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

Susana Leao, Philippe Roux, Montserrat Nunez, Eléonore Loiseau, Guillaume Junqua, Agata Sferratore, Ywann Penru, Ralph K. Rosenbaum

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2 **A worldwide-regionalised water supply mix (WSmix) for life cycle**  
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4  
5 **Susana Leão<sup>a,b,\*</sup>, Philippe Roux<sup>a</sup>, Montserrat Núñez<sup>a</sup>, Eléonore Loiseau<sup>a</sup>, Guillaume**  
6 **Junqua<sup>b</sup>, Agata Sferratore<sup>c</sup>, Ywann Penru<sup>d</sup>, Ralph K. Rosenbaum<sup>a</sup>**

7  
8 <sup>a</sup> ITAP, Irstea, Montpellier SupAgro, Univ Montpellier, ELSA Research group and ELSA-PACT Industrial  
9 Chair, Montpellier, France

10 <sup>b</sup> Ecole des Mines d'Alès, LGEI, ELSA Research Group, 6 avenue de Clavières, 30319 Alès, France

11 <sup>c</sup> Société du Canal de Provence, 966 Route de Pierrefeu, 83260 La Crau, Aix-en-Provence, France

12 <sup>d</sup> SUEZ Groupe 38, rue du Président Wilson 78230 Le Pecq, France  
13  
14

15 \* Corresponding author. E-mail address: [susana.de-oliveira-leao@irstea.fr](mailto:susana.de-oliveira-leao@irstea.fr)  
16

17 **Abstract**

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

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

### 37 **Keywords**

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

40

### 41 **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

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## 61 **1 Introduction**

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

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

81 Conventional Life Cycle Inventory (LCI) databases such as ecoinvent (Wernet et al., 2016),  
82 GaBi 6 (Thinkstep, 2016) and Quantis Water Database (QWD) (QWD, 2015) provide a water  
83 balance of flows entering and leaving the product system (Section S1 in Supplementary  
84 Material (SI)). Water input flows account for water withdrawal from the environment, and  
85 water consumption is the total water withdrawal minus the total water released back to the

86 river basin after use (ISO, 2014). However, LCI databases only include a few water sources  
87 and water treatment technologies without distinction of seasons and regions, although the ISO  
88 standard 14046 on water footprinting (ISO, 2014) recommends temporal and geographical  
89 differentiation of water flows. In terms of spatial and temporal resolution, current unit  
90 processes for water production in LCI databases represent a global annual average or a  
91 country annual average, with unknown origin if not defined by the LCA user and with no link  
92 to the water production technology applied (with the exception of tap water production in  
93 Quebec, see below). In particular, tap water, irrigation and cooling water uses are  
94 distinguished, although overall information is incomplete, both in terms of water origin and  
95 specific water production technologies.

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

105 The tap water mix for Quebec (Lesage and Samson, 2013) (called “market for tap water” in  
106 the ecoinvent database (Wernet et al., 2016)) is an example of a practical implementation of  
107 the water mix in LCA. This mix differentiates between water sources, namely surface and  
108 groundwater, and the average of tap water production technologies used in Quebec, including  
109 the network and water losses during distribution. However, it only covers one region and one  
110 type of water use on an annual basis. Ono et al. (2015) developed an inventory database for

111 water footprint based on input-output analysis of goods and services produced in Japan. While  
112 different water sources and users have been considered in this approach, the geographic and  
113 temporal differentiation is limited to annual average flows in Japan.

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

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

## 126 **2 Problem definition and objectives**

127 The WSmix concept is relatively similar to the energy mix concept. The energy mix is a  
128 worldwide standard model that determines how final energy consumption in a given  
129 geographical region breaks down by primary energy sources (e.g. fossil fuels, nuclear energy,  
130 waste and renewable energy) and by different uses (e.g. electricity generation, called  
131 electricity mix, transportation, or heating of buildings). In the same manner, the WSmix is a  
132 model describing how final water use for specific users (domestic, agriculture, industry) in a  
133 given location and season breaks down by primary water (re)sources (e.g. surface water,  
134 groundwater, precipitation) and by associated treatment and supply technologies (including

135 infrastructure and energy consumed to extract, purify, deliver, heat/cool and treat water,  
136 which is known as the water-energy nexus) (DOE, 2014).

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

147 Another important limitation observed in LCI databases is the lack of information regarding  
148 the required treatment technology or chain of technologies for a given water source to meet a  
149 specific water demand (in terms of quantity and quality). The technologies used for water  
150 withdrawal, water transportation and storage usually are not substantially different between  
151 water sources. However, important differences in technologies for water treatment actually  
152 exist, since they are designed for specific input and output quality standards (Meron et al.,  
153 2016).

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

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

### 161 **3 Methods and modelling**

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

#### 166 **3.1 Bases of the WSmix framework concept**

##### 167 *3.1.1 System definition and boundaries*

168 The WSmix represents water supply systems, which are described as withdrawal, treatment,  
169 and distribution of water from different water origins to water users (Lesage and Samson,  
170 2013; Loubet et al., 2016; Meron et al., 2016; Vince et al., 2008). Therefore, it describes  
171 water inputs to a process, while water outputs (i.e. release back to the ecosphere) are not  
172 included. Consequently, the WSmix includes the combination of water origin, technologies of  
173 water production and distribution for different water users at different spatial and temporal  
174 scales (Figure 1). These technologies should be modelled with a life cycle perspective to  
175 consider all impacts due to upstream activities (e.g. infrastructure, energy, chemicals).

176 Similarly to the energy mix and in particular the electricity mix in LCA (Frischknecht and  
177 Tuchschnid, 2008), the system boundaries for the WSmix are defined from the water  
178 resource withdrawal up to the delivery to the final user, excluding all processes during and  
179 after the use phase. It includes all interactions between the ecosphere (environment) and the  
180 technosphere (technical system), i.e. emissions and resource extractions. The only feedback

181 from water users towards WSmix is the water quality that is required for each specific use and  
182 that will define the required combination(s) of sources and technologies.

### 183 *3.1.2 Terminology and classification of the WSmix components*

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

188 A great variability of terminology and classification for water sources and water users was  
189 observed. For instance, when comparing two river basins in France for water sources, one has  
190 a water mix of four different, very aggregately defined origins, whereas the other has 10  
191 different, detailed water origins (Adour-Garonne, 2013; Loire-Bretagne, 2013). The same  
192 holds true for water users when comparing data from two river basins in Spain, one  
193 distinguishing five water users (Guadalquivir, 2013) and the other eight (Miño-sil et al.,  
194 2007). More details are given in Sections S5 and S6 in the SI.

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

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

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

213 1. The water source classification should be based on direct environmental relevance  
214 of each water source. The environmental relevance can be evaluated according to  
215 different aspects. The following parameters were considered in the WSmix  
216 classification:

217 a. *Water renewability*: Groundwater was classified into three sub-categories:  
218 alluvial, deep, and fossil groundwater, based on the different renewal rates of  
219 each water source, which is particularly low for the latter (GWF, 2014). In  
220 addition, the different levels of depth and consequently the energy required for  
221 pumping each type of groundwater were considered for the classification, as  
222 pump efficiency and type of power source vary (Pradeleix et al., 2015).

223 b. *Water deprivation impacts*: Regarding surface water, a classification into three  
224 sub-categories representing different water bodies is proposed: i) river, i.e. a  
225 water flow; ii) natural lake and wetland, i.e. standing water; and iii) spring-  
226 water, i.e. the result of an aquifer saturated to the point that the water overflows  
227 into the land surface (Perlman, 2016). From an LCIA point of view, spring-  
228 water is considered as withdrawn from surface water, thereby potentially

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

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

243 2. Inclusion of non-conventional water sources, as another category of the proposed  
244 alternative water sources (see table S11 in SI). Water scarce countries are expected to  
245 progressively rely more on those sources to alleviate water scarcity. Five categories  
246 are distinguished: seawater, brackish/saline groundwater, domestic wastewater,  
247 harvested stormwater run-off, and directly harvested rainwater. Although, the last two  
248 have the same origin (rainwater), they have a different water quality since the first is  
249 generally more polluted (Wahaso, 2016). It is currently assumed that the use of  
250 alternative water sources have generally no impact on water scarcity (Hospido et al.,  
251 2013; Muñoz et al., 2010). However, they contribute to other impact categories due to  
252 the environmental impacts associated to the energy and technology for  
253 withdrawal/collection, treatment and distribution.

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

### 267 **3.2 Water source mix (WOMix) database**

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

275 For most countries, especially the developed ones, the data needed for a global and spatially  
276 explicit WSmix are available. For instance, in Europe, data on water withdrawal for different  
277 users at river-basin and sub-river-basin level are accessible through local water management

278 plans via water agencies and national statistics. However, for some countries or regions, data  
279 are available only at country scale, and in some cases no data were found (approximately half  
280 of the countries in the world). For those cases, interpolation and aggregation of data from  
281 neighbouring countries and/or river basins could be applied (although not done in this study)  
282 to fill data gaps, based, for example, on socio-economic indicators and geographical location.  
283 Data on temporal water withdrawal variability are available only for a few countries and river  
284 basins. The vast majority of data is available with an annual resolution. For higher temporal  
285 resolution, climate indicators and human activity patterns could be applied (although not done  
286 in this study). Figure S7 in SI shows an example of temporal variability of water sources.  
287 The current WOMix worldwide-regionalized database has information for 93 countries at  
288 national level, 18 countries at river basin level, and five countries at sub-river basin level, for  
289 all water users and types of water sources (Figure 2). This database is the starting point to  
290 create WSmix LCI datasets.

### 291 **3.3 Overview of WSmix framework**

292 Figure 3 depicts the WSmix methodological framework that represents the water sources  
293 (surface, ground, sea, etc.) at the ecosphere level (environment) and all the technologies  
294 associated for withdrawal, transport, store and distribution of water at the technosphere level  
295 (technical system). Solid blue arrows (1b and 1c) represent the water flows entering from the  
296 ecosphere into the technical system and solid green arrows (1d and 1e) represent the water  
297 flows within the technosphere. After water use, water flows can be treated and reincorporated  
298 into the system to be reused after an additional treatment (3b) or returned to the environment  
299 after conventional waste water treatment (3c and 3e). Dashed blue arrows represent water lost  
300 during transport and distribution (2a and 2b) while dashed light blue arrows represent water  
301 consumed, i.e. water evaporated (2c, 3d and 4a) and the excess water transported that is

302 released into the ocean (2d) (ISO, 2014). Further details about Figure 3 are given in Table S6  
303 in SI.

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

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

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

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

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

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

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

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

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

## 355 **4 Illustrative case study**

### 356 **4.1 Description**

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

364 The functional unit (i.e. unit of reference for the comparison) was the supply of 1m<sup>3</sup> of  
365 potable public water. The LCIA method used was ILCD 2011. Moreover, water deprivation  
366 impacts were assessed with two scarcity indicators: the water stress index WSI (Pfister et al.,  
367 2009) and the AWARE index (Boulay et al., 2017). The Simapro 8 LCA software was used  
368 for the assessment.

### 369 **4.2 System modelling**

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

375 database using the “Allocation at the point of substitution” system model (Wernet et al.,  
376 2016). Since currently this database does not provide all the water elementary flows and  
377 treatment technologies required, some simplifications have been done. For example, the water  
378 input environmental flow “water, from river” was used instead of “surface water, reservoir”  
379 or “inter-basin water transfer”. Both inputs have been associated with the process “Tap water  
380 production, conventional treatment”. The same procedure was used for groundwater and sea  
381 water. The water supply network was also included and calculated considering specific  
382 variables of each country (length, lifetime and network product volume, see details in Table  
383 S18 in SI).

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

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

### 391 **4.3 Results and conclusions**

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

399 The comparison between the local WSmix for Spain, France and the average European  
400 market commonly used today in LCA studies shows great differences for all impact  
401 categories. This is explained by the fact that the European market is composed of an average  
402 of all water production technologies (in fact, the Quebec water production technologies, see  
403 figure S4 in SI) and the European electricity mix (PRe-Consultants, 2016; Wernet et al.,  
404 2016). Regarding water deprivation impacts (Section S16 in SI), since evaporation in the  
405 foreground system is disregarded in all cases, the results only concern background activities  
406 (e.g. water infrastructures, chemical production, electricity production), as they are the only  
407 processes consuming water. The results show greater impacts in Spain compared to France,  
408 which is in line with results published by EEA (2007).

409 As a conclusion of the case study, the environmental impacts associated with different water  
410 supply systems highly depend on the water sources mix, the technologies associated and the  
411 local electricity mix, which is in line with previous studies (Hospido et al., 2013; Meron et al.,  
412 2016; Stokes and Horvath, 2009; Vince et al., 2008). Also, the variability of the  
413 environmental impacts when comparing local WSmix to the European average shows that,  
414 using average processes (which is current practice in LCA) may lead to results far from the  
415 local reality. This fact supports the need and the relevance of including regionalized WSmix  
416 in LCI databases for proper water-use impact assessment.

## 417 **5 Discussion**

### 418 **5.1 Limitations and completeness**

419 The main assumptions and uncertainties of the WSmix framework are related to the water  
420 treatment technologies, water losses, and distribution networks. In particular, due to the lack  
421 of country-specific water technology inventory data, water treatment technologies used are  
422 those currently available in LCI databases. Although, the same range of technologies is used

423 for all countries, a treatment level differentiation depending on the country's development  
424 status has been introduced. Furthermore, it is assumed that the same water source type, such  
425 as "alluvial groundwater" and "deep groundwater", is subject to the same technology to meet  
426 specific user quality requirements under a given socio-economic condition. This assumption  
427 is based on this water belonging to the same water source type which therefore has similar  
428 technological treatment. This simplified approach is proposed for short-term implementation.  
429 However, more data are needed on water treatment technologies by country/river basin and  
430 for different users, as compiled on a country and city basis for tap water production by Meron  
431 et al. (2016).

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

## 437 **5.2 Compatibility and requirements for implementation in LCA**

438 In most cases, LCA practitioners do not know the water origin and associated water treatment  
439 technology applied in their LCI processes, especially in the background product system  
440 (Quinteiro et al., 2017). WSmix datasets will support LCA practitioners in their LCI  
441 modelling (see Section S17 for further information). Although, some water source types of  
442 the WSmix are already included in LCI databases and assessed by LCIA methods, the WSmix  
443 provides a higher detail not only in terms of water sources and water users, but also in terms  
444 of spatial and temporal resolution. Therefore, some adaptations to make the WSmix  
445 compatible with the currently most used LCI databases and to ensure seamless connection  
446 with LCIA methods are required. Those adaptations may imply aggregation of water source

447 types and water user categories as well as of spatial and temporal resolution, since current  
448 databases and software only allow annual and country differentiation. These aggregations rely  
449 on remaining at level 0 or 1 both for water sources and water users in order to avoid very long  
450 lists of datasets (Tables S11 and S12 in SI). Alternatively, data at level 2 could be integrated  
451 in LCA software through geographic information system (GIS) layers.

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

461 Regarding LCIA methods for assessing water degradation and consumption impacts, current  
462 software allows for the calculation of water degradation impacts through the eutrophication,  
463 acidification, and ecotoxicity impact categories in a temporally and spatially generic way  
464 (with the exception of openLCA which allows for regionalized LCIA calculation (Rodríguez  
465 and Greve, 2016)). For water consumption impact assessment, the most used scarcity indices,  
466 namely WSI (Pfister et al., 2009) and AWARE (Boulay et al., 2017) have been developed at  
467 water-basin scale with yearly or monthly resolution, although they are implemented in LCA  
468 software only at the country scale on an annual basis with distinction of agricultural, non-  
469 agricultural and unspecified uses for AWARE. However, none distinguishes between  
470 different water sources, meaning that all water origins (e.g. lake, river, and groundwater)  
471 within the boundaries of a river basin share the same characterisation factor, thus the effect of

472 using different sources does not translate into the impact score. In this context, considering  
473 that the WSmix is specified at (sub-) river basin level, per season or month, and for several  
474 water users, a great amount of datasets would have to be integrated in LCA software, which  
475 may currently have limited processing capabilities. As previously mentioned, the integration  
476 of GIS layers into LCA software could facilitate data handling. Other water use LCIA  
477 methodologies than scarcity indices have different spatial coverage and temporal resolutions  
478 (Kounina et al., 2013), and require different levels of detail in terms of water sources (Table  
479 S2 in SI), which can all be considered by the WSmix framework.

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

## 483 **6 Conclusion**

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

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

494 From a practical point of view and based on the WSmix framework developed, a database of  
495 water source mixes (WOMix) for the users identified in Figure 4 has been created (Excel file

496 in SI). Data quality differs depending on the country but most countries, especially the  
497 developed ones, have the data needed for a global and spatially explicit WSmix.

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

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

506 The first requirement is to adapt a regionalised version of the WSmix in LCA software, with  
507 specific values per sub-river-basin where the water use occurs. This can be done using GIS,  
508 either by implementing an external GIS database connected to the LCI, or, at longer term,  
509 with the integration of GIS within LCA software, as already done by openLCA (GreenDelta,  
510 2016) and Brightway2 (Mutel, 2016)).

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

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652

## 653 **Figures**

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

655 Figure 2 Countries covered by WOmix per user database

656 Figure 3 Methodological framework of water supply mix

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

659 Figure 5 WSmix applied to France and Spain

660 Figure 6 WSmix environmental impacts associated to the production of 1m<sup>3</sup> of potable public  
661 water in France and Spain compared to current market for tap water in ecoinvent

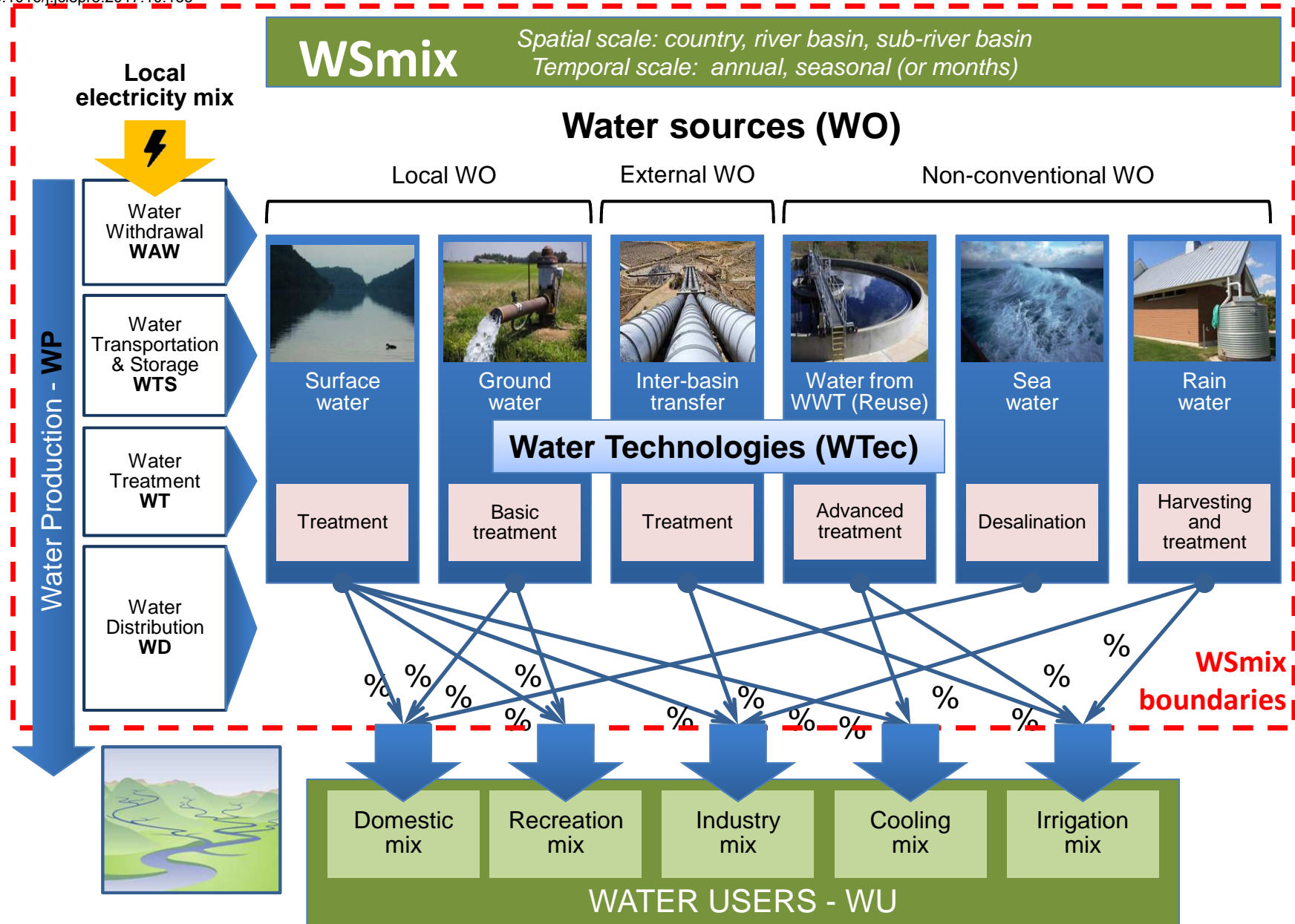
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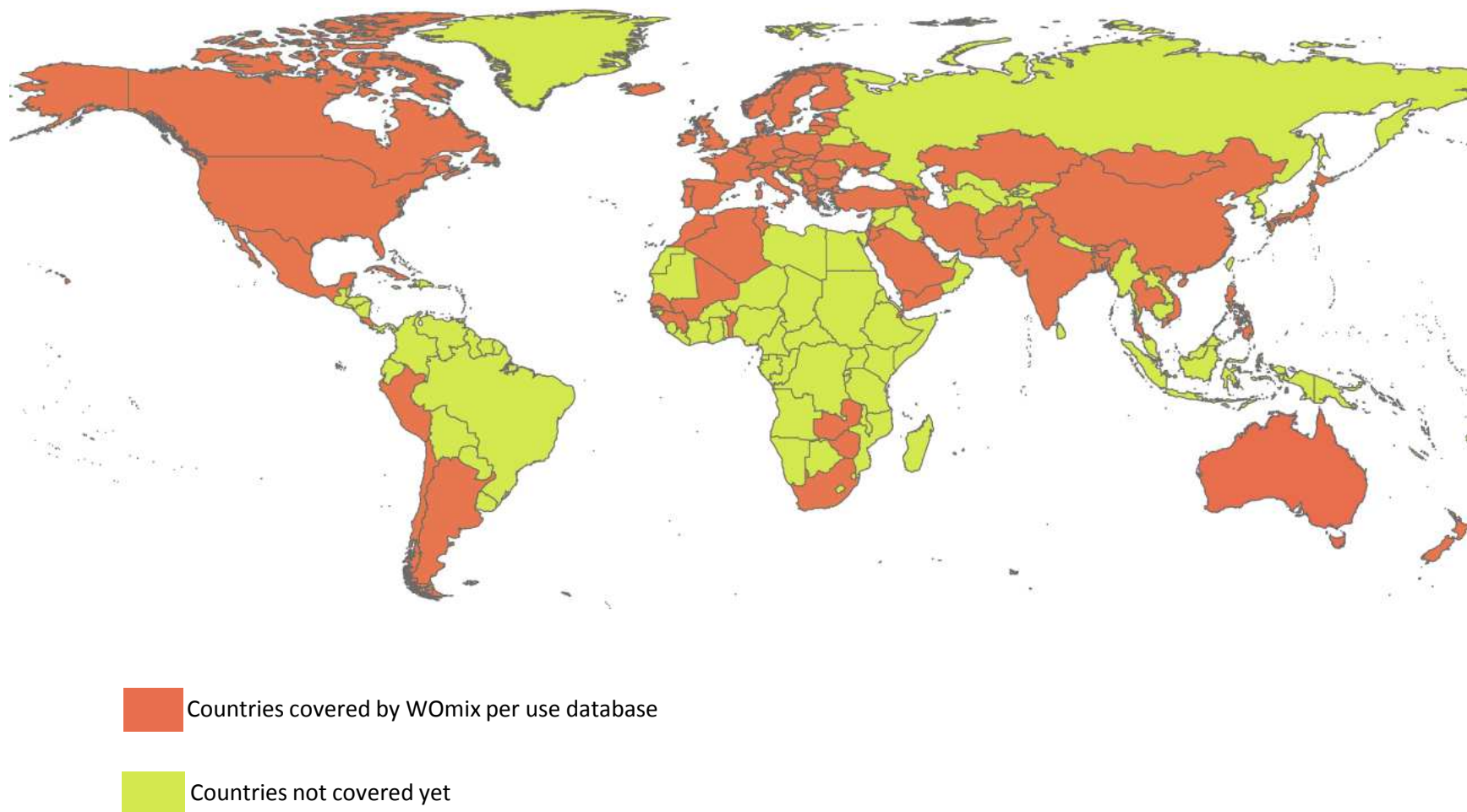
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**Figure 1** Schematic representation of the water supply mix (WSmix) concept



**Figure 2 Countries covered by WOmix per use database**

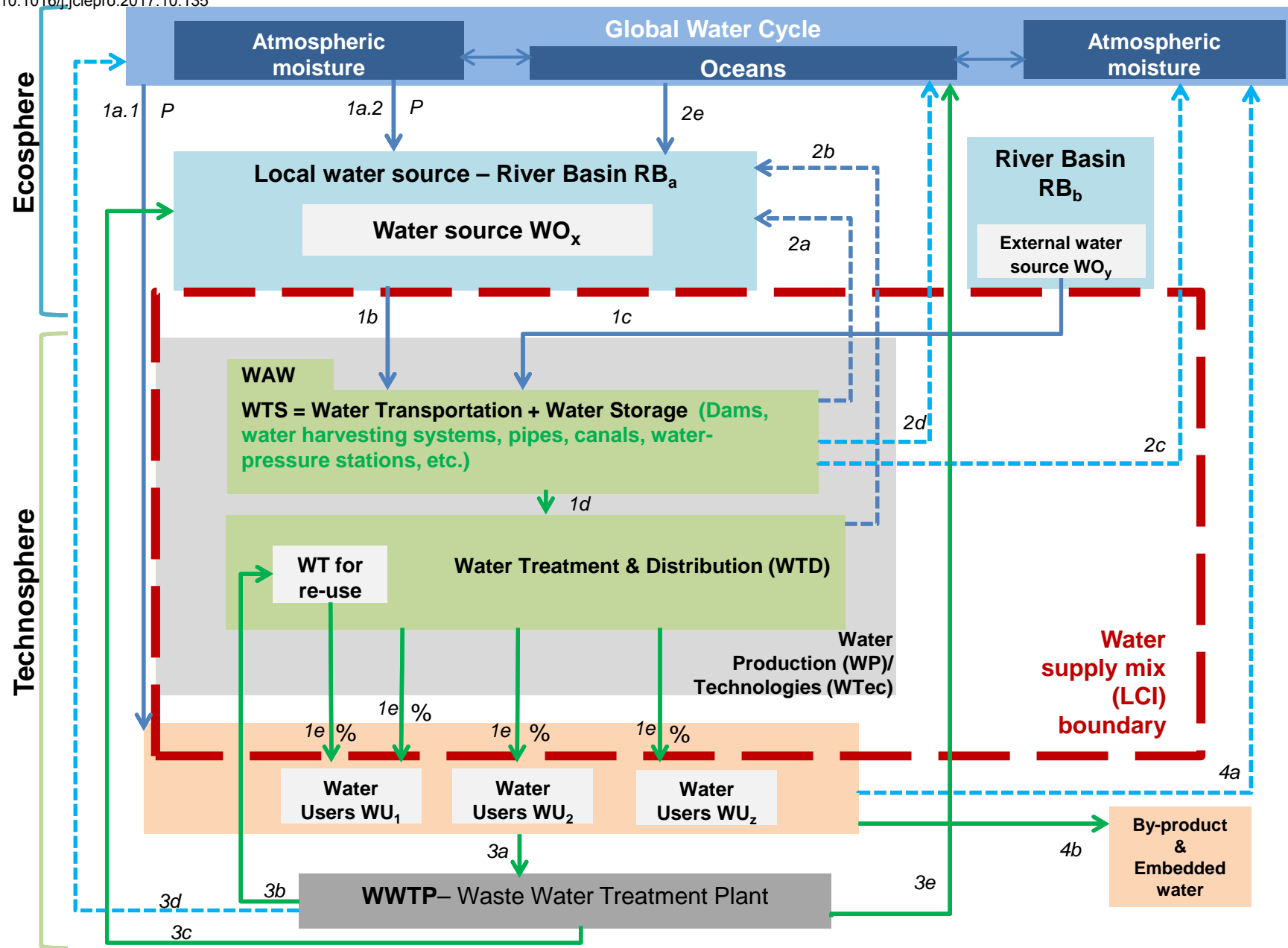






Figure 3 Methodological framework of water supply mix

## 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

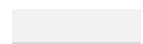

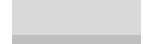




## Indices

- b= Donor RB
- x, y= Type of water source
- z= Type of water user

**Figure 3 Methodological framework of water supply mix**

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

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		Advanced treatment
	Basic treatment		Desalination
	Conventional treatment		Deionisation
	Equivalent treatments		

*\*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 <sup>1, 2, 3</sup> and \*, \*\* in Table S15 in SI

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

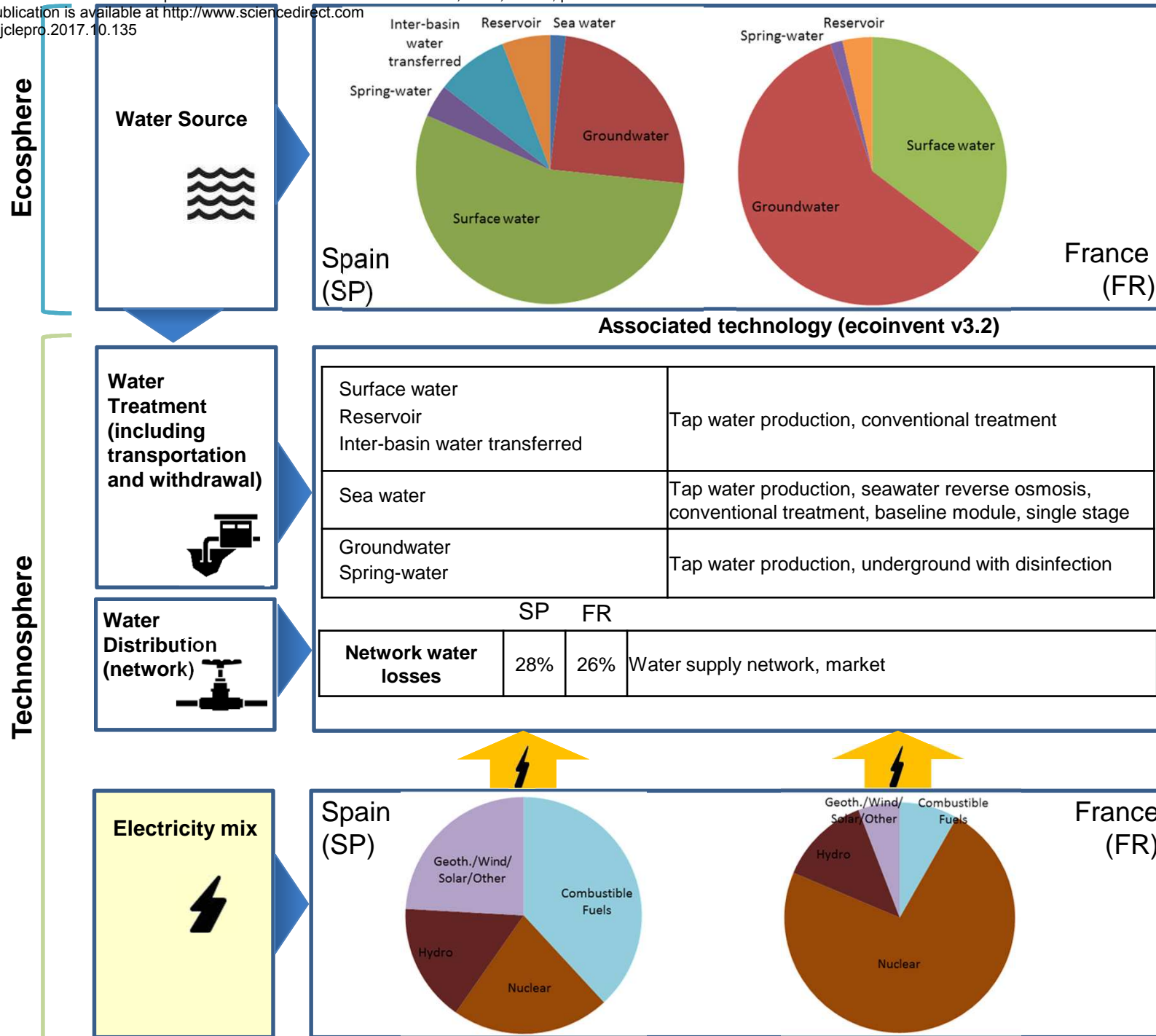
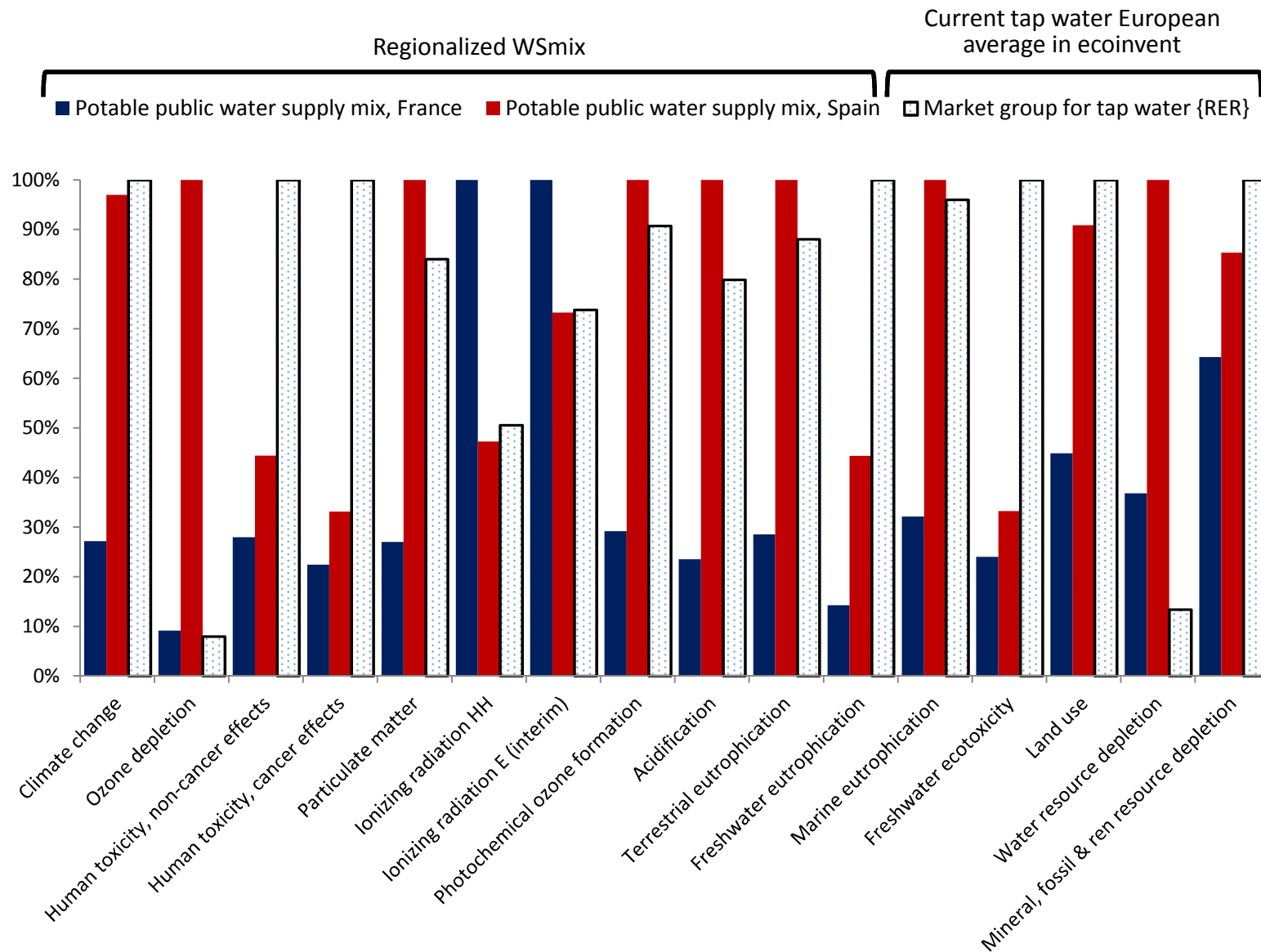


Figure 5 - WSmix applied to France and Spain



**Figure 6 - WSmix environmental impacts associated to the production of 1m<sup>3</sup> 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