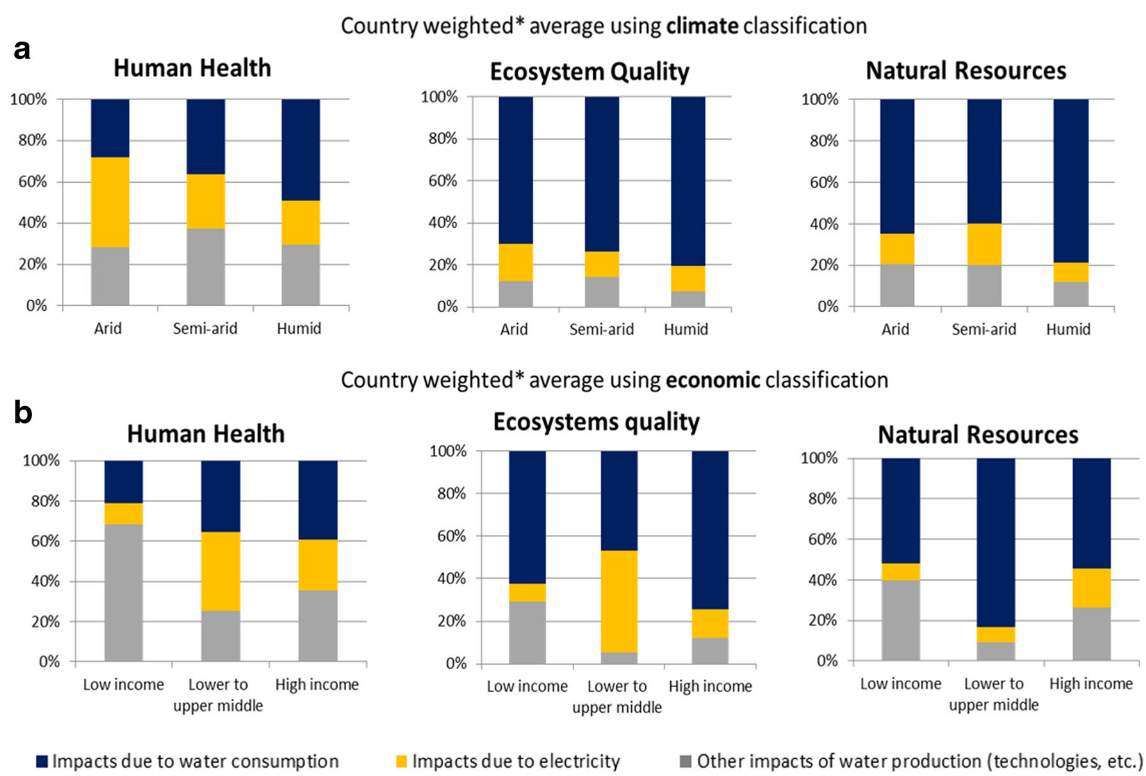
2.2.3 System modelling and LCI data

The basis to develop the LCI system models for both application cases was (1) the water sources mix (surface, ground, sea, etc.) of public water and irrigation obtained from the water source (origin) mix (WOmix) database (Leão et al. 2018) and (2) the LCI databases as listed in Table 1. Ecoinvent v3.2 was used for the public water supply modelling from water withdrawal to tap water (Wernet et al. 2016) and the Agri-footprint database for maize production (Agri-footprint 2018) using the Simapro 8 LCA software. These databases were used to model foreground (e.g. direct agricultural activities in the field) and background activities (e.g. fertiliser production and transport). For both cases, the WSmix has only been applied to foreground activities while water use for background activities came from existing databases without any changes. In practice, once the WSmix is implemented in LCI databases (as currently undertaken for ecoinvent), it will also be applicable to background processes and may also have an important influence on their water use–related impacts and thus on the LCA result if these background processes are significant contributors to the overall impact profile.

2.2.4 Life cycle impact assessment

WSmix was assessed using the life cycle impact assessment (LCIA) indicators given in Table 2. Two sets of impact assessment indicators were used, (1) a comprehensive water footprint and (2) a full LCA, considering all impact categories. A description of both approaches is given below.

The environmental impacts associated with water use have been evaluated for both water consumption and water degradation (i.e. freshwater eutrophication and freshwater



**Weighted by population; No of countries: Arid: 29, Semi-arid: 12, Humid 50. Low income: 6, Lower to upper middle: 35, high income: 50*

Fig. 3 Damage associated to the production of 1 m^3 of public water supply: classification of countries based on economic or climatic criteria

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ecotoxicity). This approach corresponds to a comprehensive water footprint as defined by ISO 14046 (2014).

In order to obtain a more holistic, overall environmental impact assessment, other impact categories such as climate change, acidification or fossil depletion associated to the elements modelled in the WSmix (e.g. infrastructures, technologies, operation, and energy) have also been assessed.

Since ReCiPe 2016 does not provide the assessment of freshwater deprivation impacts on water resource depletion, the method "Pfister et al 2010" (Pfister et al. 2011) has been added as presented in Table 2. It is based on the surplus cost to extract an additional cubic meter of water (e.g. desalination).

We note that in ReCiPe 2016 Endpoint (H) V1.00, the impacts derived from water deprivation are called "water consumption" which is inconsistent with the definition of this term in ISO 14046 where "water consumption" is the difference between water withdrawal and release and thus part of the inventory without representing any kind of impact.

3 Results and discussion

This section describes the results from the WSmix application at both country and river basin scales for both cases and discusses the importance of differentiating water sources and the spatial and temporal resolution in terms of environmental impacts. Climate and socio-economic classification of the countries (Köppen-Geiger 2017; World Bank 2017) have been used to analyse the results.

Leão et al. (2018) demonstrated the importance of regionalizing water datasets in LCI databases, given the tangible differences observed when comparing with European or global average water datasets, in terms of environmental impact associated.

This section shows to what extent the environmental impacts associated with WSmix can vary between countries and, therefore, the importance to use regionalized WSmix when modelling human activities.

3.1 Case 1: public water supply service

The results obtained for 91 countries are given at endpoint level for the three areas of protection (AoP) (Fig. 2).

3.1.1 Endpoint assessment for the full LCA

Figures 2 and 3 show the results for 1-m^3 public water supply of 91 countries for three AoP: (a) human health, (b) ecosystem quality, and (c) resources.

Regarding the total global damage on human health (Fig. 2a), results are higher from water supply in the Arab states of the Persian Gulf countries (Kuwait, Qatar, Saudi Arabia, and United Arab Emirates) followed by West African countries (Benin, Mali and Senegal), North Africa (Algeria), and South East Asia (India and Bangladesh). The high impact on global human health from water supply in the Persian Gulf countries is caused by intensive use of desalination (approximately 100% in Qatar and Kuwait and 50% in Saudi Arabia (Leão et al. 2018)), which is an energy-intensive process using fossil energy for electricity production that has large indirect impacts on global warming and fine particulate matter formation resulting in human respiratory impacts (and also toxicity due to the production of

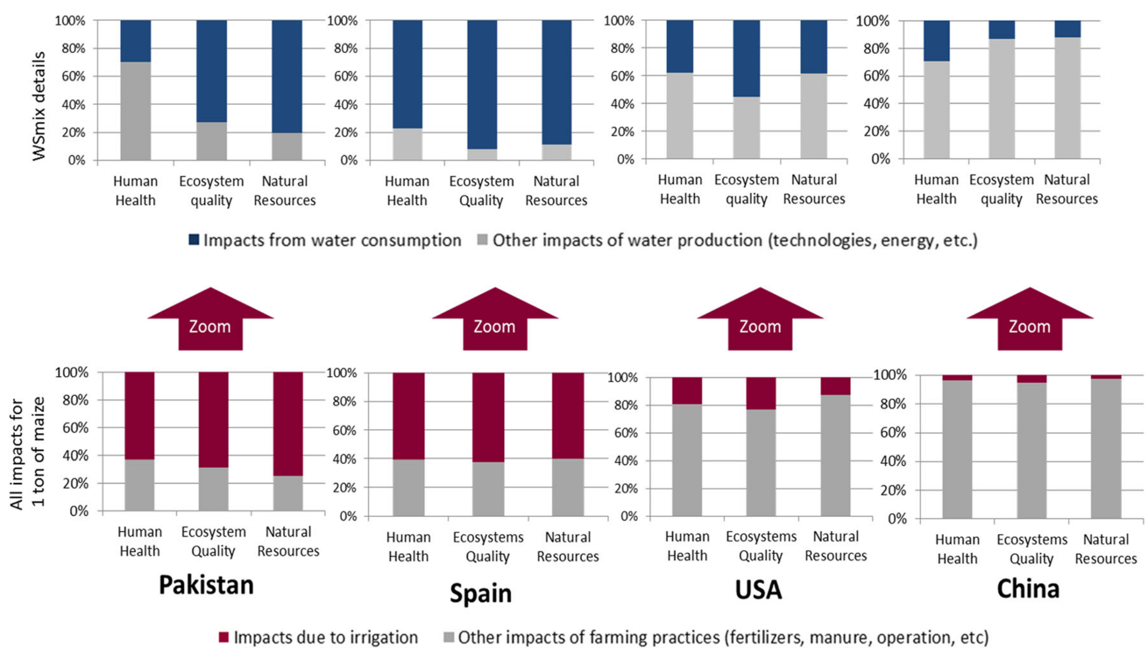

Fig. 4 Impacts associated to the production of 1 t of maize in different places of the world (at farm gate) with a zoom on irrigation (WSmix) contribution

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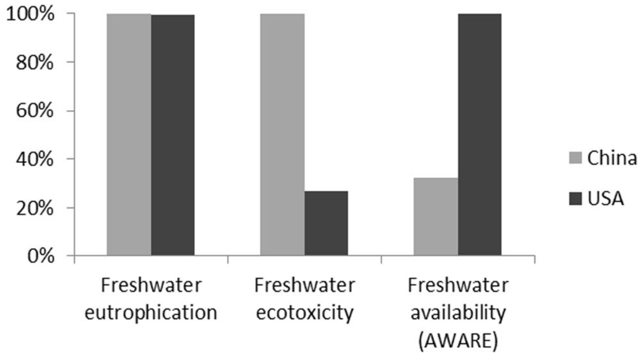


Fig. 5 Comprehensive midpoint water footprint results for China and USA for the production of 1 t of maize

specific desalination components such polyvinylchloride membranes). The human health damage from water supply in countries with lower human development indexes (HDI) is due to the indirect impacts linked with the technologies and energies used for water production and the local impacts derived from water deprivation, potentially resulting in malnutrition and disease in the population (UNESCO 2003).

Regarding the global damage on ecosystem quality (Fig. 2b), once again Persian Gulf countries are the most critical contributors. This is related to indirect impacts from electricity and polyvinylchloride production. For the rest of the countries, damage on ecosystem quality is essentially due to local impacts from water deprivation on terrestrial (the large majority) and aquatic ecosystems.

Finally, concerning the impacts related to the AoP resources (Fig. 2c), these are clearly higher for water supply in Saudi Arabia and Iran. While fossil and mineral resource scarcity is the cause of the greatest impact from water supply in Saudi Arabia, water depletion and mineral resources are the largest contributors for Iran. More examples of countries where water supply critically contributes to this AoP are Israel and Pakistan because of the high potential impact on water resources depletion. In Spain, public water supply has a greater potential impact on fossil and mineral resource depletion compared to other European countries.

Figure 3 shows the impacts of 1-m^3 public water supply comparing three main contributors: water consumption, electricity production, and impacts associated to infrastructures, technologies, etc., considering a classification of the countries based on socio-economic or climatic criteria.

Figure 3 shows that applying both environmental and socio-economic criteria, the contribution of water deprivation associated with the supply of public water is significant for the three areas of protection. Impacts related to infrastructure and technologies have a larger contribution in the area of protecting human health, both in socio-economic and climate classification. Moreover, electricity production contributes greatly to the impacts in both classifications, particularly in arid countries on human health and in lower-to-upper middle–income countries on human health and ecosystem quality. It is noteworthy that some of these impacts are occurring locally while most occur elsewhere, induced by the life cycles of technologies, energy carriers and infrastructures used for water production. More details and results at the midpoint level are given in Section S4 in the ESM.

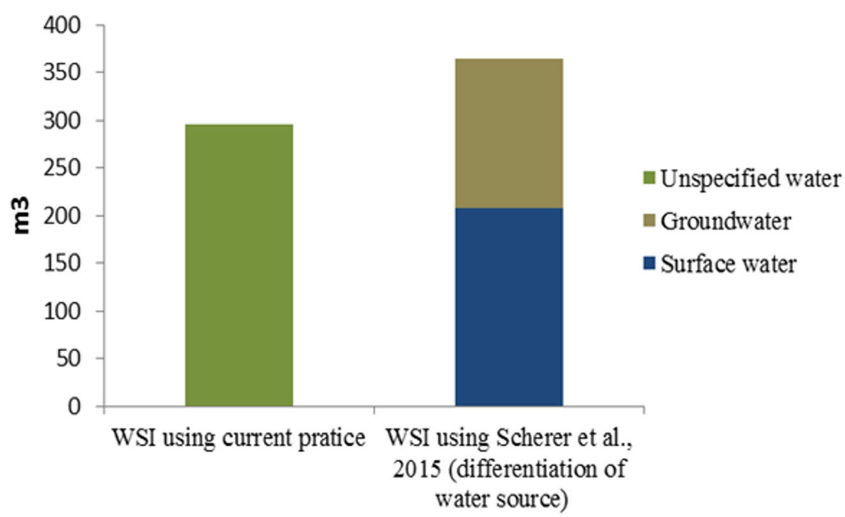
3.2 Case 2: irrigation for maize production

This section presents the results at endpoint and midpoint level (i.e. comprehensive water footprint) for irrigated maize production in four of the world's largest maize-producing regions, applying the respective local WSmix for irrigation.

3.2.1 Endpoint assessment for the full LCA

The results show that the contribution of the irrigation water supply to the total impacts of maize production is significant

Fig. 6 Comparison of WSI associated to 1 m^3 of irrigated maize in the Mississippi watershed using current practice in LCA (left bar) and using WSI differentiating water sources (right bar)



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in different parts of the world (Fig. 4). In particular, 60% of the impacts in Pakistan and Spain are due to irrigation in the three areas of protection. Although, in the USA, the impact associated with fertilisers, operation, etc. is larger; the impacts from irrigation are not negligible (~20%). In China, nearly 100% of the impacts of maize production are due to impacts not related to irrigation. One of the main factors contributing to this is the electricity production, mainly based on fossil carbon.

By separating the impacts associated only with irrigation and hence WSmix (top of Fig. 4), we observe considerable impacts on water deprivation, Spain having the largest impacts per ton of maize followed by Pakistan. This is because water treatment technologies used are basic, and water consumption through evapotranspiration is important.

Finally, while Pakistan and Spain have higher impacts for water deprivation compared to other impacts (due to high water scarcity), the opposite is observed for the USA (except for ecosystem quality) and China (due to diesel and electricity production). Results at midpoint level are given in Section S4 in the ESM.

3.2.2 Midpoint assessment for the comprehensive water footprint

Comprehensive midpoint water footprint results of maize production in the world's two main producing countries (using their respective local WSmix for irrigation) are shown below (Fig. 5).

While the production of maize in China is mainly contributing to water degradation (freshwater ecotoxicity) due to substance emissions into the soil (i.e. phorate, carbofuran and atrazine), the production of maize in the USA is greatly contributing to water deprivation. This type of results is important for understanding the main drivers behind the water footprint of a product, supporting e.g. eco-labeling of products.

3.3 Comparison to current practice

3.3.1 Importance of differentiating water sources

This sub-section illustrates the effect on calculated results of using current water stress indexes (that do not distinguish water sources) compared to distinguishing water sources (WOmix). The different results obtained (Fig. 6) are justified by the difference in the generic characterisation factor for an unspecified water source (0.499) and specific ones for each water source (0.595 for surface and 0.640 for groundwater) (Scherer et al. 2015). The model developed by Scherer et al. (2015) can only be applied if a WOmix is available. Further details are given in Table S4 in the ESM.

WSI given by Scherer et al. (2015) are available for water consumption and water withdrawal, distinguishing downstream and upstream river basins; an average between both has been used for water consumption.

Starting from hydro-ecological insights that the impact of groundwater withdrawal is different from that of surface water withdrawal (Döll et al. 2012; USGS 2018), such a difference can be expected and may be seen as contributing to more realistic impact results compared to treating all water sources as equally impacting. This advocates for the development of water deprivation characterisation factors to allow a differentiation between water sources worldwide as well as accounting for the distribution of water mass changes between compartments (surface water, soil moisture, ground water, etc.) after withdrawal or release in a mechanistic approach (Núñez et al. 2018).

3.3.2 Potential effect of LCI system modelling assumptions on human health

Water quality has a direct effect on human health. In particular, low-income and lower-to-upper middle–income countries do

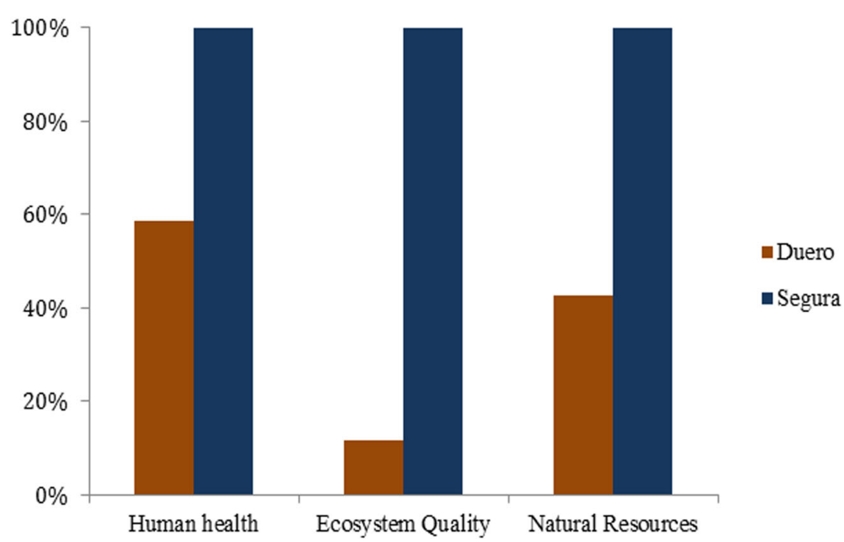

Fig. 7 Supply of 1-m^3 public water in two contrasted river basins (in terms of water sources mix and climate conditions) in Spain

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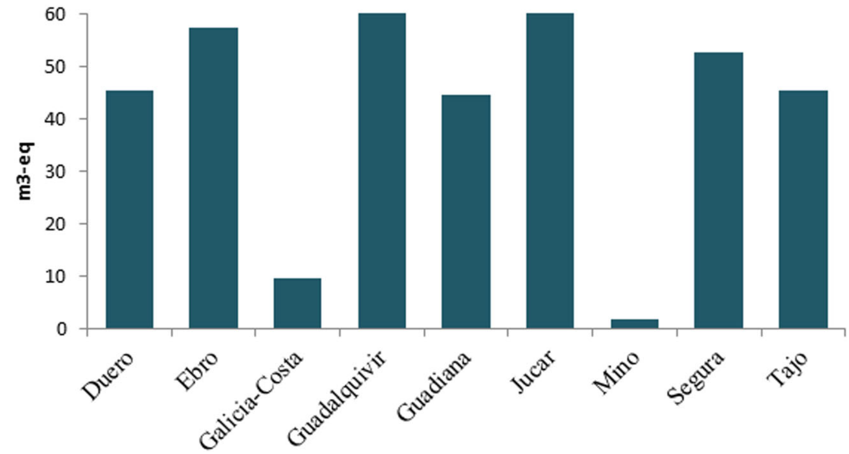

Fig. 8 Water-availability impacts for 1 m^3 of irrigation water for the main river basins in Spain according to AWARE

not always have clean and safe water, unlike high-income countries. Approximately 30% of the world population still lives with a basic sanitation service, unimproved, limited or collected water to drink directly from surface water sources (WHO 2017).

In this context, for the creation of the system models for public water (Section 2.2.1), we made assumptions based on these facts and on the WSmix approach by Leão et al. (2018), so that the resulting impacts are as realistic as possible. Boulay et al. (2011) proposed the concept of adaptation capacity to water availability change (i.e. water quantity and quality changes). According to this approach, in the case of low water quality and if economic resources are sufficient, technological adaptation/compensation is assumed. Otherwise, people in developing countries use available water even if it is of poor quality, which then causes diseases that affect human health according to WHO (2017).

In this context, while the local impacts related to operation and technologies of public water supply are not relevant in these countries (given its low or even inexistent implementation), the same cannot be said in relation to human health effects related to low water quality (WHO 2017).

While the impacts on human health due to water deprivation are already accounted for in some LCIA methods (through the lack of water for irrigation (food) and consequently malnutrition), the consideration of impacts on human health due to the lack of safe potable water still needs improvements (Pradinaud et al. 2018). To solve this limitation, Pradinaud et al. (2018) propose a framework with impact pathways from water pollution to human health, as well as to ecosystem quality and natural resources impacts.

3.4 Spatial and temporal variability

To show the environmental impacts associated with the use of different water sources to supply different water users in specific regions at river basin scale and with temporal variation, the WOmix database published by Leão et al. (2018), the starting point to build regionalized WSmix, has been used (see Figs. 7, 8, and 9). The environmental impacts associated with the supply of public water in two contrasted river basins in terms of WOmix in Spain are shown below (Fig. 7).

The large differences for the three AoPs (in particular for ecosystem quality) are related to the climatic situation of each

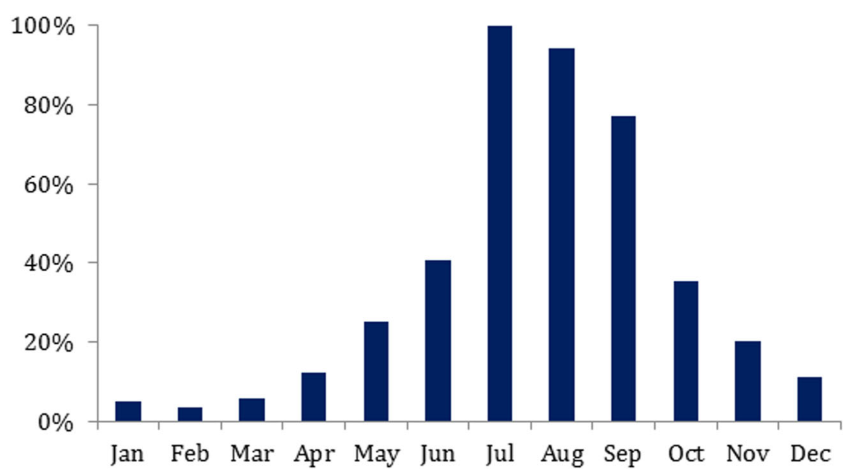

Fig. 9 Monthly water use impacts of 1 m^3 of public water assessed with AWARE

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river basin and associated water scarcity (see Fig. S2 in the ESM), as well as to the different water treatment technologies used, which are more advanced in the case of the Segura basin (i.e. desalination). The following graph shows the differences in the impact of irrigation water in Spanish river basins.

Guadalquivir and Jucar have the highest impact followed by Ebro and Segura since they have a higher characterisation factor (CF). Galicia-Costa and Mino have very little or almost no impact, given the large amount of rainfall, and hence water availability, that occurs in these basins, resulting in a low CF. The environmental impacts associated with the supply of public water in the Duero river basin with temporal resolution is presented below (Fig. 9).

There is a wide variation in monthly water use impacts, and as expected, there is a greater impact in the summer months. It is important to note that Fig. 9 represents the sum of all water sources supplied in the Duero basin. However, there is also a water sources mix variation between months (Duero CHG de 2012) that may incur different environmental impacts.

3.5 Uncertainties and data gaps

In this study, regionalized WSmix have been applied to foreground systems but not to country-specific background processes (e.g. WSmix used for electricity or fertiliser production). This may not be significant for water consumption impacts in agriculture where irrigation is the activity that deprives the most (FAO 2016). However, this can lead to less accurate and more uncertain results for most other water uses. In addition, due to the lack of data on country-specific technologies used, several assumptions were made using the technologies available in LCI databases. The level and proportion of treatment technologies used was differentiated between high-income, low-income, and lower-to-upper middle–income countries. However, the range of technologies available in LCI databases was typically modelled based on data from high-income countries (in particular for Quebec, the only region for which technologies are available in LCI databases). Therefore, uncertainties are associated with these assumptions. It is therefore necessary to include the country-specific technological treatment in LCI databases (i.e. water treatment technologies used in each country).

In addition, the national electricity mix, which has a major influence on the impact profile of a m^3 of water from the WSmix, is missing in LCI databases for some non-European countries (e.g. Argentina or Benin). In these cases, the average global (GLO) electricity mix has been used which increases uncertainty.

4 Conclusions and outlook

The WSmix has been operationalised and applied in LCI databases. Its added value and usability has been demonstrated by application at a worldwide scale for two different users. It has been shown that the WSmix has a great influence on the environmental profile of water supply for different users considering different climatic and socio-economic conditions; however, some methodological developments are still needed to improve its robustness. The interdependence between water and energy (i.e. water-energy nexus) is clearly established, which reinforces the approach of a regionalized WSmix linked with national/regionalized electricity mix.

While the WSmix allows distinguishing different water sources (which is one of its main purposes), current LCIA methods quantify the same impacts for water deprivation no matter the type of water sources used. The consideration of spatial and temporal variability for water use should be improved in both LCI and LCIA.

In terms of perspectives, regionalized characterisation factors differentiating water sources worldwide are needed for an appropriate assessment of the impact related to water sources, which is already facilitated by the WSmix on the level of LCI. In addition, impact assessment methods based on mechanistic modelling of water deprivation impacts are needed in order to differentiate impacts associated with different water sources (surface water, ground water, etc.) (Núñez et al. 2018). It is important to emphasise that the operationalization of WSmix was done at the country scale; however, in the future, it should also be implemented at the (sub-) river basin scale. This is especially important considering the environmental impacts associated with water sources at more local scales. Leão et al. (2018) presented a proposal to make it operational at finer scales.

Country-specific technology data related to water production for different users as well as specific data on irrigation water transport should be included in LCI databases to increase the accuracy of LCA results on water use. In addition, the influence on the environmental impact of the WSmix implementation should also be assessed for background datasets, especially for non-water related products and services where water is not a major elementary flow in the foreground system.

Finally, we note that WSmix can be expected to vary in the future driven by climate and socio-economic changes. Consequently, a projection of WSmix into future scenarios is required for attributional LCA using processes functioning beyond 2030 and for consequential LCA. This was developed by Leão et al. (2019) and the next step is now to operationalise their prospective water supply mix (P-WSmix) in LCI databases, given its benefits in certain LCA studies, as well as in supporting regional adaptation strategies for future water supply management.

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Abbreviations AoP, Area of protection; LCA, Life cycle assessment; LCI, Life cycle inventory; LCIA, Life cycle impact assessment; WOmix, Water source (i.e. origin) mix; WSmix, Water supply mix; GDP, Gross domestic product

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