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

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

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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 1m³ 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 1m³ 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 1m³ of potable public
661 water in France and Spain compared to current market for tap water in ecoinvent

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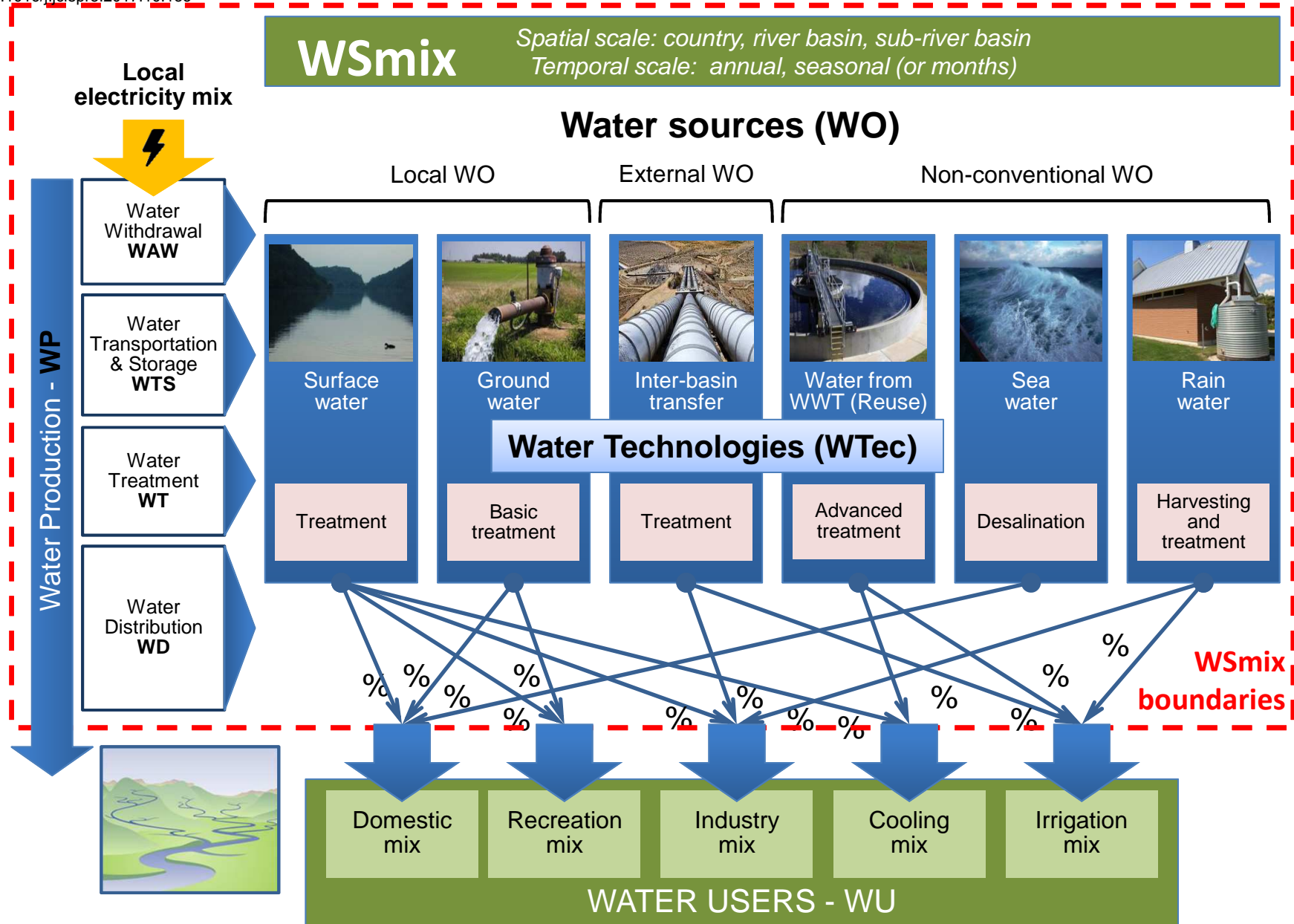


Figure 1 Schematic representation of the water supply mix (WSmix) concept

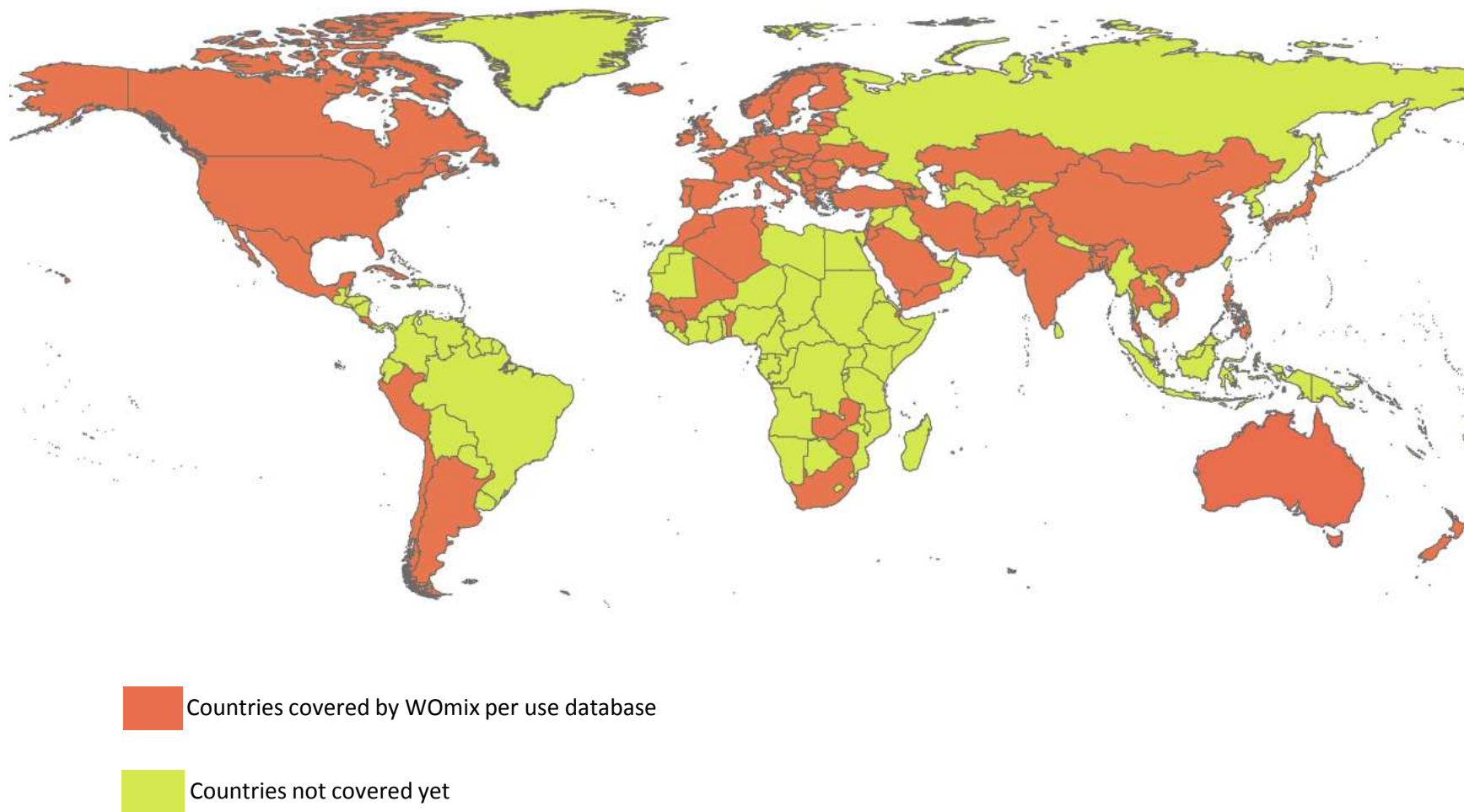


Figure 2 Countries covered by WOmix per use database

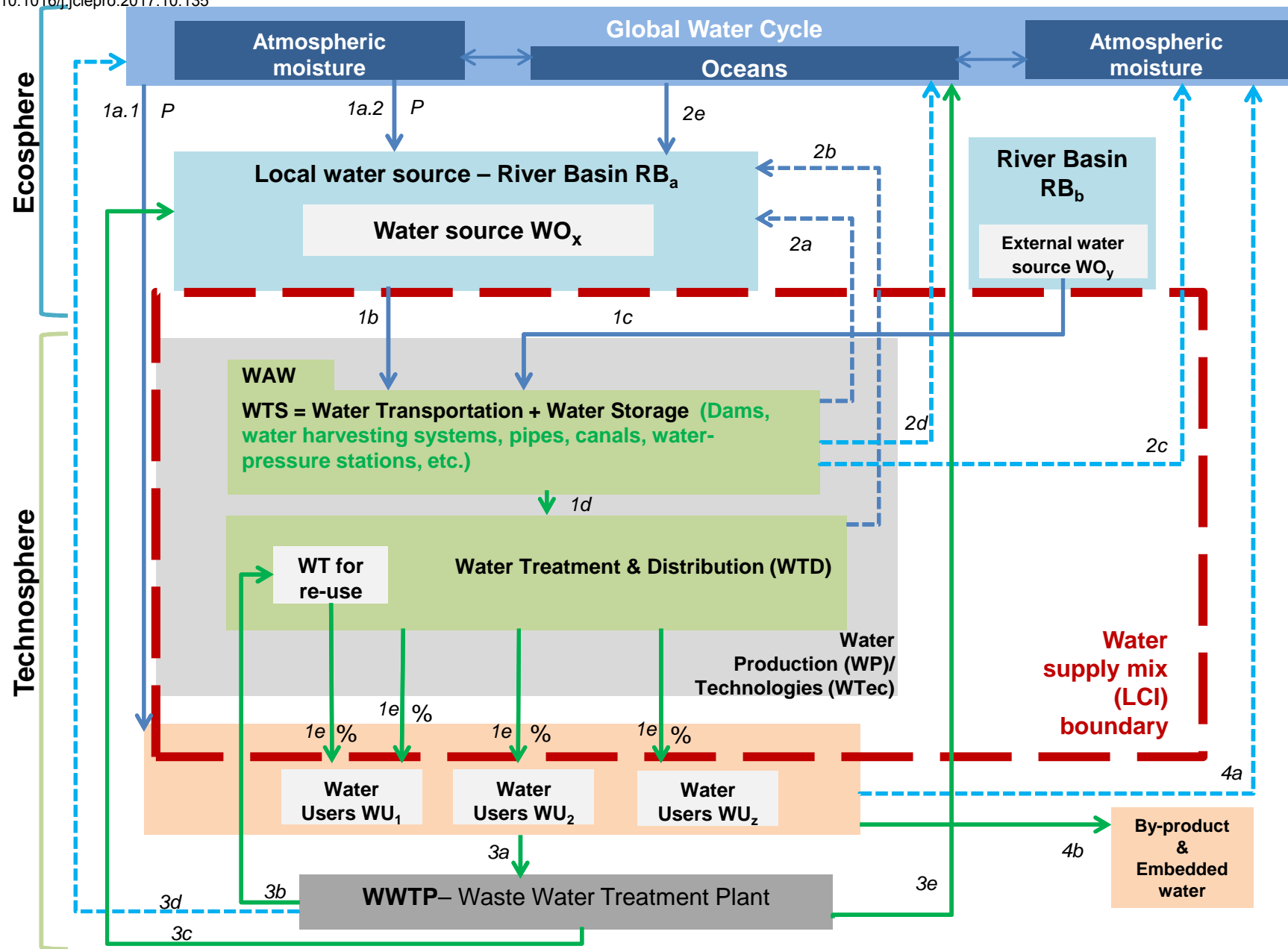






Figure 3 Methodological framework of water supply mix

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

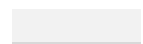

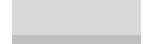




Indices

- 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 ³	Non-potable public water ³		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 ^{1,2})															
Reservoir (groundwater origin ^{1,2})	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 ^{1,2} or unknown origin)															
Directly harvested rainwater															
Reservoir (surface water origin ^{1,2} 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 ^{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

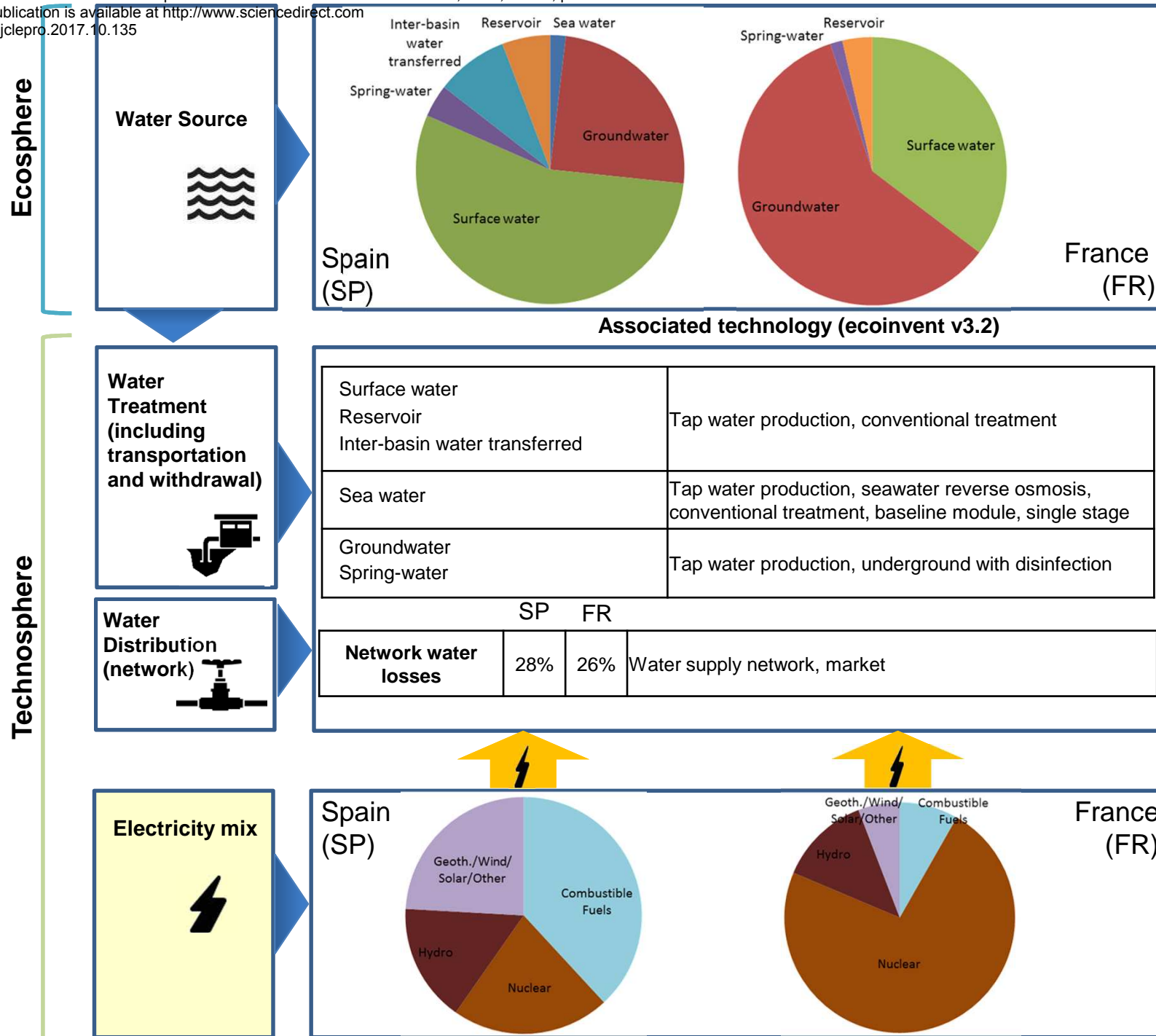


Figure 5 - WSmix applied to France and Spain

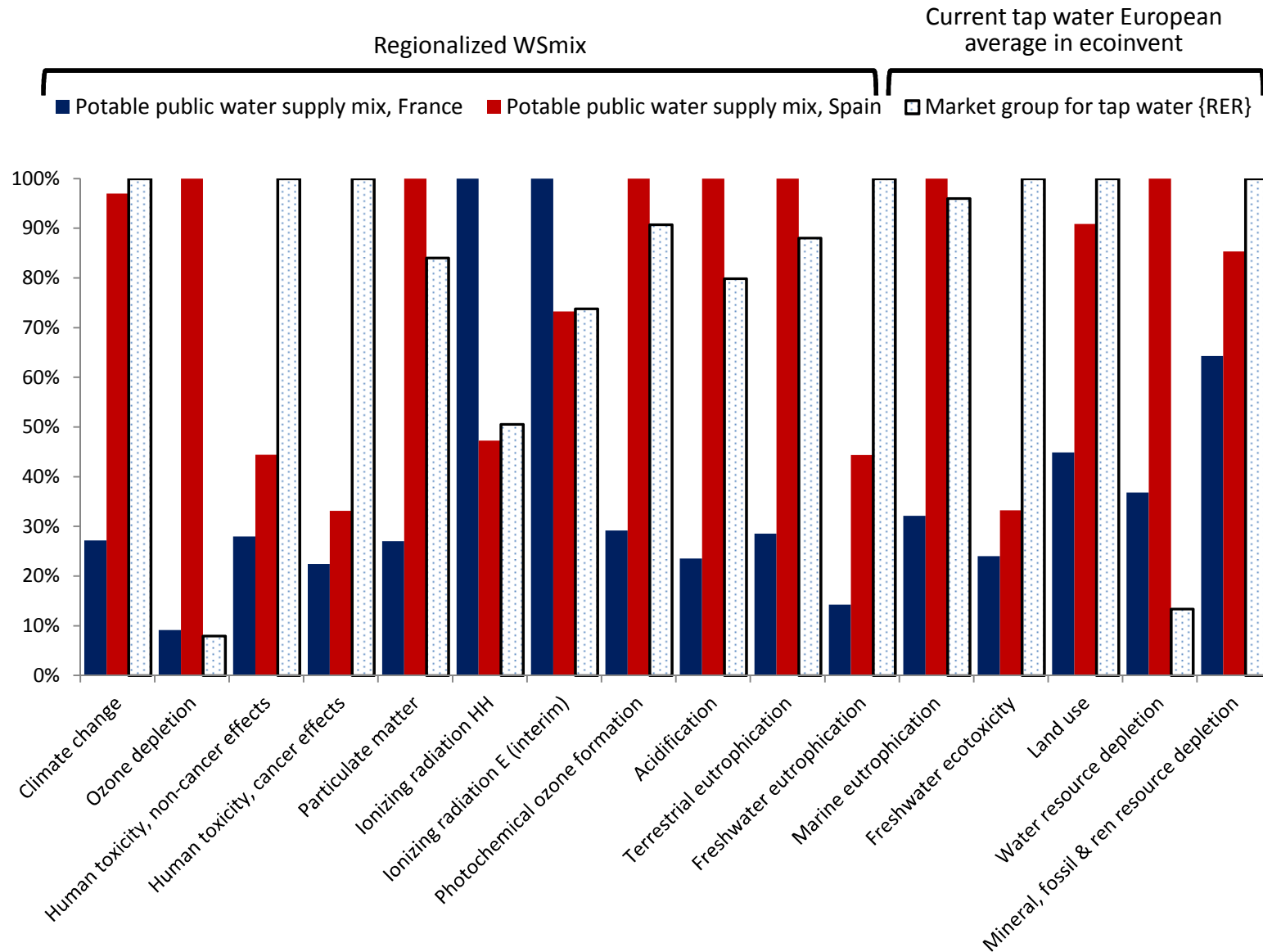


Figure 6 - WSmix environmental impacts associated to the production of 1m³ of potable public water in France and Spain compared to current market for tap water in ecoinvent

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