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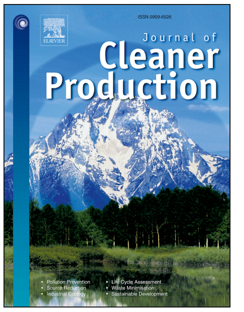

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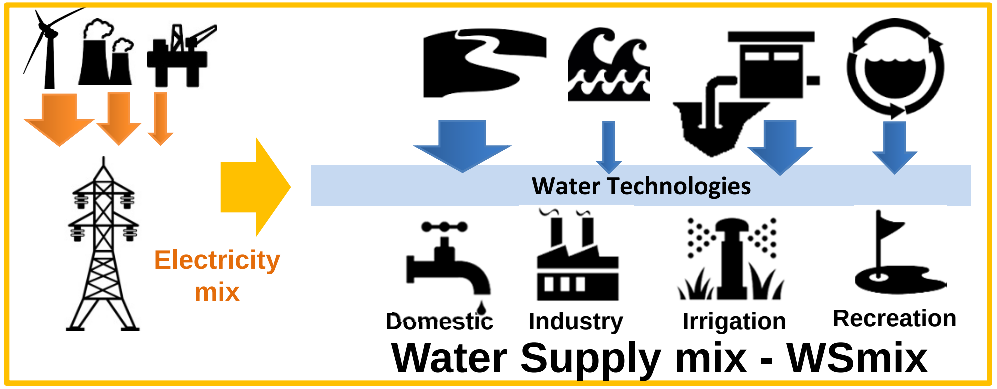
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A worldwide-regionalised water supply mix (WSmix) for life cycle inventory of water use

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Abstract

Water utilities draw different water sources (surface and groundwater), including increased use of alternative sources (e.g. desalinated water, reused water, inter-basin water transfers) to supply freshwater to different users (domestic, agriculture, etc.). The combination of water sources and technologies (including infrastructures and energy) results in a regional water supply mix (WSmix) for each specific use. Existing Life Cycle Inventory (LCI) databases used in Life Cycle Assessment (LCA), do not include these mixes when modelling processes, leading to a poor representation of water supply systems and related environmental impacts. To fill this gap, this paper proposes a consistent framework for modelling a regional WSmix at worldwide scale. The WSmix framework includes the scope and system boundaries definition as well as a standardisation of terminology and classification of water sources and users. To facilitate implementation of the WSmix, this paper provides a worldwide database of water source mixes per user and a technology matrix linking water sources to water production technologies, including the connection with the local electricity mix.

The relevance of including the WSmix in LCI databases for proper water-use impact assessment is demonstrated with an illustrative case study. The paper finally concludes on the need of using the regionalized WSmix in routine LCA, which is just as straightforward as the use of the regionalized electricity supply mix. Besides, the developed WSmix provides interesting insights beyond the LCA scope to support the strategic management of water sources at various scales including the global scale.

Keywords

Life Cycle Assessment, worldwide database, water footprint, water users, water-energy nexus, water sources

Abbreviations – Glossary

GIS	Geographic Information System
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
P	Precipitation
RB	River Basin
WE	Water Evaporation
WL	Water Losses
WP	Water Production
WO	Water sources
WOmix	Water source mix per user
WSmix	Water Supply mix
WU	Water Users
WTD	Water Treatment & Distribution
WTec	Water Technologies
WTR	Water Transportation
WWTP	Waste Water Treatment Plant

Table of content

1 Introduction

Water demand is increasing worldwide, especially due to population growth (FAO, 2011), while water availability in many regions is likely to decrease due to climate change and socio-economic development patterns (WWDR4, 2012). The water variability in space, time and source has repercussions on the environment and on the management of water sources (Zhou et al., 2015).

Water utilities face a challenge to supply water to different users (domestic, agriculture, industry) during the entire year. They must address seasonal scarcity and human and ecosystem need fluctuations by combining different local conventional water sources (surface and groundwater), including increased use of alternative water sources, i.e. desalinated water, reused water, harvested rainwater (IWA, 2015a). In many cases, the water used by a specific user is coming from a mix of local and sometimes imported water sources rather than a single source (Hemmeter et al., 2016; IWA, 2015a). Depending on the origin of abstracted water, the geographical location (water abundant or scarce), the technologies used for water production (simple or advanced treatment, desalination, energy source, etc.), the volume being extracted and the season of the year (wet/dry), the resulting environmental impacts of producing a cubic meter of supplied water can be completely different. However, information on water supply systems is very limited in existing databases used in environmental assessment methods, such as Life Cycle Assessment (LCA) and Water Footprint, leading to a poor estimation of their impacts.

Conventional Life Cycle Inventory (LCI) databases such as ecoinvent (Wernet et al., 2016), GaBi 6 (Thinkstep, 2016) and Quantis Water Database (QWD) (QWD, 2015) provide a water balance of flows entering and leaving the product system (Section S1 in Supplementary Material (SI)). Water input flows account for water withdrawal from the environment, and water consumption is the total water withdrawal minus the total water released back to the river basin after use (ISO, 2014). However, LCI databases only include a few water sources and water treatment technologies without distinction of seasons and regions, although the ISO standard 14046 on water footprinting (ISO, 2014) recommends temporal and geographical differentiation of water flows. In terms of spatial and temporal resolution, current unit processes for water production in LCI databases represent a global annual average or a country annual average, with unknown origin if not defined by the LCA user and with no link to the water production technology applied (with the exception of tap water production in Quebec, see below). In particular, tap water, irrigation and cooling water uses are distinguished, although overall information is incomplete, both in terms of water origin and specific water production technologies.

To handle the diversity of water sources when the specific water origin is unknown, Hospido et al. (2013) introduced the concept of water mix for irrigation in LCA and provided a proof of concept for a river basin in Spain. They described a procedure to incorporate a water profile mix in the LCI for irrigation and evaluated the influence of that profile on the life cycle impact assessment (LCIA) level in terms of water consumption impacts. Their scenarios include the use of alternative water sources such as desalination or regenerated water to cover all irrigation demand. Energy use associated to the supply of each water resource type was also quantified and evaluated in terms of Global Warming Potential. Despite the interest of that model, it was only applied in one river basin and to one user (agriculture).

The tap water mix for Quebec (Lesage and Samson, 2013) (called “market for tap water” in the ecoinvent database (Wernet et al., 2016)) is an example of a practical implementation of the water mix in LCA. This mix differentiates between water sources, namely surface and groundwater, and the average of tap water production technologies used in Quebec, including the network and water losses during distribution. However, it only covers one region and one type of water use on an annual basis. Ono et al. (2015) developed an inventory database for water footprint based on input-output analysis of goods and services produced in Japan. While different water sources and users have been considered in this approach, the geographic and temporal differentiation is limited to annual average flows in Japan.

A summary of different approaches applied in LCA and other fields for the consideration of a water mix in LCA is presented in Section S4 in SI. So far, examples in LCA only include information on location and user type, whereas, seasonal variation and inventory related to infrastructures and technologies (energy, materials, chemicals, etc.) are often not considered.

This paper proposes a consistent water supply mix (WSmix) model for implementation in LCA, including harmonization of terminology and classification of water sources and users. Integrating the WSmix in LCI databases provides local water mix profiles for processes in LCA, depending on their location and with different spatial and temporal scales, which will also allow LCIA methods to assess trade-offs between the various environmental impacts associated to a given local mix. Besides that, it will also be useful for other fields related to water sources management, supply and treatment technologies as well as water use and consumption patterns.

2 Problem definition and objectives

The WSmix concept is relatively similar to the energy mix concept. The energy mix is a worldwide standard model that determines how final energy consumption in a given geographical region breaks down by primary energy sources (e.g. fossil fuels, nuclear energy, waste and renewable energy) and by different uses (e.g. electricity generation, called electricity mix, transportation, or heating of buildings). In the same manner, the WSmix is a model describing how final water use for specific users (domestic, agriculture, industry) in a given location and season breaks down by primary water (re)sources (e.g. surface water, groundwater, precipitation) and by associated treatment and supply technologies (including infrastructure and energy consumed to extract, purify, deliver, heat/cool and treat water, which is known as the water-energy nexus) (DOE, 2014).

However, the development of a worldwide WSmix for LCA raises several methodological issues. First, current LCI databases only differentiate surface water, groundwater, seawater and precipitation, but do not include alternative water sources such as inter-basin water transfer or reused wastewater, which are gaining importance as part of adaptation strategies, especially in arid and semi-arid countries. Furthermore, there is lack of harmonization between existing LCI databases and LCIA models. Some models directly consider water consumption, i.e. evaporation, transpiration, integration into a product, or release into a different river basin or the sea (Mila i Canals et al., 2009; Pfister et al., 2009a), while others, such as the models by Boulay et al. (2011) and WBCSD (2015) are based on the inventory of water withdrawal and water released.

Another important limitation observed in LCI databases is the lack of information regarding the required treatment technology or chain of technologies for a given water source to meet a specific water demand (in terms of quantity and quality). The technologies used for water withdrawal, water transportation and storage usually are not substantially different between water sources. However, important differences in technologies for water treatment actually exist, since they are designed for specific input and output quality standards (Meron et al., 2016).

The goals of this paper are: 1) To develop a consistent WSmix framework to harmonize LCI modelling practice of water supply systems ensuring consistent links with existing LCI databases and LCIA methods. 2) To provide a first database of water source (or Origin) mixes (WOmix) for different users at a global scale and a technological matrix linking water sources to water production technologies in order to operationalize practical implementation of the

WSmix in LCA studies. 3) To demonstrate the relevance of including the regional WSmix in LCI databases for proper water-use impact assessment through an illustrative LCA case study.

3 Methods and modelling

This section describes the conceptual basis of the WSmix framework and discusses how to implement it in practice based on both a WOmix database for different users and a technological matrix linking water sources to water production technologies. Finally, the overall WSmix framework is presented.

3.1 Bases of the WSmix framework concept

3.1.1 System definition and boundaries

The WSmix represents water supply systems, which are described as withdrawal, treatment, and distribution of water from different water origins to water users (Lesage and Samson, 2013; Loubet et al., 2016; Meron et al., 2016; Vince et al., 2008). Therefore, it describes water inputs to a process, while water outputs (i.e. release back to the ecosphere) are not included. Consequently, the WSmix includes the combination of water origin, technologies of water production and distribution for different water users at different spatial and temporal scales (Figure 1). These technologies should be modelled with a life cycle perspective to consider all impacts due to upstream activities (e.g. infrastructure, energy, chemicals).

Similarly to the energy mix and in particular the electricity mix in LCA (Frischknecht and Tuchschmid, 2008), the system boundaries for the WSmix are defined from the water resource withdrawal up to the delivery to the final user, excluding all processes during and after the use phase. It includes all interactions between the ecosphere (environment) and the technosphere (technical system), i.e. emissions and resource extractions. The only feedback from water users towards WSmix is the water quality that is required for each specific use and that will define the required combination(s) of sources and technologies.

3.1.2 Terminology and classification of the WSmix components

The WSmix framework is consistent with existing data on water sources and water use, and also with LCI data, LCIA methods, and LCA software to be directly usable by LCA practitioners. At the same time, it is flexible enough to adapt to future LCIA methods and software developments.

A great variability of terminology and classification for water sources and water users was observed. For instance, when comparing two river basins in France for water sources, one has a water mix of four different, very aggregately defined origins, whereas the other has 10 different, detailed water origins (Adour-Garonne, 2013; Loire-Bretagne, 2013). The same holds true for water users when comparing data from two river basins in Spain, one distinguishing five water users (Guadalquivir, 2013) and the other eight (Miño-sil et al., 2007). More details are given in Sections S5 and S6 in the SI.

Therefore, harmonization is required prior to incorporation of such data into the WSmix. Bayart et al. (2010) developed a consistent classification of water sources and water users for LCA. The authors presented a set of freshwater categories according to the water origin and the water quality, where the quality can be determined with a functionality approach. According to Bayart et al. (2010), water is considered functional for a particular user if its quality parameters meet quality standards defined for a specific use. Boulay et al. (2011) operationalized the functionality approach (see Table S5 in SI) by using a list of 136 water quality parameters (physico-chemical characteristics, microbiology, organic matter, etc.) to define the functionality of water quality categories (i.e. its usability for different users) for three water origins, namely surface water, groundwater, and rain water.

Despite the interest of this approach, it fails to consider that the same user may actually use different qualities of water in function of geographic and socio-economic conditions (Pradinaud et al., in review). Moreover, the number of parameters required for the best estimate of water quality does limit its applicability worldwide. Finally, the water source categories are too aggregated, with no distinction, for instance, between fossil and renewable groundwater, as recommended by Kounina et al. (2013).

To propose a sound classification of water sources and users that addresses both LCA and water management requirements, a set of criteria has been defined:

1. The water source classification should be based on direct environmental relevance of each water source. The environmental relevance can be evaluated according to different aspects. The following parameters were considered in the WSmix classification:
    a. *Water renewability:* Groundwater was classified into three sub-categories: alluvial, deep, and fossil groundwater, based on the different renewal rates of each water source, which is particularly low for the latter (GWF, 2014). In addition, the different levels of depth and consequently the energy required for pumping each type of groundwater were considered for the classification, as pump efficiency and type of power source vary (Pradeleix et al., 2015).
    b. *Water deprivation impacts*: Regarding surface water, a classification into three sub-categories representing different water bodies is proposed: i) river, i.e. a water flow; ii) natural lake and wetland, i.e. standing water; and iii) spring-water, i.e. the result of an aquifer saturated to the point that the water overflows into the land surface (Perlman, 2016). From an LCIA point of view, spring-water is considered as withdrawn from surface water, thereby potentially

contributing to surface water deprivation and impacts on surface water-dependent ecosystems.

c. *Anthropogenic changes in the natural water flow of streams or rivers*: Building of dams and off-river storage as well as diversion of flows with levees and other structures may contribute to the loss of biological diversity and ecological functions in aquatic and terrestrial ecosystems (NSW, 2013). Therefore, inter-basin water transfers and reservoirs (water retained in dams) were considered in the classification. They are both part of the proposed alternative water sources, and are included in the categories of external and artificial standing water sources, respectively (see Table S11 in SI). The origin of water transferred/stored was distinguished since the associated water treatment will be different. The main interest to include reservoirs in the WSmix are temporal considerations such as water storage in wet season for use during dry season (Scherer and Pfister, 2016).

2. Inclusion of non-conventional water sources, as another category of the proposed alternative water sources (see table S11 in SI). Water scarce countries are expected to progressively rely more on those sources to alleviate water scarcity. Five categories are distinguished: seawater, brackish/saline groundwater, domestic wastewater, harvested stormwater run-off, and directly harvested rainwater. Although, the last two have the same origin (rainwater), they have a different water quality since the first is generally more polluted (Wahaso, 2016). It is currently assumed that the use of alternative water sources have generally no impact on water scarcity (Hospido et al., 2013; Muñoz et al., 2010). However, they contribute to other impact categories due to the environmental impacts associated to the energy and technology for withdrawal/collection, treatment and distribution.

3. Exclusive consideration of water uses related to water withdrawal (i.e. off-stream water use in LCA terminology (Bayart et al., (2010)). The water users were defined according to classifications used in local water management plans and suggested by other authors in addition to traditional large water consumption collectives (i.e. agriculture, cooling, and domestic). Sub-groups of water users have been included (for example, "agriculture" split into "irrigation", "livestock", "planted forestry", and "aquaculture (off-stream)") as the environmental impacts associated to the required water treatments may be different (see Section S6 in SI).
4. Maximum preservation of the level of detail considered in local water management plans and water agencies in terms of terminology and adherence to international standards such as those of the International Water Association (IWA) (IWA, 2015b), Aquastat (FAO, 2016), FAO (FAO, 2003) and ISO 14046 (ISO, 2014) (see Table S4 in SI).

3.2 Water source mix (WOmix) database

To facilitate implementation of the WSmix, this paper provides a worldwide database of water source mixes per user at different spatial scales (country, river basin and sub-river basin) and, in a first stage, at annual temporal scale (Excel file in SI). Several data sources were analysed ranging from local water management plans (including direct contact with national or regional water agencies) to databases from international agencies such as Aquastat (FAO, 2016) and Eurostat (European commission, 2016), and scientific literature (Sections S5 and S6 in SI).

For most countries, especially the developed ones, the data needed for a global and spatially explicit WSmix are available. For instance, in Europe, data on water withdrawal for different users at river-basin and sub-river-basin level are accessible through local water management plans via water agencies and national statistics. However, for some countries or regions, data are available only at country scale, and in some cases no data were found (approximately half of the countries in the world). For those cases, interpolation and aggregation of data from neighbouring countries and/or river basins could be applied (although not done in this study) to fill data gaps, based, for example, on socio-economic indicators and geographical location.

Data on temporal water withdrawal variability are available only for a few countries and river basins. The vast majority of data is available with an annual resolution. For higher temporal resolution, climate indicators and human activity patterns could be applied (although not done in this study). Figure S7 in SI shows an example of temporal variability of water sources.

The current WOmix worldwide-regionalized database has information for 93 countries at national level, 18 countries at river basin level, and five countries at sub-river basin level, for all water users and types of water sources (Figure 2). This database is the starting point to create WSmix LCI datasets.

3.3 Overview of WSmix framework

Figure 3 depicts the WSmix methodological framework that represents the water sources (surface, ground, sea, etc.) at the ecosphere level (environment) and all the technologies associated for withdrawal, transport, store and distribution of water at the technosphere level (technical system). Solid blue arrows (1b and 1c) represent the water flows entering from the ecosphere into the technical system and solid green arrows (1d and 1e) represent the water flows within the technosphere. After water use, water flows can be treated and reincorporated into the system to be reused after an additional treatment (3b) or returned to the environment after conventional waste water treatment (3c and 3e). Dashed blue arrows represent water lost during transport and distribution (2a and 2b) while dashed light blue arrows represent water consumed, i.e. water evaporated (2c, 3d and 4a) and the excess water transported that is released into the ocean (2d) (ISO, 2014). Further details about Figure 3 are given in Table S6 in SI.

The water technologies included in the WSmix are the technologies used for water production (Figure 1). The environmental profile of each water technology is intrinsically linked to the local electricity mix.

Figure 4 shows the classification of water sources (WO_x and WO_y), water users (WU_z), and associated technologies (WTec) for the WSmix. Depending on the type of water source and the specific user need, a treatment technology or set of technologies are proposed (see below). Six families of water technologies are regarded, all available in current LCI databases: deionisation, desalination, conventional treatment, advanced treatment, basic treatment and no treatment (Table S7 in SI). In doing so, the functionality principle (Bayart et al., (2010) and Boulay et al., (2011)) is avoided.

For instance, Figure 4 shows that for public water uses, spring-water, alluvial, deep, and fossil groundwater usually require a conventional treatment for groundwater. Eventually, specific treatments for mineral compounds (e.g. Fe, Mn, NH_4, H_2S, etc.), depending on the geochemistry, can be applied (Suez, 2016). However, for other water users, these water sources may only need a basic treatment or even no treatment at all. Similarly, a conventional treatment for surface water is often used for river, natural lakes, wetlands, and direct rainwater harvested (assuming that it undergoes the same treatment as a river) for public water uses, while other users may only need a basic treatment or no treatment.

Water from inter-basin water transfers and water from reservoirs are both special cases regarding the type of treatment technology to apply. Depending on the origin of the transported and stored water and the user needs, the treatment technology will differ. In case of lack of information on water origin, a conservative assumption that the water transferred/stored is surface water, which usually has lower quality, has been adopted.

Seawater and brackish water are assumed to require the same treatment technologies for all users. This is a simplification since a distinction between technologies in function of the feeding water stream and the technological evolution should be done (Subramani and Jacangelo, 2015).

For domestic waste water and harvested stormwater run-off, it is assumed that the water needs specific treatment to be (re-)usable depending on the type of user and socio-economic conditions. For instance, neither of both sources is considered to be used for public water uses. However, domestic waste water may be used for irrigation after advanced treatment in developed countries and without treatment in developing countries (WHO, 2012). Harvested stormwater run-off may often be heavily polluted (e.g. with hydrocarbons, pathogens, pesticides, nitrates and other fertilizers). Therefore, it is assumed to be used only for “manufacturing (raw water)” with a basic treatment and for irrigation and recreation after an advanced treatment. Given the high cost and the frequently insufficient control of urban planning globally, it is considered that the advanced treatment is only applied in industrialized/developed countries (Parkinson and Mark, 2005).

Finally, the water distribution network (including water losses and evaporation) may vary from country to country and between regions of each country due to local specificities (Farley and Trow, 2003). In order to include it in the WSmix, the same relation as in the tap water mix of Quebec (Lesage and Samson, 2013) has been used, where the distribution network is calculated as a function of the yearly transported amount of water, the network’s lifetime and length. Detailed information on water losses and evaporation for WSmix is given in Section S10 in SI.

As illustrated in Figure S8 in SI, the implementation of regionalized WSmix is based on the water sources mix per user obtained from the WOmix database and the respective water technologies.

Further information regarding the description and harmonization of the water users and sources, as well as aggregation to a more generic level needed in case of lack of information (level 0 and level 1) are given in Tables S11 to S14 in SI.

4 Illustrative case study

4.1 Description

To demonstrate the relevance of including WSmix in LCI databases, an illustrative case study has been conducted. A comparison of current practice and an application of the WSmix to assess the environmental impacts of potable water supply in two countries, Spain and France, were performed. These two countries have been chosen as all relevant information is available and because they have contrasted water origins per user, leading to different associated treatment technologies. In addition, their electricity mixes are completely different (Figure 5) (IEA, 2017).

The functional unit (i.e. unit of reference for the comparison) was the supply of 1m^3 of potable public water. The LCIA method used was ILCD 2011. Moreover, water deprivation impacts were assessed with two scarcity indicators: the water stress index WSI (Pfister et al., 2009) and the AWARE index (Boulay et al., 2017). The Simapro 8 LCA software was used for the assessment.

4.2 System modelling

To carry out the case study, two systems have been created in Simapro 8, i.e. WSmix of potable public water in France and Spain, respectively. The starting point to build the WSmix models was the volume and the proportion of different water sources withdrawal in each country (see WOmix database in SI, Figure 5 and Table S18 in SI). The water elementary flows and the processes for the water technologies were selected from the ecoinvent 3.2

database using the "Allocation at the point of substitution" system model (Wernet et al., 2016). Since currently this database does not provide all the water elementary flows and treatment technologies required, some simplifications have been done. For example, the water input environmental flow "water, from river" was used instead of "surface water, reservoir" or "inter-basin water transfer". Both inputs have been associated with the process "Tap water production, conventional treatment". The same procedure was used for groundwater and sea water. The water supply network was also included and calculated considering specific variables of each country (length, lifetime and network product volume, see details in Table S18 in SI).

It is considered that the water evaporation from the whole water supply system is negligible (assuming that the use of open channels for water transportation is not significant in this particular case). Only water losses through leaks released to groundwater (i.e. not evaporated) were regarded. The respective electricity mix of each country was an input of each water technology used (Figure 5).

Finally, a comparison between both country-specific WSmix and the production of public water supply using the "market for tap water, European average (RER)" has been done.

4.3 Results and conclusions

The LCA results show that the environmental impacts of the supply of $1m^3$ of potable public water from mixed sources vary widely and are highly dependent on the country. In addition, there is a strong influence of the local electricity mix in the WSmix, which highlights the role of the water-energy nexus. For instance, the difference of impacts (Figure 6) between France and Spain is due to the composition of their respective electricity mixes, which is mainly nuclear in France (contributing to ionizing radiation) and mainly fossil fuel-based in Spain (contributing to climate change and other emission-based impacts).

The comparison between the local WSmix for Spain, France and the average European market commonly used today in LCA studies shows great differences for all impact categories. This is explained by the fact that the European market is composed of an average of all water production technologies (in fact, the Quebec water production technologies, see figure S4 in SI) and the European electricity mix (PRe-Consultants, 2016; Wernet et al., 2016). Regarding water deprivation impacts (Section S16 in SI), since evaporation in the foreground system is disregarded in all cases, the results only concern background activities (e.g. water infrastructures, chemical production, electricity production), as they are the only processes consuming water. The results show greater impacts in Spain compared to France, which is in line with results published by EEA (2007).

As a conclusion of the case study, the environmental impacts associated with different water supply systems highly depend on the water sources mix, the technologies associated and the local electricity mix, which is in line with previous studies (Hospido et al., 2013; Meron et al., 2016; Stokes and Horvath, 2009; Vince et al., 2008). Also, the variability of the environmental impacts when comparing local WSmix to the European average shows that, using average processes (which is current practice in LCA) may lead to results far from the local reality. This fact supports the need and the relevance of including regionalized WSmix in LCI databases for proper water-use impact assessment.

5 Discussion

5.1 Limitations and completeness

The main assumptions and uncertainties of the WSmix framework are related to the water treatment technologies, water losses, and distribution networks. In particular, due to the lack of country-specific water technology inventory data, water treatment technologies used are those currently available in LCI databases. Although, the same range of technologies is used for all countries, a treatment level differentiation depending on the country's development status has been introduced. Furthermore, it is assumed that the same water source type, such as "alluvial groundwater" and "deep groundwater", is subject to the same technology to meet specific user quality requirements under a given socio-economic condition. This assumption is based on this water belonging to the same water source type which therefore has similar technological treatment. This simplified approach is proposed for short-term implementation. However, more data are needed on water treatment technologies by country/river basin and for different users, as compiled on a country and city basis for tap water production by Meron et al. (2016).

Regarding water losses and evaporation, due to lack of data, it is assumed that there are no differences between the types of network with respect to the type of use. However, more research is needed to assess the influence of these differences on the WSmix, and also the effect of urbanism, i.e. population density, on the network infrastructure, as shown by Roux et al. (2011) for the sewer network.

5.2 Compatibility and requirements for implementation in LCA

In most cases, LCA practitioners do not know the water origin and associated water treatment technology applied in their LCI processes, especially in the background product system (Quinteiro et al., 2017). WSmix datasets will support LCA practitioners in their LCI modelling (see Section S17 for further information). Although, some water source types of the WSmix are already included in LCI databases and assessed by LCIA methods, the WSmix provides a higher detail not only in terms of water sources and water users, but also in terms of spatial and temporal resolution. Therefore, some adaptations to make the WSmix compatible with the currently most used LCI databases and to ensure seamless connection with LCIA methods are required. Those adaptations may imply aggregation of water source types and water user categories as well as of spatial and temporal resolution, since current databases and software only allow annual and country differentiation. These aggregations rely on remaining at level 0 or 1 both for water sources and water users in order to avoid very long lists of datasets (Tables S11 and S12 in SI). Alternatively, data at level 2 could be integrated in LCA software through geographic information system (GIS) layers.

Compared to the electricity mix, the implementation of the WSmix in LCI databases may be more elaborate given all the variables associated with it. While an electricity mix is supplied with only a voltage differentiation (high voltage, low voltage and medium voltage), water quality requirements vary among water users, and therefore, embedded environmental impacts will be very different depending on the user, affecting both water sources and water production technologies. The apparent complexity of WSmix data collection and database implementation can be adapted to different levels of detail. Therefore, depending on the goal and scope of the study, available data and LCIA method used, the LCA practitioner will be able to choose the level of complexity required for the inventory.

Regarding LCIA methods for assessing water degradation and consumption impacts, current software allows for the calculation of water degradation impacts through the eutrophication, acidification, and ecotoxicity impact categories in a temporally and spatially generic way (with the exception of openLCA which allows for regionalized LCIA calculation (Rodríguez and Greve, 2016)). For water consumption impact assessment, the most used scarcity indices, namely WSI (Pfister et al., 2009) and AWARE (Boulay et al., 2017) have been developed at water-basin scale with yearly or monthly resolution, although they are implemented in LCA software only at the country scale on an annual basis with distinction of agricultural, non-agricultural and unspecified uses for AWARE. However, none distinguishes between different water sources, meaning that all water origins (e.g. lake, river, and groundwater) within the boundaries of a river basin share the same characterisation factor, thus the effect of using different sources does not translate into the impact score. In this context, considering that the WSmix is specified at (sub-) river basin level, per season or month, and for several water users, a great amount of datasets would have to be integrated in LCA software, which may currently have limited processing capabilities. As previously mentioned, the integration of GIS layers into LCA software could facilitate data handling. Other water use LCIA methodologies than scarcity indices have different spatial coverage and temporal resolutions (Kounina et al., 2013), and require different levels of detail in terms of water sources (Table S2 in SI), which can all be considered by the WSmix framework.

Finally, the terminology used in the inventory flows should be consistent with that of the impact assessment methods to ensure a coherent interface between the LCI and LCIA for the classification step.

6 Conclusion

From a conceptual point of view, the proposed WSmix framework allows combining water sources (e.g. surface, ground, sea) and related technologies to meet the needs of a user (e.g. domestic, irrigation, industry) at a specific time (season) and location (country and/or sub-river basin) at a worldwide scale.

The case study highlights the relevance of including a WSmix in LCI databases for a consistent water-use related impact assessment in LCA. It will support LCA practitioners of different sectors (e.g. industry, energy, agriculture) to carry out a consistent environmental assessment of water use along the supply chain of their products and services. The WSmix will be useful in routine assessment of water-use related impacts, being just as straightforward as using the regional electricity supply mix in LCA.

From a practical point of view and based on the WSmix framework developed, a database of water source mixes (WOmix) for the users identified in Figure 4 has been created (Excel file in SI). Data quality differs depending on the country but most countries, especially the developed ones, have the data needed for a global and spatially explicit WSmix.

The WSmix framework and global regionalized WSmix database/maps also provide interesting insights beyond the LCA scope to support strategic management of water sources at any scale including the global scale. For instance, it is useful when quantitative data are required to assess the (global) vulnerability of water sources or the future water supply security in cities and densely populated regions.

Perspectives on the long-term implementation of WSmix rely on two main requirements: i) spatialization of LCA, and ii) forthcoming LCIA developments that differentiate water sources in order to account for differences in their impact profiles (Núñez et al., 2016).

The first requirement is to adapt a regionalised version of the WSmix in LCA software, with specific values per sub-river-basin where the water use occurs. This can be done using GIS, either by implementing an external GIS database connected to the LCI, or, at longer term, with the integration of GIS within LCA software, as already done by openLCA (GreenDelta, 2016) and Brightway2 (Mutel, 2016)).

The second requirement is to make the WSmix compatible with future LCIA models for water consumption impact assessment. These evolve towards models considering the interconnections between water compartments within the river basin which are thus capable of differentiating several water source compartments (Núñez et al., 2016). The flexible WSmix framework has been designed bearing in mind such future requirements and is already adapted to forthcoming generations of water use LCIA indicators.

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Figures

Figure 1 Schematic representation of the water supply mix (WSmix) concept

Figure 2 Countries covered by WOmix per user database

Figure 3 Methodological framework of water supply mix

Figure 4 Correspondence between water source, water users, and water treatment technologies used in the WSmix

Figure 5 WSmix applied to France and Spain

Figure 6 WSmix environmental impacts associated to the production of $1m^3$ of potable public water in France and Spain compared to current market for tap water in ecoinvent

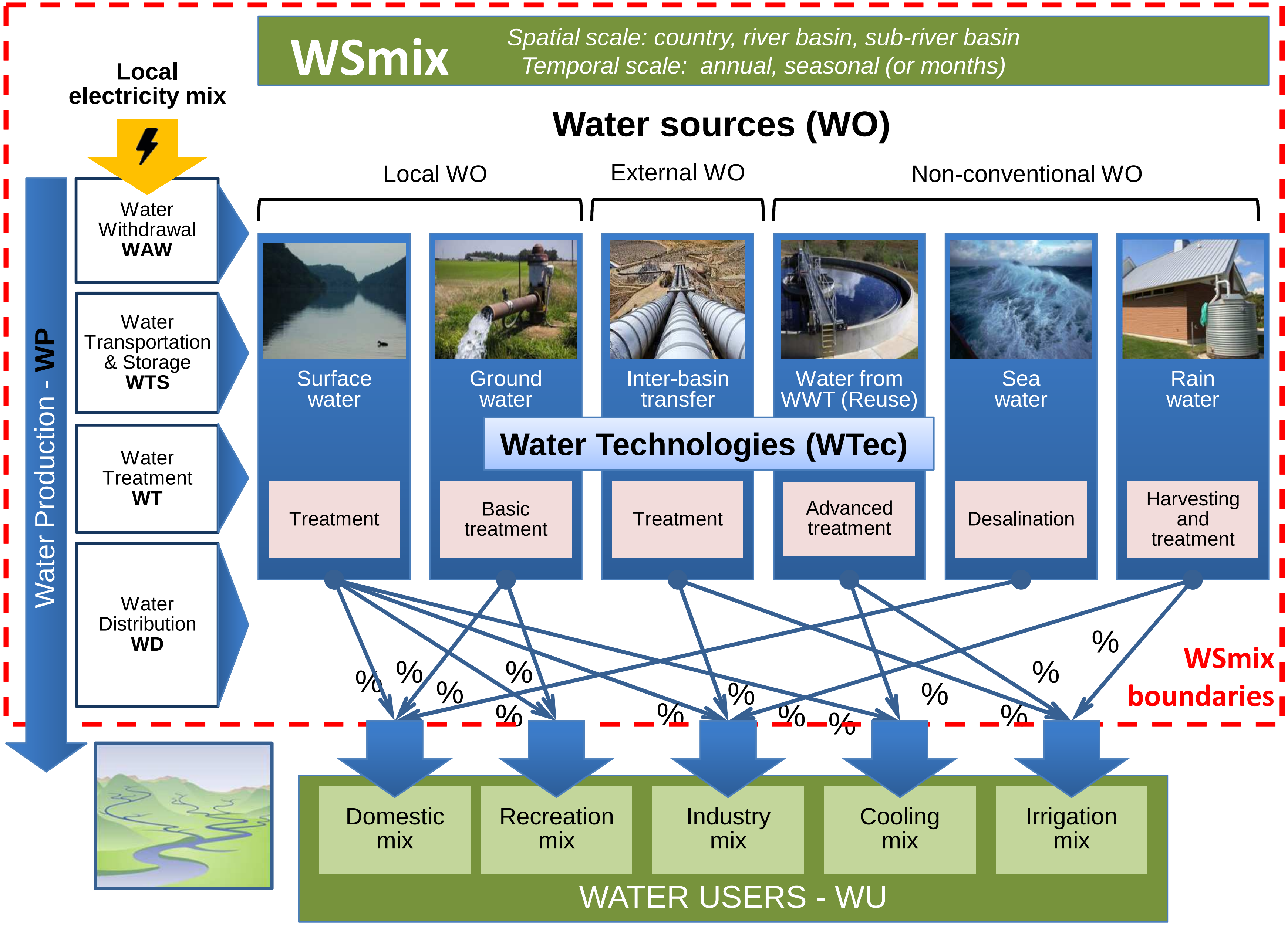

Figure 1 Schematic representation of the water supply mix (WSmix) concept

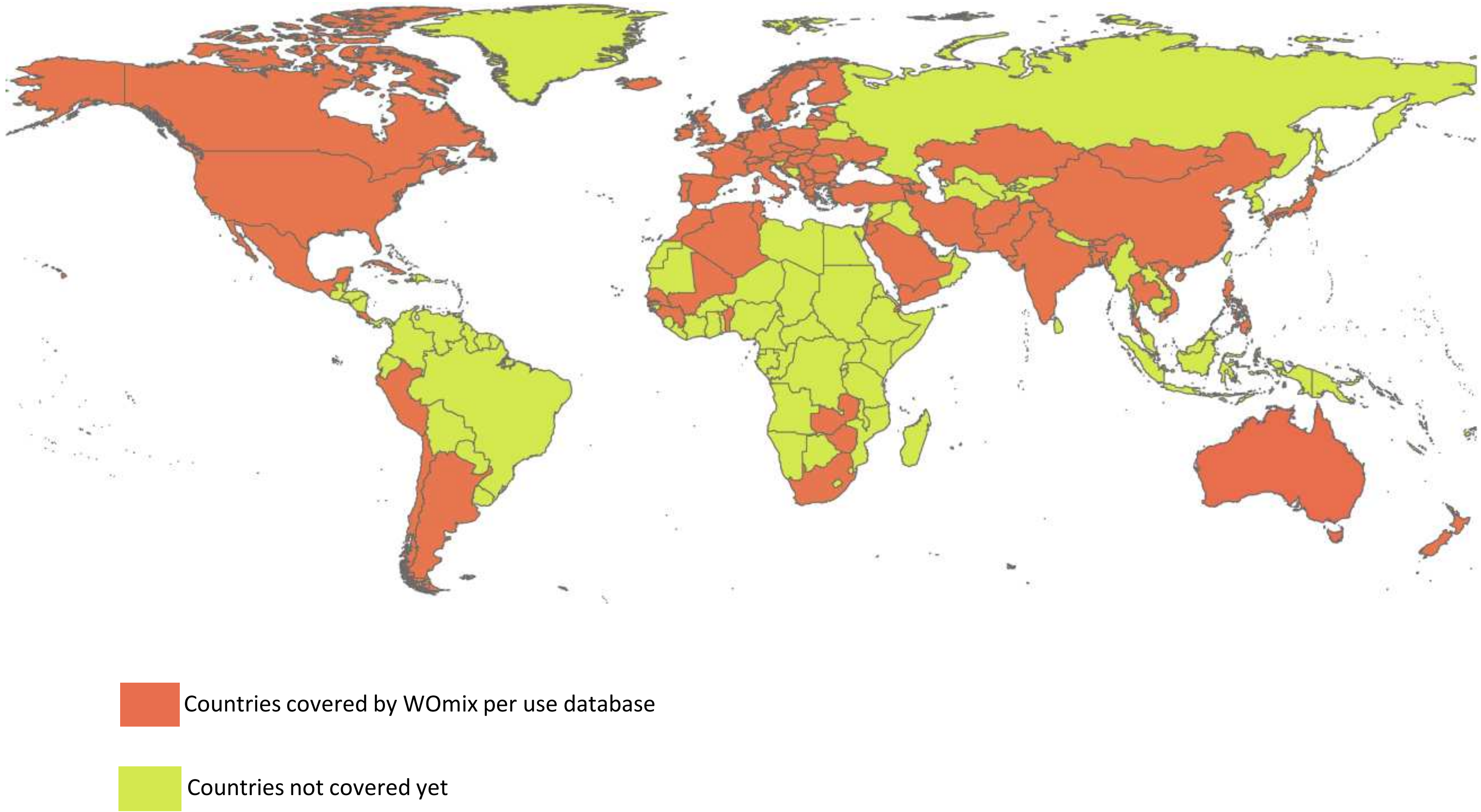

Figure 2 Countries covered by WOmix per use database

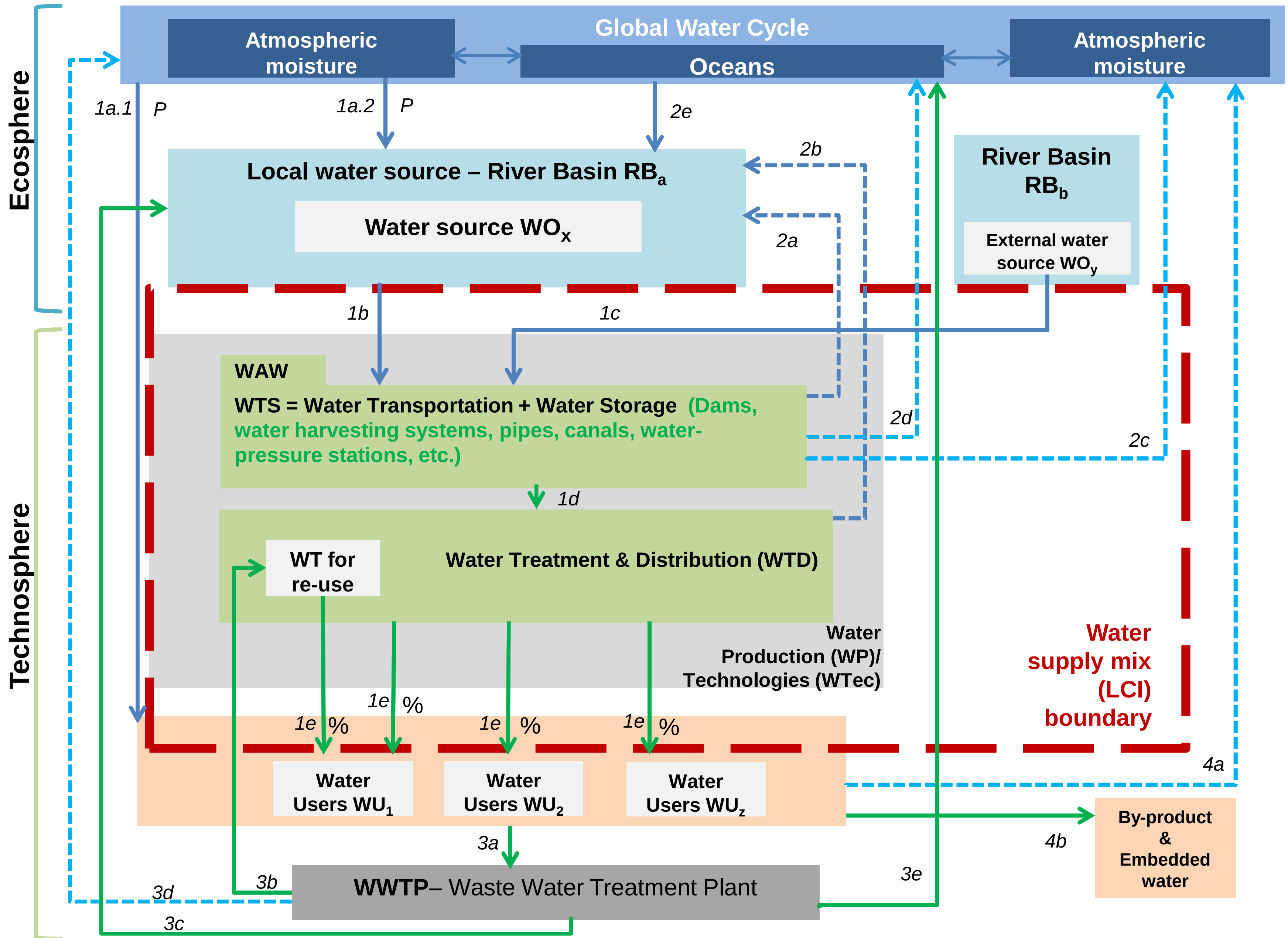

Figure 3 Methodological framework of water supply mix

Legend

Water source flow from ecosphere

Water source flow from technosphere

Water evaporation to global water cycle and water released into ocean

Water losses during transportation and distribution

Water flows

1a.1= Direct precipitation supply to the user (e.g. natural irrigation)
1a.2= Precipitation into the water bodies of the river basin (RB)
1b= Water source flow from the ecosphere and transported and possibly stored before treatment and distribution to the user
1c= Water source flow transferred from a neighboring river basin
1d= Water source flow coming from water transportation & storage (WTS) to water treatment and distribution (WTD)
1e= Water source flow treated and supplied to the user
2a= Local water losses due to transportation
2b= Local water losses due to the distribution network
2c= Evaporation to the atmosphere
2d= Excess water from transportation which is released into the ocean
2e= Water source flow from the ocean
3a= Water source flow to the water treatment plant after use
3b= Reused wastewater
3c= Water released into the local environment after treatment
3d and 4a= Evaporation to the atmosphere
3e= Water released into the ocean after treatment
4b= By-products (embedded water) obtain from the water activities

Indices

b= Donor RB

x, y= Type of water source

z= Type of water user

Figure 3 Methodological framework of water supply mix

<table>
<tr><th rowspan="2">Water user / Water source</th><th rowspan="2">Potable public water[3]</th><th colspan="2">Non-potable public water[3]</th><th colspan="3">Manufacturing</th><th rowspan="2">Cooling</th><th colspan="2">Irrigation</th><th colspan="2">Livestock</th><th colspan="2">Aquaculture (off-stream)</th><th rowspan="2">Planted Forestry</th><th rowspan="2">Recreation</th></tr>
<tr><th>Option 1</th><th>Option 2</th><th>Pure water</th><th>Softened water</th><th>Raw water</th><th>Option 1</th><th>Option 2</th><th>Option 1</th><th>Option 2</th><th>Option 1</th><th>Option 2</th></tr>
<tr><td>Alluvial groundwater</td><td rowspan="6">Conventional treatment for groundwater (a)</td><td rowspan="6">Conventional treatment for groundwater (i)</td><td rowspan="6">No treatment*</td><td rowspan="11">Deionisation - Reverse osmosis (d)</td><td rowspan="13">Equivalent treatment to potable public water (l)</td><td rowspan="11">Basic treatment (g)</td><td rowspan="6">n.a. (h)</td><td rowspan="11">Equivalent treatment to no-potable public water (option 2)</td><td rowspan="13">Equivalent treatment to no-potable public water (option 2)</td><td rowspan="6">Conventional treatment for groundwater (a), (k)</td><td rowspan="11">Equivalent treatment to non-potable public water (option 2)</td><td rowspan="11">Equivalent treatment to non-potable public water (option 2)</td><td rowspan="15">Equivalent treatment to irrigation (option 2)</td><td rowspan="11">Equivalent treatment to non-potable public water (option 2)</td><td rowspan="11">Equivalent treatment to non-potable public water (option 2)</td></tr>
<tr><td>Deep groundwater</td></tr>
<tr><td>Fossil groundwater</td></tr>
<tr><td>Spring-water</td></tr>
<tr><td>Inter-basin water transferred (groundwater origin [1,2])</td></tr>
<tr><td>Reservoir (groundwater origin[1,2])</td></tr>
<tr><td>River</td><td rowspan="5">Conventional treatment for surface water</td><td rowspan="5">Conventional treatment for surface water (i)</td><td rowspan="5">No treatment** (j)</td><td rowspan="7">Basic treatment (g)</td><td rowspan="5">Conventional treatment for surface water (k)</td></tr>
<tr><td>Natural lake/Wetland</td></tr>
<tr><td>Inter-basin water transferred (surface water origin[1,2] or unknown origin)</td></tr>
<tr><td>Directly harvested rainwater</td></tr>
<tr><td>Reservoir (surface water origin[1,2] or unknown origin)</td></tr>
<tr><td>Sea water</td><td rowspan="2">Advanced treatment - Ultrafiltration (c)</td><td rowspan="2">n.a. (b)</td><td rowspan="2">n.a.</td><td rowspan="2">n.a (b)</td><td rowspan="2">n.a.</td><td rowspan="2">n.a.</td><td rowspan="2">n.a. (b)</td><td rowspan="2">n.a. (b)</td><td rowspan="2">No treatment** (j)</td><td rowspan="2">n.a. (b)</td><td rowspan="2">Conventional treatment for surface water</td></tr>
<tr><td>Brackish water/Saline groundwater</td></tr>
<tr><td>Domestic waste water</td><td>n.a.</td><td>n.a.</td><td>n.a.</td><td>n.a.</td><td>Advanced treatment - ultrafiltration (e)</td><td>n.a.</td><td>Basic treatment (m)</td><td>Advanced treatment ultrafiltration (e), (f)</td><td>No treatment** (j)</td><td>n.a.</td><td>No treatment** (j)</td><td>n.a. (f)</td><td>Advanced treatment ultrafiltration (e), (f)</td><td>Advanced treatment ultrafiltration (n), (e)</td></tr>
<tr><td>Harvested stormwater run-off</td><td>n.a.</td><td>n.a.</td><td>n.a.</td><td>n.a.</td><td>n.a.</td><td>Basic treatment (m)</td><td>n.a.</td><td>Advanced treatment - ultrafiltration (e)</td><td>n.a.</td><td>n.a.</td><td>n.a.</td><td>n.a.</td><td>n.a.</td><td>Advanced treatment ultrafiltration (n), (e)</td></tr>
<tr><td>Data sources for the selection of the treatment tecnologies</td><td>Ref [1, 3, 4]</td><td>Ref [2, 6]</td><td>Ref [2, 6]</td><td>Ref [2, 4]</td><td>Ref [2, 4]</td><td>Ref [2]</td><td>Ref [1, 2, 3, 4]</td><td>Ref [2, 6, 7]</td><td>Ref [2, 8]</td><td>Ref [2]</td><td>Ref [5]</td><td>Ref [2, 7]</td><td>Ref [2, 8]</td><td>Ref [2]</td><td>Ref [2, 9]</td></tr>
</table>

Ref. [1] Meron et al. (2016), Ref. [2] Based on expert judgment based on knowledge and experience of the authors and processes available in LCI databases, Ref. [3] Hydranet (2016), Ref. [4] Suez (2016), Ref. [5] IWMI (2010) , Ref. [6] WHO (2016), Ref. [7] FAO (2016), Ref. [8] WHO (2012), Ref. [9] NSW (2006)

No treatment
Basic treatment
Conventional treatment
Equivalent treatments
Advanced treatment
Desalination
Deionisation

**Option 1 and option 2 allows a differentiation for developed and developing country (see more details in SI, table S12)*

Note: see comments from (a) to (n), indices [1, 2, 3] and *, ** in Table S15 in SI

Figure 4 Correspondence between water source, water users, and water treatment technologies used in the WSmix

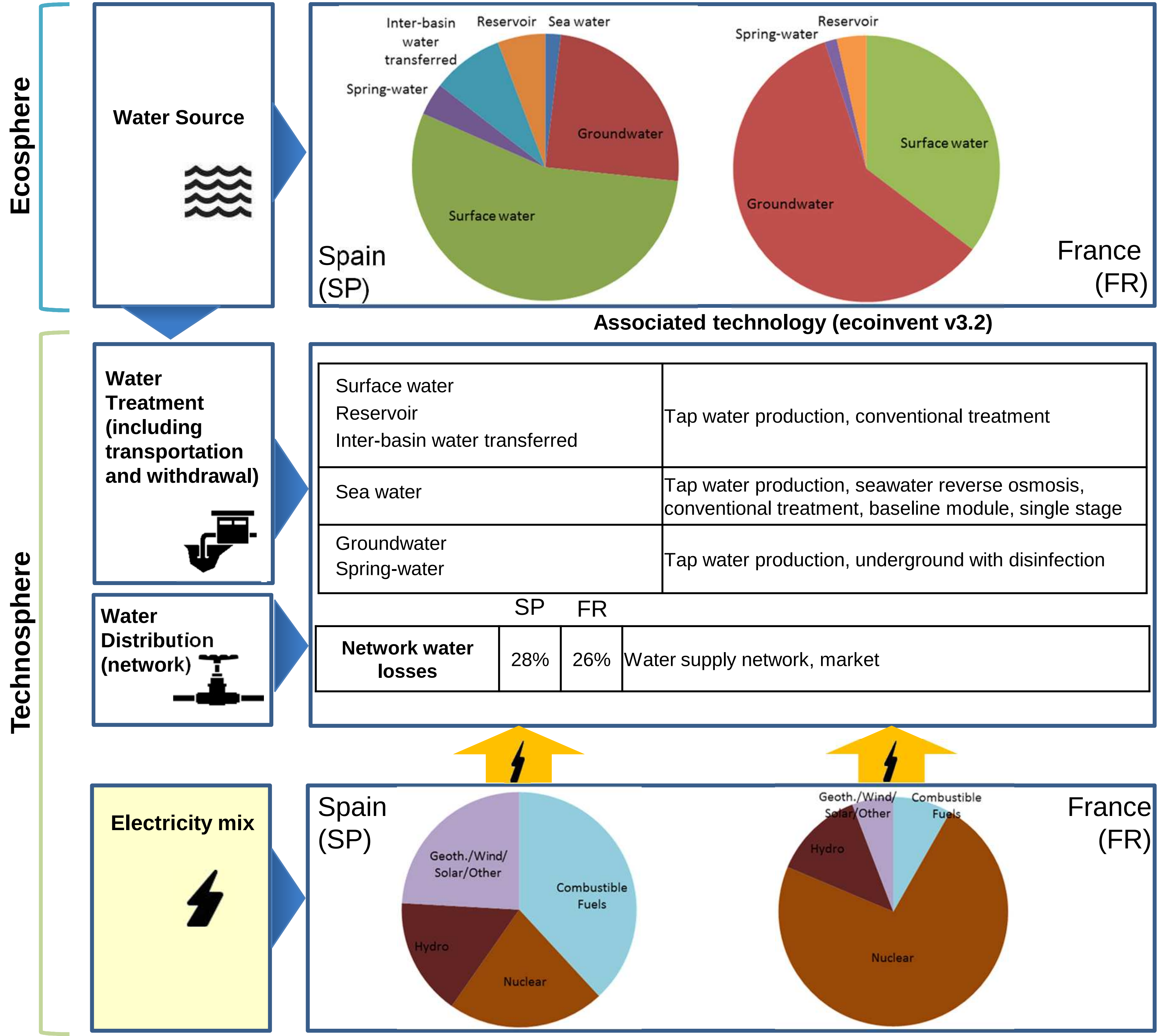

Figure 5 - WSmix applied to France and Spain

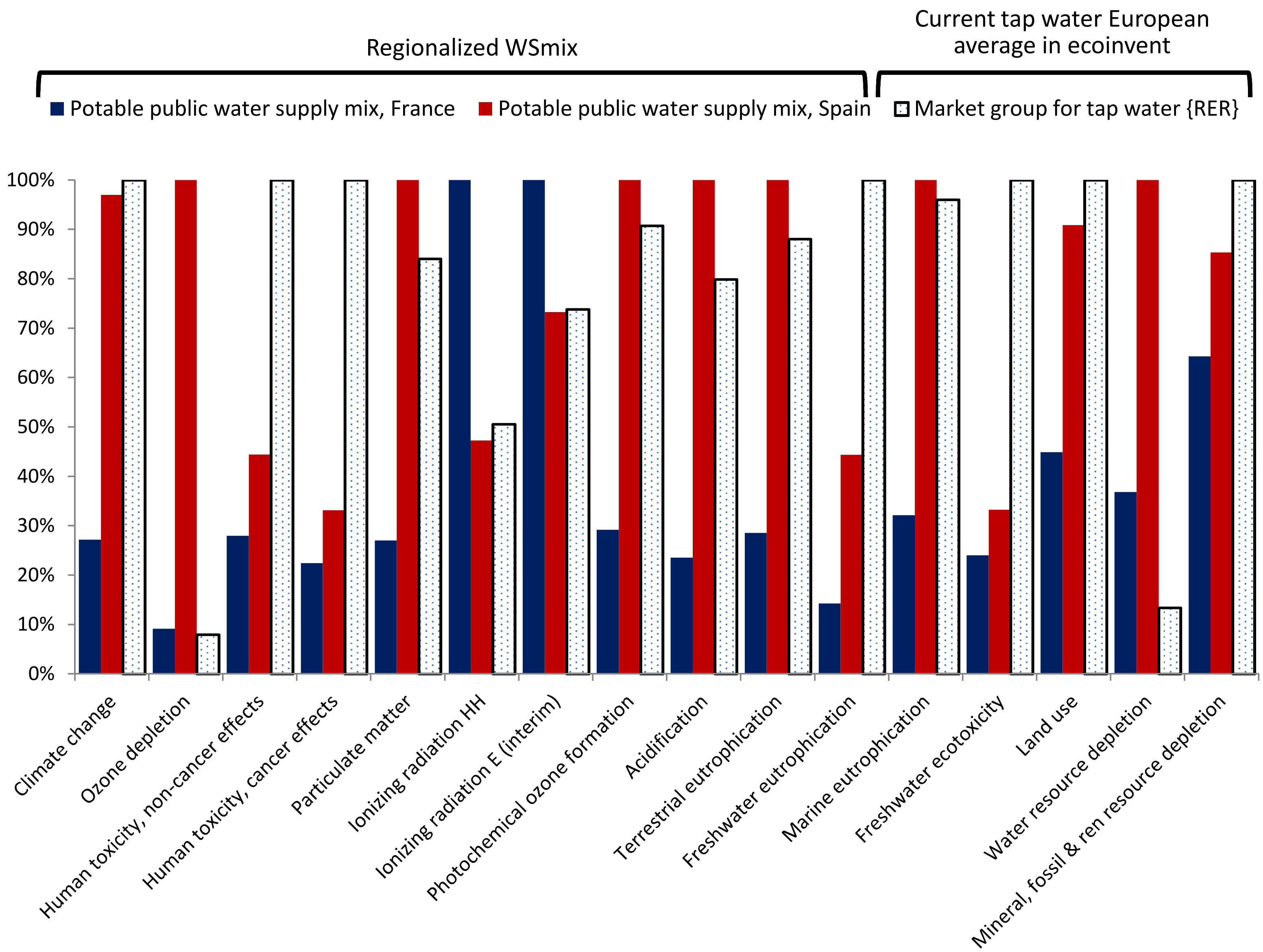

Figure 6 - WSmix environmental impacts associated to the production of 1m³ of potable public water in France and Spain compared to current market for tap water in ecoinvent

Highlights:

- A Water Supply mix (WSmix), in analogy with the electricity mix, is framed
- The WSmix is the regional combination of water sources per water user worldwide
- A water source mix database at country & (sub) river-basin is built per water user
- Environmental impacts of WSmix also depend on electricity mix (water-energy nexus)
- The WSmix will allow routine assessment of water-use related impacts in LCA