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3
4 **Defining freshwater as a natural resource: A framework linking water use to the**
5 **area of protection natural resources**

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30 *Purpose* While many examples have shown unsustainable use of freshwater resources, existing LCIA methods for
31 water use do not comprehensively address impacts to natural resources for future generations. This framework aims
32 to (1) define freshwater resource as an item to protect within the Area of Protection (AoP) natural resources, (2)
33 identify relevant impact pathways affecting freshwater resources, and (3) outline methodological choices for impact
34 characterization model development.

35 *Method* Considering the current scope of the AoP natural resources, the complex nature of freshwater resources and
36 its important dimensions to safeguard safe future supply, a definition of freshwater resource is proposed, including
37 water quality aspects. In order to clearly define what is to be protected, the freshwater resource is put in perspective
38 through the lens of the three main safeguard subjects defined by Dewulf et al. (2015). In addition, an extensive
39 literature review identifies a wide range of possible impact pathways to freshwater resources, establishing the link
40 between different inventory elementary flows (water consumption, emissions and land use) and their potential to
41 cause long-term freshwater depletion or degradation.

42 *Results and discussion* Freshwater as a resource has a particular status in LCA resource assessment. First, it exists
43 in the form of three types of resources: flow, fund, or stock. Then, in addition to being a resource for human economic
44 activities (e.g. hydropower), it is above all a non-substitutable support for life that can be affected by both
45 consumption (source function) and pollution (sink function). Therefore, both types of elementary flows (water
46 consumption and emissions) should be linked to a damage indicator for freshwater as a resource. Land use is also
47 identified as a potential stressor to freshwater resources by altering runoff, infiltration and erosion processes as well
48 as evapotranspiration. It is suggested to use the concept of recovery period to operationalize this framework: when
49 the recovery period lasts longer than a given period of time, impacts are considered to be irreversible and fall into
50 the concern of freshwater resources protection (i.e. affecting future generations), while short-term impacts effect the
51 AoP ecosystem quality and human health directly. It is shown that it is relevant to include this concept in the impact
52 assessment stage in order to discriminate the long-term from the short-term impacts, as some dynamic fate models
53 already do.

54 *Conclusion* This framework provides a solid basis for the consistent development of future LCIA methods for
55 freshwater resources, thereby capturing the potential long-term impacts that could warn decision makers about
56 potential safe water supply issues in the future.

57

58 **Keywords:** Life cycle impact assessment, Freshwater resources, Water use, Long-term depletion, Long-term
59 pollution

60

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85 1. Introduction

86 Effective management of water resources is required to enable long-term sustainable development outcomes. Given
87 the life-supporting function that freshwater provides in sustaining ecosystems, society's agriculture and human
88 consumption (UNEP, 2009), as well as the other functions of water in industry, its management is recognized as
89 being vitally important for both the environment and the economy. Currently, freshwater resources in many regions
90 are at risk of being overexploited. Most of the major aquifers in the world's arid and semi-arid zones are experiencing
91 rapid rates of groundwater depletion (Famiglietti, 2014), which has increased worldwide from 126 km³a⁻¹ in 1960
92 to 283 km³a⁻¹ in 2000, and is potentially large enough to contribute measurably to sea-level rise (Konikow and
93 Kendy, 2005; Wada et al., 2010). Surface water systems in many regions are also being overexploited, like the
94 Colorado River (Wildman, Jr. and Forde, 2012), with many river systems subject to river basin closure (Falkenmark
95 and Molden, 2008), and most global freshwater withdrawals occurring in watersheds already experiencing extreme
96 water stress (Ridoutt and Pfister, 2010). At the same time, water quality degradation is occurring in many river, lake
97 and groundwater systems. For instance, in Latin America, Africa and Asia, it has been estimated that organic
98 pollution has increased between 1990 and 2010 in almost two-thirds of all rivers, while severe and moderate salinity
99 pollution already affects around one-tenth of all river stretches in these three continents (UNEP, 2016). Observed
100 pollution can sometimes be persistent, as is the case of PCB contamination in the Hudson river (The Hudson River
101 Natural Resource Trustees, 2013). In addition, significant groundwater pollution has also widely occurred, although
102 this is difficult to quantify globally since many groundwater resources have no adequate water quality monitoring
103 programs (Foster et al., 2013; Lemming et al., 2010; Sampat, 2001). Given the importance of freshwater as a resource
104 and the unsustainable overexploitation and degradation occurring in many regions, approaches are required to
105 facilitate understanding of environmental impacts to freshwater resources in a decision-making context.

106 Previous work in water footprinting and virtual water assessments has described freshwater resources in terms of
107 *green* and *blue water* (terms written in italics throughout the manuscript are defined in table S1 of Electronic
108 Supplementary Material, ESM). In this terminology, soil moisture regenerated by precipitation (green water) is
109 differentiated from run-off and percolation (blue water), and serve as two separate resources managed differently
110 the water cycle (Falkenmark and Rockström, 2006). The differentiation of green and blue water resources was
111 adopted early on with guidelines on how to include them in volumetric water footprint assessments (Hoekstra et al.,
112 2011) with the main goal of addressing water management in supply chains by considering global sustainable
113 resource limits (Hoekstra and Wiedmann, 2014). This terminology is not used in the ISO standard on water

114 footprinting, which is based on life cycle assessment (LCA) (ISO 14046, 2014) where the water flows from different
115 media compartments (e.g. soil and groundwater) are separately accounted for in the inventory (Pfister et al., 2015)
116 with respect to the provision of a functional unit (ISO, 2006). Thus, the impact assessment methods can be applied
117 to the specific inventory flows, which has resulted in mainly blue water consumption impacts having been addressed
118 thus far. The two approaches for LCA and water footprinting are similar in principle and both quantify water use,
119 but they differ in the communication of their results (Boulay et al., 2013), which requires proper declaration of
120 applied methods when reporting footprint results (Pfister et al., 2017). Related issues exist with other ‘footprint’,
121 LCA and ecolabelling schemes that may lead to confusion amongst public policy, business and consumer decision
122 makers (Ridoutt et al., 2015). Therefore improved standardization, consistent terminology and improved
123 transparency overtime is required so that results can be understood and interpreted by stakeholders.

124 Over the past decade, life cycle impact assessment (LCIA) methods have been developed to include water use
125 impacts alongside other environmental impact categories, such as contributions to climate change, and the LCA
126 framework was adopted as an underlying basis for the ISO standard on water footprinting (ISO 14046, 2014).
127 Current LCIA methods typically define three Areas of Protection (AoP): human health, ecosystem quality and
128 natural resources (Verones et al., 2017). Existing LCIA methods for water use have generally been developed to
129 provide proxy midpoint indicators for water scarcity or user deprivation, or to provide endpoint indicators for the
130 AoP human-health and ecosystem quality (Kounina et al., 2013). By comparison, few methods have attempted to
131 incorporate water resource impacts within impact pathways to the AoP natural resources, only addressing selected
132 parts of the resource problem, and thus insufficiently developed to provide meaningful results (Kounina et al., 2013).
133 Furthermore, time horizons are important aspects of resource depletion, i.e. how long the water is depleted. Previous
134 methods have been vague about this subject, referring for example, to overexploitation (Milà i Canals et al., 2009;
135 Pfister et al., 2009). There is therefore a need to explicitly address the freshwater depletion time horizon.

136 To take into account the described complexity of water resource use and impact assessment, this paper aims to (1)
137 define freshwater resources as an item to protect within the AoP natural resources, (2) identify relevant impact
138 pathways affecting freshwater resources, and (3) outline methodological choices for the development of impact
139 characterization models.

140 **2. Aligning freshwater resources with the AoP natural resources**

141 There has been substantial debate over the conceptualization and purpose of the AoP natural resources and the
142 underlying safeguard subjects, especially with regard to identifying what exactly we wish to protect or maintain
143 (Dewulf et al., 2015; Sonderegger et al., 2017; van Oers and Guinée, 2016). Therefore, including freshwater
144 resources in the AoP natural resources embeds the freshwater resource in an ongoing discussion. This section
145 presents how frameworks and concepts established for the AoP natural resources can shed light on the role of
146 freshwater as a resource to protect.

147 **2.1. Current scope of the AoP natural resources**

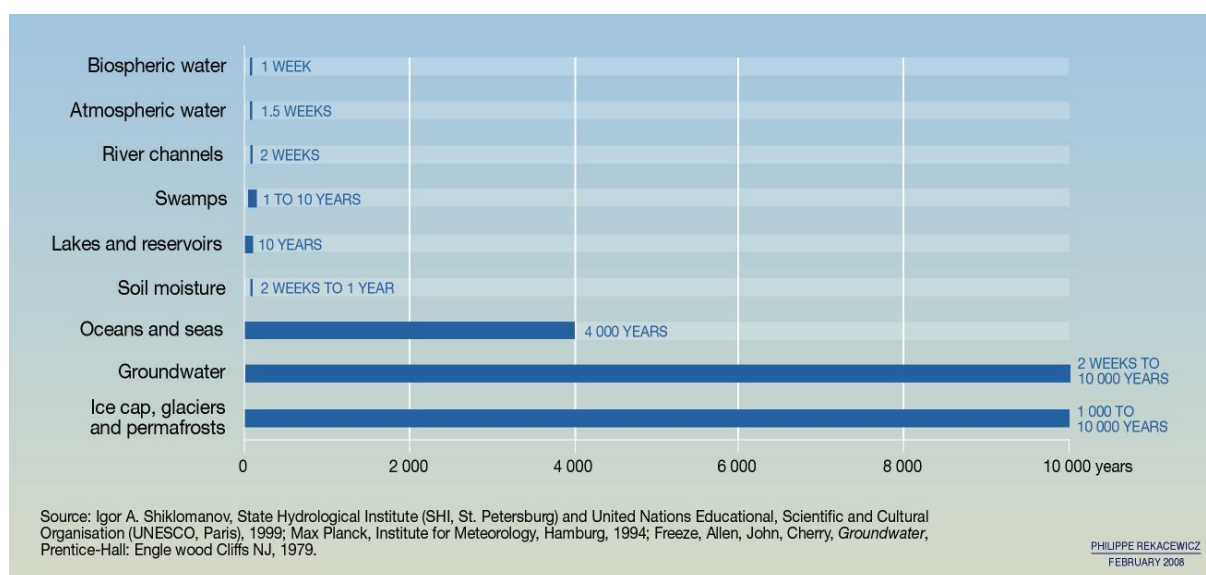
148 Initially, the AoP natural resources addressed resources such as fossil fuels and mineral ores by quantifying long-
149 term reductions in resource availability, or potential impacts of reduction on future generations. Resource
150 functionality, related to the quality state (e.g. “a chemical or physical form that renders the material unavailable for
151 any foreseeable future use by society”), has also been investigated (Stewart and Weidema, 2005). Depletion of these
152 resources has been defined as “the decrease of the unique natural configurations of elements in resources in the
153 environment” (van Oers et al., 2002). Today, the concept of natural resources in LCA encompasses a much broader
154 definition, including abiotic resources (minerals and fossil fuels as well as water and land) as well as biotic resources
155 (such as wild flora and fauna), that at some point in time were deemed useful for humans (Sonderegger et al., 2017).
156 However, this wide range of natural resources cannot be captured by most methods and their indicators, and there is
157 a lack of consistency between methods (Sonderegger et al., 2017). Dewulf et al. (2015) have elaborated upon this
158 AoP by establishing different perspectives on what should be safeguarded with respect to natural resources. They
159 identify three main safeguard subjects: Asset of Natural Resources, Provisioning Capacity, and Global Functions.
160 Thus, generally speaking, protecting natural resources within an environmental LCA context aims to ensure
161 availability and functionality of natural resources for future human use.

162 **2.2. Freshwater: a complex natural resource**

163 Freshwater has been identified in the literature as a natural resource to be protected (Dewulf et al., 2015; Sala et al.,
164 2017; Sonderegger et al., 2017). From a resource perspective, previous research has proposed to either preserve
165 *freshwater resources availability* for future generations (Bayart et al., 2010; Kounina et al., 2013; Milà i Canals et
166 al., 2009) or provide it through backup technology (Pfister et al., 2009). However, the status of freshwater and its
167 boundaries within the AoP natural resources have been undefined until now, potentially limiting the development
168 of impact assessment methods. This may be explained by the fact that freshwater resources have a number of specific
169 and complex characteristics compared to mineral and fossil resources, three of which are described as follows.

- 170 - In addition to being a resource for human economic activities (e.g., hydropower, cooling, industry ...),
171 freshwater is above all a non-substitutable support for (human and ecosystem) life. “Freshwater is a vital
172 resource in sustaining both ecosystem health and human survival” (Bayart et al., 2010). This is an important
173 point because it may lead to double-counting among the three AoPs (natural resources, human health and
174 ecosystem quality). Indeed, once a freshwater resource is affected by human intervention, the users (human and
175 ecosystems) dependent on this resource may be impacted. Bayart et al. (2010) therefore recommended that
176 “natural resource damage categories may be disregarded if the cause-effect chain is modeled up to the human
177 health and ecosystem quality categories”. Thus, it is required to determine whether and how the freshwater
178 resource may be impacted beyond those pathways affecting its users. In other words, are there any potential
179 impacts that are not covered by the AoPs human health and ecosystem quality which should be included in the
180 AoP natural resources?
- 181 - The freshwater resource has a particular status as it is both a withdrawal compartment for consumption (source
182 function) and a receiving compartment for emissions (sink function). “Lakes, for example, are sinks for inputs
183 of water, and the materials and pollutants carried in the water, thereby being sensitive barometers of human
184 activities in their surrounding watersheds” (UNEP, 2009). Both types of elementary flows (emissions and water
185 consumption) should be linked to a damage indicator for freshwater as a resource. However, the way the AoP
186 natural resources has been approached so far reflects the fact that only extraction and consumption (or
187 dissipation) can impact natural resources (Sonderegger et al., 2017). Today, water degradation due to emissions
188 is only considered in impacts on ecosystem quality and human health (e.g. toxicity or eutrophication), and more
189 generally there is no existing approach linking polluting emission flows with potential damage to natural
190 resources.
- 191 - Natural resources can be classified according to their renewability rate. Three categories are considered in
192 function of their renewability rate: (1) *stock resources* are finite resources, not regenerated within a human
193 lifetime (2) *fund resources* are regenerated within a human lifetime and (3) *flow resources* are continuously
194 (re)generated (Dewulf et al., 2015; Sonderegger et al., 2017). The particularity of freshwater resources is that
195 they can satisfy each of these categories (Koehler, 2008; Milà i Canals et al., 2009), with a renewability rate
196 ranging from a few days to several thousand years (**Fig. 1**), and even a flow resource such as a river can undergo
197 irreversible impacts (Pfister et al., 2009). Biospheric, atmospheric and solid freshwater (e.g., ice caps, glaciers,
198 and permafrost) may not be considered a “usable” resource because they generally cannot be harnessed (see

199 **Fig. S1** in ESM), and are thus excluded from the scope of freshwater resources as part of the AoP natural
 200 resources.

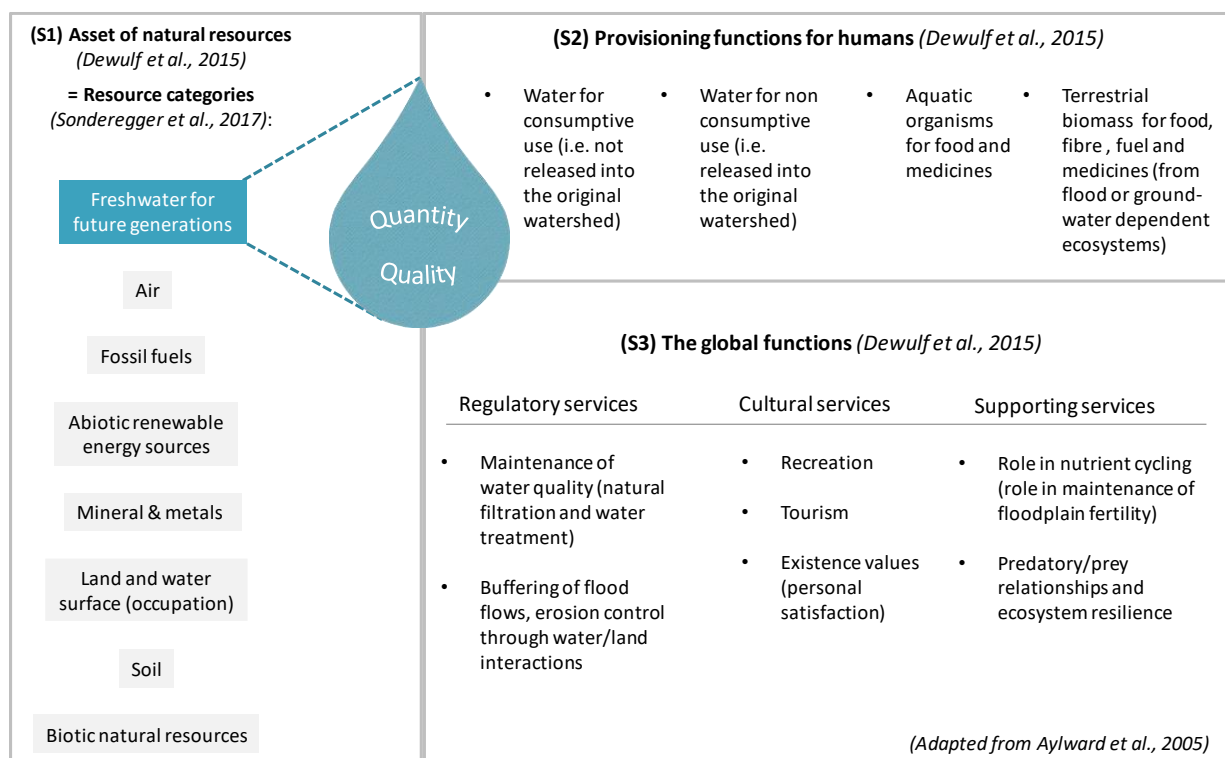


201
 202 **Fig. 1:** Estimated average residence time of water resources - from Virtual Water Graphics report of UNEP (2008)

203 **2.3. Safeguard subjects and dimensions of freshwater resources**

204 In order to define what is to be protected, freshwater resources are considered through the lens of the three safeguard
 205 subjects defined by Dewulf et al. (2015) (**Fig. 2**). The first safeguard subject (S1) is the asset of natural resources as
 206 such, regardless of how they might be used and/or the purpose they serve. This refers to the different *specific assets*
 207 (also called *resource categories* in Sonderegger et al. (2017)) constituting the natural resources. Freshwater is clearly
 208 one of these specific assets, however, it is essential to recognize and integrate the temporal nature of this concept,
 209 i.e. freshwater resources for future generations. The second safeguard subject refers to their provisioning functions
 210 for humans (S2), and the third one concerns their global function relative to more global interactions and regulation
 211 between the natural and human-industrial environment (S3). In other words, S2 focuses on the functions directly
 212 provided to humans such as domestic, industrial, agricultural, hydroelectric and transport functions, whereas S3
 213 addresses regulatory, cultural and supporting services, as exhaustively described in Aylward et al (2005). **Fig. 2**
 214 illustrates these safeguard subjects and highlights the importance of the quality and quantity of water. Indeed, to
 215 maintain most of these provisioning and global functions, two dimensions of freshwater resources must be preserved:
 216 the quantity (physical availability) and the quality These two dimensions are defined as per FAO/HLPE (2015): (1)
 217 the physical availability (quantity) “through rainfall, rivers and aquifers in a particular region” and (2) the quality of
 218 water: “in terms of Food Security and Nutrition (FSN) has different implications according to its uses; water quality

219 needs for irrigation vary by crop, are high for food processing, food preparation and drinking, and are important for
 220 health and hygiene.” (FAO/HLPE, 2015). We consider that stability of water, i.e. limiting the quantity and quality
 221 fluctuations through time, is implicitly covered by how impacts on water quantity and quality are (or will be)
 222 characterized in LCIA. Freshwater quantity and quality are properties of the physical resource and so can be
 223 interpreted as assets to protect within the safeguard subject S1,
 224



225
 226 **Fig. 2:** The freshwater resource seen through the lens of the three safeguard subjects (S1, S2, S3) defined by Dewulf et al. (2015).

227 As soon as one of the two dimensions: the quantity or quality is *irreversibly impacted*, freshwater resources and their
 228 provisioning or global functions for future generations are threatened. Irreversible impacts means naturally
 229 irreversible during a very long period at the scale of the human life span (thus affecting future generations), but the
 230 precise definition of irreversibility is critical since it depends on the considered time horizon (see Section 3). We
 231 therefore propose the following definition of the freshwater resource as an asset to protect within the AoP natural
 232 resources:

233 *Freshwater reservoir (a stock, fund or flow) that is potentially useful to provisioning functions for human users*
 234 *(including dependencies on other freshwater ecosystem services), in the future.*

235 **3. Defining ‘Impact’ on freshwater as part of the AoP Natural resources**

236 **3.1. Existing methods**

237 So far, freshwater as part of the AoP natural resources has always been approached from a quantitative perspective:
238 the quantity of freshwater remaining for potential future users.

239 Milà i Canals et al. (2009) proposed a midpoint impact category named freshwater depletion based on an adaptation
240 of the abiotic depletion potential approach (ADP; (Guinée and Heijungs, 1995)). This indicator acknowledged that
241 the consumption of an overexploited groundwater resource (stock or fund resource) could damage the natural
242 (freshwater) resources AoP. Pfister et al. (2009) proposed an endpoint indicator based on the withdrawal-to-
243 availability (WTA) ratio. This indicator assesses the contribution of freshwater overexploitation to damage on
244 natural resources. When the WTA ratio is above one (the modeled withdrawal is larger than the modeled
245 availability), then the share of water use above renewability is the depleted share. This model does not distinguish
246 flow or fund, surface or groundwater resources. Thus, even the consumption of a flow freshwater resource can
247 impact the AoP natural resources, as is the case of rivers feeding the Aral Sea. Then, the damage to freshwater
248 resource is expressed in “surplus energy”, using the desalinisation backup-technology approach (Pfister et al., 2009).

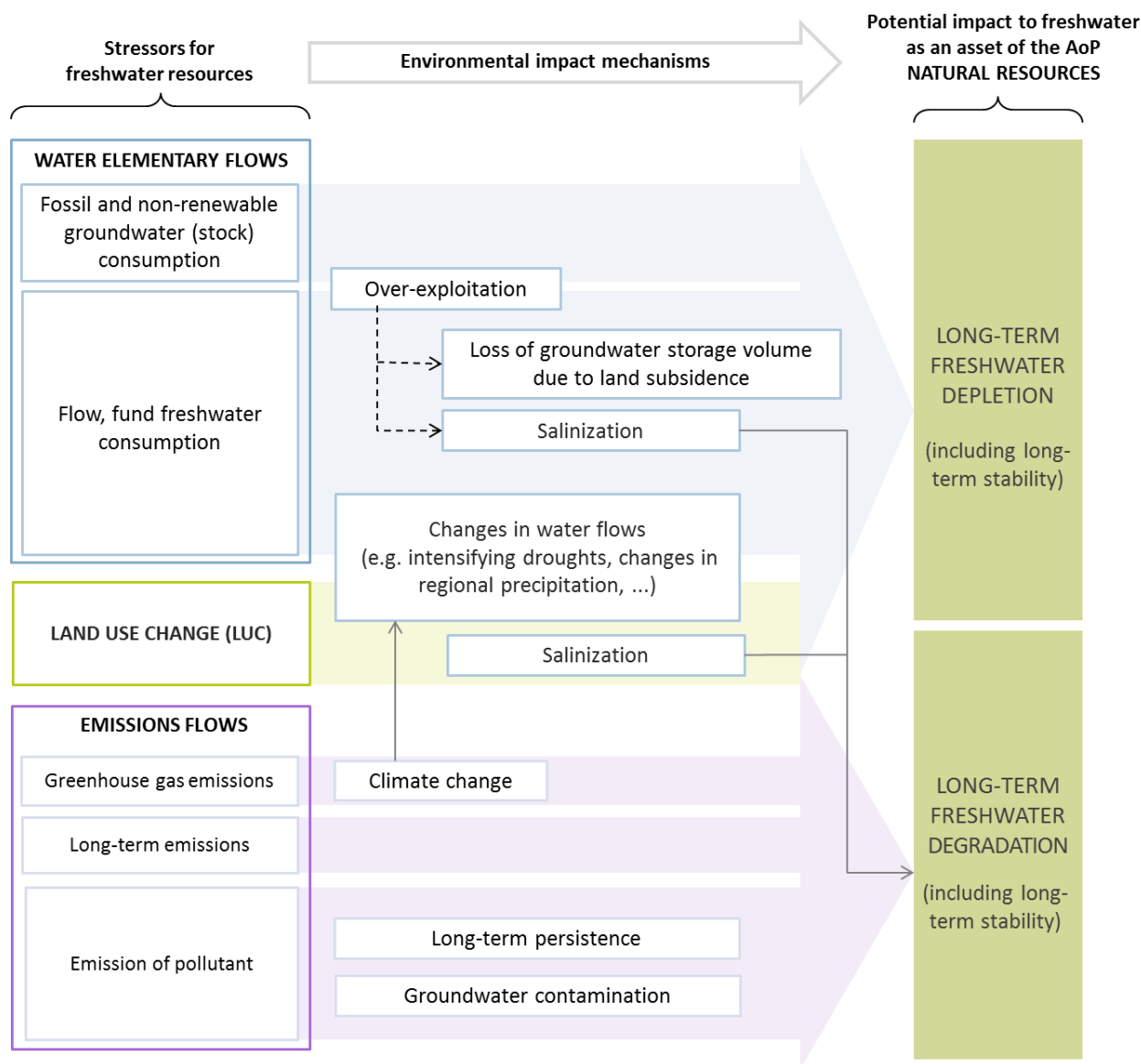
249 The method of Milà i Canals et al. (2009) requires a specific inventory for freshwater depletion: the water elementary
250 flows have to be categorized distinguishing water stocks (groundwater/fossil water) and over-abstracted water funds
251 (groundwater/aquifers) from the other water flows. Whereas in the model of Pfister et al. (2009) the water elementary
252 flows only have to be characterized by their geographic location. The information about the potential to be depleted
253 is included in the impact assessment stage.

254 Since existing indicators are not addressing all threats to freshwater resources, next section identifies the wider range
255 of possible threats.

256 **3.2. Which stressors for freshwater resources?**

257 This section describes the different causality chains and related environmental interventions (water consumption
258 and emissions), identified as stressors, that can irreversibly impact the two dimensions of the freshwater resources
259 (quantity and quality). We thus distinguish long-term freshwater depletion from long-term freshwater degradation
260 impacts. An overview of these stressors is presented in **Fig. 3**. The description of this wide range of possible threats

261 to freshwater resources highlights the fact that stock, as much as flow and fund freshwater resources are subject to
 262 irreversible changes.



263

264 **Fig. 3:** Identification of the stressors involved in the freshwater resources cause-effect chains

265 *3.2.1. Long-term freshwater depletion*

266 Like other resources (e.g. metals), freshwater cannot strictly speaking be depleted, but can be locally and temporarily
 267 depleted, or dissipated (to refer to the term employed for metals). However, it is common to use the term “resource
 268 depletion” (Stewart and Weidema, 2005).

269 > **Fossil and non-renewable groundwater (stock) consumption**

270 Although freshwater is largely a renewable resource, there are also isolated and local non-renewable groundwater
271 stocks, whose consumption may directly lead to their depletion. This *non-renewable groundwater* is often called
272 *fossil groundwater* due to its slow-recharge rates, although different definitions exist as reported by UNESCO
273 (2006). “Non-renewable groundwater resource is a groundwater resource available for extraction, of necessity over
274 a finite period, from the reserves of an aquifer which has a very low current rate of average annual renewal but a
275 large storage capacity. Fossil groundwater is water that infiltrated usually millennia ago and often under climatic
276 conditions different to current ones, and that has been stored underground since that time”. Countries that are
277 currently considered as the most dependent on non-renewable groundwater resources are Saudi Arabia, Libya and
278 Algeria; significant use also occurs in Australia, Iran, Egypt, Tunisia, Botswana, Mauritania and Peru (Foster et al.,
279 2013; Margat and van der Gun, 2013). Such consumption raises questions of intergenerational equity since each
280 cubic meter consumed from these resources results in irreversible quantitative changes at the local level, e.g. fossil
281 groundwater pumping for irrigation in the central and southern US High Plains (Scanlon et al., 2012).

282 > **Direct and indirect effects of freshwater resources over-exploitation**

283 A situation of *over-exploitation* occurs when the groundwater abstraction exceeds the natural groundwater recharge
284 over extensive areas and some decades (Wada et al., 2010). In many cases, current groundwater abstraction rates are
285 not physically sustainable in the long-term (Foster et al., 2013). Wada et al. (2010) provide a global overview of
286 fund groundwater depletion and point out many of the well-known hot spots of groundwater depletion (e.g. North-
287 Eastern Pakistan) that pose a threat to the security of water supply for future generations. Since flows and funds are
288 connected (Nuñez et al., 2016), over-exploitation of aquifers may deplete surface water flows and vice versa, as is
289 the case of the Aral Sea (Micklin, 2007). For instance, the modern Molasse basin in Europe and the northern part of
290 the High Plain Ogallala groundwater storage reserves have been subjected to continuous depletion, jeopardizing the
291 maintenance of spring and river base flows as well as lakes, lagoons and wetlands (Custodio, 2002; Gleeson et al.,
292 2015, 2010).

293 In addition to depleting the local freshwater reservoir, overexploitation may also have other indirect consequences
294 (depending on local conditions) on freshwater resources in the broader sense. Excessive groundwater pumping and
295 aquifer depletion can cause the aquifer system to compact, resulting in permanent loss of groundwater storage
296 volume in the aquifer system. Extensive subsidence of aquifers due to groundwater extraction around the world has
297 been well documented (Galloway and Burbey, 2011). This issue has been widely recognized (Galloway and Burbey,
298 2011), but is currently neglected in LCA and should find its place in the framework of freshwater resources impacts.

299 Furthermore, over-exploiting groundwater resources in coastal areas may potentially lead to marine intrusion and
300 salinization effects (Amores et al., 2013). The latter is discussed in Section 3.2.2, dedicated to long-term freshwater
301 pollution.

302 > **Climate change impacts on freshwater resources (long-term stability)**

303 Climate change is a concern for the long-term stability of freshwater resources. Direct impacts on freshwater
304 resources are related to natural recharge of groundwater resources by precipitation or through interaction with
305 surface freshwater bodies. Some authors observed that the direct effect of climate change on water scarcity has been
306 shown to be limited compared to the effect of the expected increase in human water consumption by 2050 (Pfister
307 et al., 2011). However, increased extreme weather conditions and irreversible effects on freshwater resources' long-
308 term stability are important. Indeed, Jiménez Cisneros et al. (2014) stated that the relationship between climate
309 change and freshwater resources is of relevant concern and interest, as climate change is projected to alter the
310 frequency and magnitude of extreme climate events like floods and droughts, affecting the surface- and groundwater
311 dynamics. In the context of our study, climate change and related freshwater issues can be seen as irreversible
312 processes since even if greenhouse gas concentrations were to be stabilized, warming and sea-level rise would
313 continue for centuries. In addition to the effects of anthropogenic global warming, Wada et al. (2013) have
314 demonstrated that human water consumption acts as an additional stress on freshwater resources, intensifying the
315 magnitude and frequency of effective hydrological drought for the coming decades. For instance, they established
316 that human water consumption alone increased global drought frequency by a factor of 27 (± 6) % and intensified
317 the magnitude of hydrological droughts up to a factor of 5 (10-500 %). Such intensified droughts cause persistent
318 low flow conditions, which can lead to long-term impacts on freshwater resources.

319 > **Land use change effects on freshwater resources**

320 Land use change refers to the transformation of one land use into another in a transition that carries significant
321 changes to land properties (e.g., soil, above and belowground carbon content, etc.) (Koellner et al., 2013). Changes
322 in land use affect the water cycle, which is reflected by the partitioning of precipitation and solar radiation at the soil
323 and vegetation surfaces, and can affect long-term freshwater availability. The descriptions of these effects typically
324 follow a water yield or atmospheric water supply approach to the water cycle (Ellison et al., 2012). Land use change
325 can affect surface permeability and soil conditions that favor runoff over infiltration and percolation of precipitation
326 under new land use conditions. For instance, cropland and pasture have shallower root systems, smaller leaf area
327 index and greater albedo than forests, thereby reducing evapotranspiration and favoring percolation (local freshwater

328 availability) and runoff (downstream water availability). These effects have typically been observed in paired-
329 catchment studies (Ellison et al., 2012) and may be observed in regions of recent and intense land use change activity.
330 For example, soybean-dominated watersheds in the Amazon region showed greater streamflow than forested
331 watersheds, mainly due to stream dependency on baseflow and high soil infiltration rates (Hayhoe et al., 2011).

332 Land use change can modify evapotranspiration flows with potential effects on atmospheric water vapor supply.
333 This supply can be reduced (e.g. through deforestation) or augmented (e.g. through irrigation) (Rost et al., 2008)
334 with consequences on the atmospheric water balance and regeneration of precipitation through regional evaporation
335 recycling (Quinteiro et al., 2015; van der Ent et al., 2010). For instance, deforestation of tropical forest into
336 agricultural land reduces evapotranspiration with potential effects on distant precipitation (Keys et al., 2016).
337 Changes in regional precipitation (either increases or decreases) can, in turn, affect long-term water availability in
338 rivers and streams, as well as groundwater recharge.

339 Effects of land use change on the water cycle are thought to be able to return to original conditions (e.g. potential
340 natural vegetation as described by Koellner et al., 2013), but regeneration times can extend over several decades
341 based on the type of ecosystem (Curran et al., 2014). The consideration of regenerative processes can therefore
342 complicate the relationship between land use change and freshwater availability for future generations.

343 3.2.2. *Long-term freshwater degradation*

344 The quality of freshwater resources for future generations could be threatened by irreversible pollution, due to the
345 nature of pollutants (persistent), their emission chronology (long-term) and the local characteristics of the receiving
346 media. Even without any quantitative changes, the degree of freshwater usability for future users may diminish. The
347 pollution sources considered should only be anthropogenic; naturally occurring pollution, such as the arsenic lakes
348 in Chile, is considered part of a natural equilibrium and hence disregarded in LCIA, except for models using
349 background concentrations.

350 > **Long-term emissions**

351 Long-term emissions refer to processes that release pollutants into the environment over several hundreds or even
352 thousands of years, such as landfills and mine tailings. Freshwater resources can potentially be impacted by these
353 long-term pollutions. In fact, acid drainage of abandoned mines can be a source of both surface and groundwater
354 pollution for decades, as illustrated by the gold mining activities in South Africa (Tutu et al., 2008; Winde and
355 Sandham, 2004) or the Rio Tinto system in Spain, where mining activities (mainly copper, silver, gold, pyrite) that

356 began at the Copper and Bronze Age and ended in 1998, generated 5,000 years of pollution (Davis et al., 2000). P.
357 Younger (1997) studied the longevity of minewater pollution and showed that the poorest water quality discharged
358 from abandoned mines can be expected to occur within the first 40 years, after which an on-going generation of
359 acidity will persist for several hundred years until mineral sources are depleted. The case of uranium contamination
360 is also a classic example of water/sediment long-term pollution due to mining (Winde and Sandham, 2004). This
361 issue requires a dynamic inventory. The case of long-term metal emissions from landfills, and how to handle them,
362 are well-known topics of discussion in LCA (Bakas et al., 2015; Hellweg and Frischknecht, 2004; Hirschier et al.,
363 2010).

364 > **Persistence**

365 Persistence refers to pollution from an emission that occurs now, but which remains in the environment for a very
366 long period of time. “In many parts of the world, we are only just beginning to discover contamination caused by
367 practices of 30 or 40 years ago” (Sampat, 2001). This issue is subdivided into three issues depending on the nature
368 of the pollutant and the receiving media: (1) heavy metal contamination, (2) persistent organic pollutant
369 contamination, and (3) groundwater contamination.

370 - *Heavy metal contamination (the expression “heavy metals” in LCA can include metals such as lead, metalloids*
371 *such as arsenic or nonmetals such as selenium):* These trace elements are naturally present in surface or
372 groundwater, with concentrations dependent on local geological and climatic conditions. However, because of
373 their use in various human activities (industry, building, agriculture), they are also discharged into freshwater
374 or soil from point or diffuse sources. Their toxic properties impact ecosystems and humans, and their presence
375 degrades freshwater quality. The bio-physicochemical conditions of a given freshwater compartment can induce
376 changes in metallic forms (e.g. oxidation levels or complexation), favoring precipitation and thus
377 immobilization, or solubilization and thus mobilization of these elements. However, metals are never degraded
378 but remain in the environment in different dissolved or particulate forms.

379 - *Persistent organic pollutants (POPs) contamination:* Persistent organic pollutants are not naturally occurring
380 in the environment. These molecules have been synthesized by humans and are characterized by a long lifetime
381 in the environment. They have been widely used by various human activities such as industry (due to their
382 chemical stability) or in agriculture (as pesticides). POPs are mainly hydrophobic compounds, and although
383 their concentrations in water remains very low, due to low solubility constants, they may be present on
384 particulate matter or sediments, and may bio-accumulate within the aquatic food web. They slowly degrade via

385 physical, chemical or biological processes. The massive use of certain organochlorine pesticides, such as
386 Chlordecone in the French Antilles, is a good example of persistent freshwater pollution. In the French Antilles,
387 this insecticide was banned in 1993, and recent studies reveal its frequent presence in soils, rivers, spring water,
388 but also in drinking water and food crop produce (Cabidoche et al., 2009). It is assumed that only lixiviation is
389 able to slowly reduce soil contamination, and thus increase aquifer contamination and ultimately affect springs
390 and rivers over hundreds of years (Cabidoche and Lesueur Jannoyer, 2011). Another well-known example of a
391 highly persistent chemical is polychlorinated biphenyl (PCB) with many sites in the world revealing high levels
392 of environmental PCB contamination, even 40 years after having been banned. The case of the Hudson River
393 PCB contamination (The Hudson River Natural Resource Trustees, 2013) attests that freshwater resources,
394 including sediments and the aquatic food web, can be polluted for decades. Most of these persistent and toxic
395 substances were introduced in the middle of the twentieth century.

396 - *Groundwater contamination*: Low groundwater renewability rates (stock or fund freshwater resource) and low
397 pollutant degradation in underground conditions can make pollution very persistent, which implies
398 contamination over several generations. While many problems of groundwater quality degradation have been
399 identified (as for example by Demlie and Wohnlich, 2006 or Sampat, 2001), it is likely that many other
400 contaminated aquifers are not detected due to inadequate groundwater quality monitoring (Foster et al., 2013).
401 The evolution of pollutants in groundwater systems may differ substantially from that in surface water systems
402 due to the influence of geochemical processes, aerobic/anaerobic conditions and differing temperature or
403 pressure profiles. Modelling these pollution processes would require the development of chemical fate models
404 specific to the groundwater compartment.

405 > **Freshwater salinization**

406 Many human interventions may trigger long-term freshwater salinization. It can be associated with a land use change
407 causing waterlogging, with irrigation or brine disposal releasing salts through leaching or runoff, or overuse of a
408 water body causing saline intrusion (Payen et al., 2016). Surface and groundwater salinization potentially affects all
409 three AoP, but only the AoP human health and ecosystem have been addressed by LCIA models so far (Amores et
410 al., 2013; Zhou et al., 2013), thus neglecting the AoP natural resources. Payen et al. (2016) suggest considering that
411 permanent freshwater quality degradation represents a damage to resources for future generations, using
412 permanently saline aquifers as an example.

413 > **Climate change impacts on freshwater quality (long-term stability)**

414 In addition to having potential, irreversible impacts on the physical freshwater availability (see Section 3.2.1.),
415 climate change may also irreversibly affect water quality. The IPCC Report (2008) establishes that the increase in
416 temperatures and changes in extreme events (e.g., floods and drought) will exacerbate many forms of water
417 pollution, for example dissolved organic carbon, pathogens, as well as thermal pollution. The report also states that
418 freshwater resources in coastal areas are threatened by sea-level rise resulting in the salinisation of coastal aquifers
419 and estuaries (IPCC, 2008).

420 **3.3. Trade-offs with other AoPs and freshwater depollution**

421 *3.3.1. Trade-offs with other AoPs*

422 Even though this study focuses on impacts of water use from a resource perspective, several interlinkages and trade-
423 offs to other AoPs may exist. For instance, fossil groundwater withdrawal is considered a long-term depletion of
424 freshwater resources (**Fig. 3**). However, if a large share of this withdrawal is neither evaporated nor integrated into
425 a product, but discharged into surface waters for example, this water is made available for aquatic ecosystems and
426 other human needs. Thus, negative, long-term consequences from a resource perspective can cause short-term
427 benefits in other AoPs (Berger and Finkbeiner, 2013). This complexity highlights the need for a comprehensive
428 assessment addressing all relevant impact pathways and AoPs in a complete water footprint profile as recommended
429 by ISO 14046 (2014).

430 *3.3.2. Freshwater depollution*

431 As shown in **Fig. 3**, impacts of freshwater use can result from long-term freshwater depletion or pollution. However,
432 some processes may withdraw polluted water, purify it to a level required for the operation, and discharge water that
433 is of higher quality than the water withdrawn initially. The question of if and how this freshwater depollution should
434 be credited depends on several aspects. In most of the cases, depolluted water will be discharged into a flow
435 freshwater compartment (e.g. a river). In such cases, the depollution is not considered beneficial from a resource
436 perspective but can cause benefits for human users and ecosystems, if the water is cleaner than the receiving
437 compartment. Thus, the benefit can be considered by means of impact assessment methods for water use considering
438 quality aspects (e.g. Boulay et al., 2011), or as negative emissions in traditional, emission-oriented impact categories
439 (e.g. human- or eco-toxicity.) However, this approach raises two issues of consistency. First, this is equivalent to
440 crediting the whole potential impact of a removed pollutant molecule, without considering that this molecule may
441 have already caused impacts before its removal. This leads to an overestimation of the benefit from the removal. For

442 a correct implementation, the potential impact to credit must be the integration of its (avoided) impacts from the
443 moment when the pollutant is removed to its final degradation or sequestration (i.e. it is no longer bioavailable)
444 instead of integrating over its entire environmental lifetime from its emission onwards. The latter is how a pollutant
445 characterization factor is (usually) calculated. For persistent pollutants, this overestimation may be substantial due
446 to their prolonged presence and activity in the environment. Secondly, we raise the question of hysteresis of impact
447 assessment models. The cause-effect chains of LCIA models are not necessarily reversible, or at least have neither
448 been developed nor tested for an application assuming an inverse logic of the pathway, even though that is how they
449 are used when applying credits (calculated as avoided impacts).

450 However, if the depolluted water is discharged into a fund or stock freshwater compartment, the depollution can
451 have positive effects from a resource perspective, if the water is cleaner than the receiving compartment. In such a
452 case, credits determined by the respective characterization models seem justified.

453 **4. Operationalization and consequences on methodological choices**

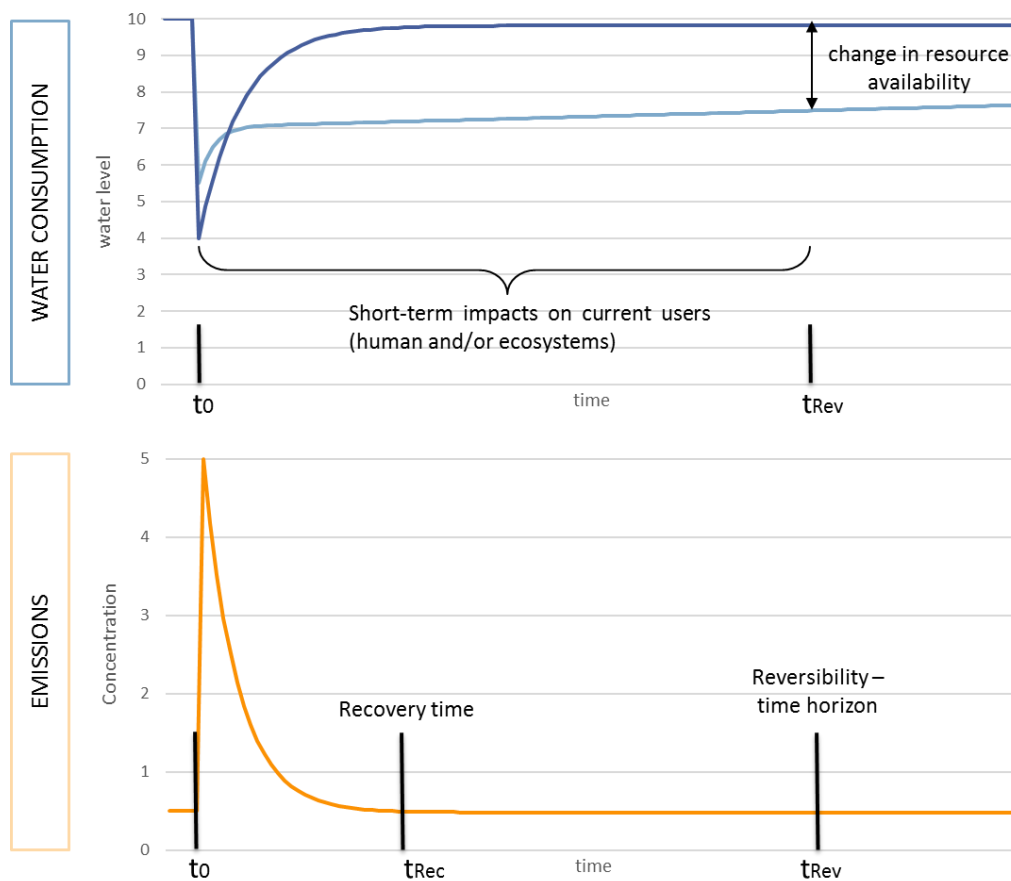
454 **4.1. Definition of a recovery period for freshwater resources**

455 According to the particularities of freshwater resources previously described, on the one hand, current freshwater
456 consumption and pollution lead to impacts on downstream users. This aspect is already addressed by available LCIA
457 methods. On the other hand, changes happening today may irreversibly reduce freshwater availability or its degree
458 of usability in the future, thus leading to physical scarcity and/or lack of the quality needed for future uses. As
459 previously discussed, the latter issues concern the AoP natural resources.

460 Some of the long-term impacts affecting freshwater resources could naturally revert, and quantitative and/or
461 qualitative properties of freshwater resources may be restored. Typically, such processes occur over long periods of
462 time, if at all (e.g. consumption of fossil groundwater). The time required to restore freshwater resources quality or
463 quantity is called *recovery period*, and, according to Chapman (1996), can be defined as the restoration time needed
464 for an aquatic environment to recover, once the cause of water quality degradation or consumption has ended. In

465 **Fig. 4**, the recovery period (t_{Rec}) is defined by the following two main impact pathways (i.e. consumption and
466 emissions) as: the *duration of water absence* which follows freshwater consumption (i.e. the time required by the
467 freshwater compartment to naturally re-establish its level prior to consumption), or the *duration of pollution presence*
468 following the emission of a pollutant (i.e. the time required to naturally decontaminate, also called natural
469 attenuation). Reversibility and irreversibility are concepts intrinsically linked to a time-scale and so it is the

470 distinction and classification of impacts between short or long-term, as processes may be reversible in very long
 471 time-horizons but irreversible in the human time-scale. When the recovery period lasts longer than an arbitrarily
 472 selected period (t_{Rev} in **Fig. 4**), changes in the properties of the aquifer are considered ‘irreversible’ and fall into the
 473 concern of the AoP natural resources. The selection of the time horizon (t_{Rev}) distinguishing between reversibility
 474 and irreversibility is a normative choice which typically depends on how the concept of future generations is
 475 quantitatively operationalized. Several options could be considered, e.g. current life expectancy, average life span,
 476 or 100 years as suggested by UNESCO/WHO/UNEP (1996) as the time horizon for irreversible freshwater
 477 degradation. None of these choices is necessarily right or wrong but they are indeed more or less appropriate in
 478 different contexts. It is therefore advisable to test alternative time-horizons when modeling in order to assess the
 479 sensitivity of this choice, after having clearly defined its rationale.



480
 481 **Fig. 4:** Illustration of water consumption (light and dark blue) and a pulse emission (orange), where t_0 = time at which the
 482 intervention occurs, t_{Rec} = recovery time, and t_{Rev} = reversibility time horizon, distinguishing the boundary between short and
 483 long-term, potential impacts. The curves are drawn for illustrative purposes only and show different ideal patterns i.e. full
 484 recovery within the time horizon (orange), almost complete recovery (dark blue) and partial recovery (light blue)

485 **4.2. Operationalization of the recovery period**

486 This section discusses the different possibilities to define how long the perturbation will last and whether the impacts
487 fall into the AoP natural resources. The life cycle inventory can offer some indication on this, for example, when
488 water consumption is associated with an elementary flow categorized as ‘fossil groundwater’, or when emissions to
489 groundwater resources are labeled as ‘long-term’ (e.g. emissions from a landfill). However, inventories may use
490 definitions of short and long-term not necessarily aligned with the meanings discussed in the previous section. A
491 comprehensive classification of inventories based on the temporal distinction between fund and stock freshwater
492 resources as well as short-term and long-term emissions might, at first, look like a sensible solution to the issue.
493 However, such an approach would present limitations: (i) a generic water body, like a lake for example, could be
494 both a fund and a stock resource depending on its own specificities and geographic location, (ii) most of the time,
495 the practitioner does not know the renewability rate of the freshwater resource of concern, and (iii) all the different
496 causality chains described in Section 3.2 cannot be associated to a specific inventory, for example, such an inventory
497 could not reflect a situation of overexploitation. Instead, the quantification of the recovery period could be performed
498 by modelling the response of the water body to freshwater consumption and emission of pollutants, taking into
499 account local hydrology and biogeochemical parameters, among others. In principle, such modeling could be
500 included within the impact assessment stage, so as to discriminate between short and long-term impacts. With
501 regards to emissions, the fate modeling provides information about the duration of freshwater pollution, and new
502 developments in LCIA models have shown that dynamic fate modelling scientifically sounds relevant for persistent
503 pollutants such as metals (Fantke et al., 2015; Shimako et al., 2017). However, it is important to remember the high
504 uncertainties associated with the dispersion of pollutants in groundwater or with the quantification of complex and
505 non-linear relationships regulating the interactions between the aquifer and surface water. Hence, simplified
506 assessments may lead to potentially misleading results. Moreover, it is important to remember that LCIA methods
507 have been historically developed on the basis of the ‘ceteris paribus’ assumption, which means that the quantification
508 of impacts is performed under the assumption that the only change occurring in the system under investigation is
509 the considered intervention. While this assumption has already been proven challenging for short-term assessments,
510 it is quite intuitive that it does not hold true for the long-term (e.g. for $t_{rev} = 100$ years) assessment, as major changes
511 to the system under investigation will likely have occurred.

512 **4.3. What should a freshwater resource impact indicator reflect?**

513 For the specific impact pathways based on over-exploitation or stock freshwater consumption, Bayart et al. (2010)
514 recommend to quantify damage to human life and ecosystems at the endpoint level, and to assess reduced availability
515 of freshwater resources for future generations through a midpoint indicator. In particular, they provide the following
516 recommendations:

- 517 - A midpoint indicator should express the consumptive use of freshwater going beyond the renewability rate
518 during a given time period and could be expressed in cubic meters of freshwater equivalent depleted;
- 519 - An endpoint indicator could in theory express the environmental damage due to future scarcity, however
520 “modeling future scenarios of depletion and environmental damage due to scarcity will be complex, especially
521 with regard to current and future human use” (Bayart et al., 2010), the reasons being: (i) “the choice between a
522 deficiency or compensation scenario depends on socio-economic parameters that are extremely difficult to
523 predict”, (ii) “future technological innovations are uncertain” and (iii) “some potential freshwater uses for which
524 water depletion would be an impediment have likely not been identified yet” (Bayart et al., 2010).

525 Finally, Bayart et al. (2010) end their discussion by suggesting the quantification of these impacts using the concept
526 of surplus energy required for future resource extraction, which is in line with a compensation scenario. Since the
527 framework presented in this paper encompasses a much wider range of possible impact pathways to freshwater
528 resources, including the qualitative aspect, more general recommendations are required, although the same reasoning
529 applies. That is, freshwater resource indicator(s) should express potential irreversible changes in both availability
530 (quantity) and degree of usability (quality) of freshwater remaining for future human needs. Then, in theory, such
531 indicator(s) may address the impacts on future generations due to the loss of provisioning functions of freshwater
532 resources (S2) as well as their global functions (S3). However, Sala et al. (2017) have discussed the feasibility of
533 adopting S2 and S3 perspectives, and assessing losses of global functions (S3) “looks to be unfeasible for the time
534 being as there is currently insufficient modeling that can capture the complexity fully, as there is a lack of quantitative
535 factors to characterize it, and also they can be seen as going beyond ‘classical environmental LCA’. This is
536 particularly true when the potential impacts assessed occur in a future scenario, and within this future context, the
537 same applies for S2, also in consideration of the fact that any arbitrary selection of one particular scenario could
538 hardly be justified. Thus, a freshwater resources indicator(s) should not attempt to predict future potential human
539 behavior with regard to water depletion or pollution, but should rather stay as close as possible to biophysical
540 parameters so as to flag potential long-term impacts.

541 In case the user intends to aggregate into AoPs it is useful to consider the endpoint indicators and whether the units,
542 representativeness, and underlying assumptions and methods of calculation are consistent enough to allow such
543 aggregation.

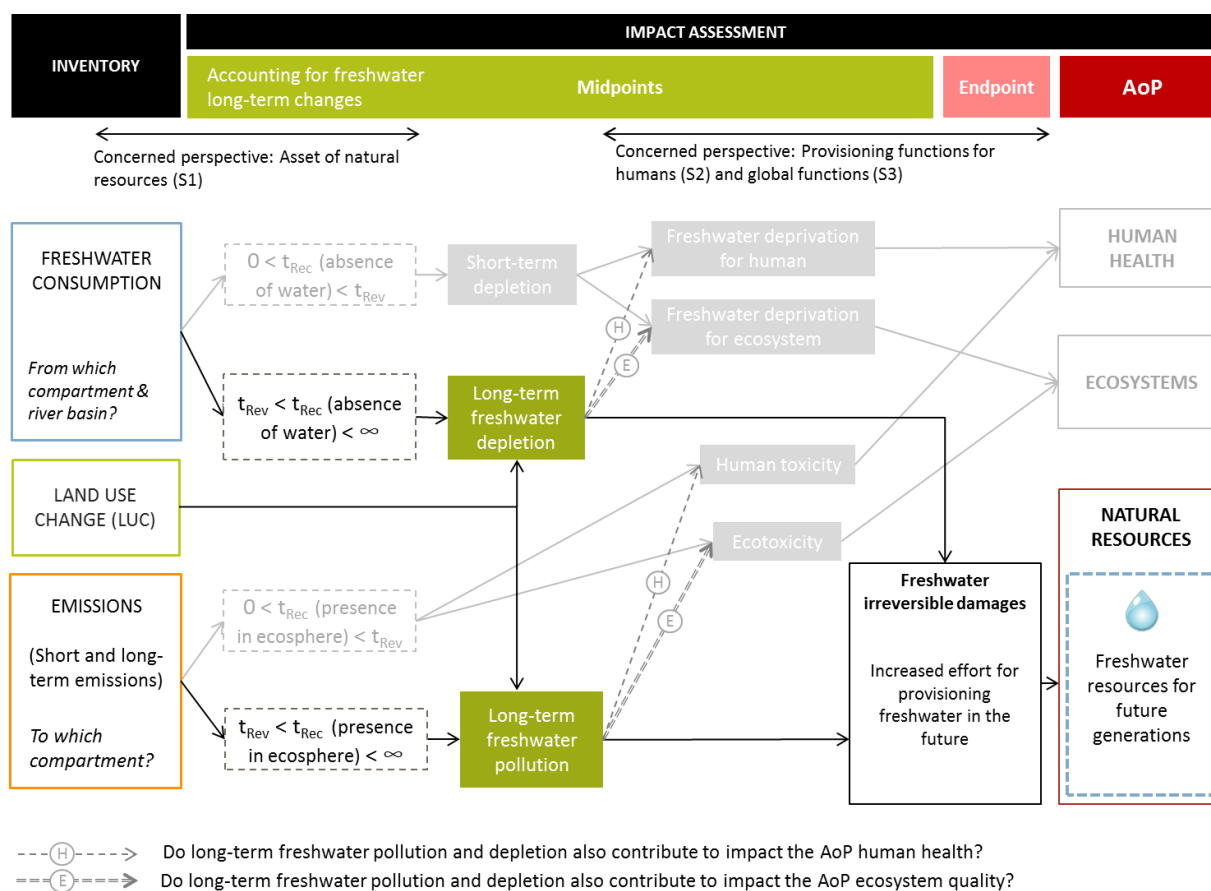
544 **4.4. Do long-term impacts also concern ecosystem quality and human health?**

545 This framework states that long-term impacts on freshwater is a concern of the AoP natural resources. Two questions
546 are discussed in this section: (1) does the inclusion of freshwater resource impacts in the AoP natural resources
547 overlap with existing links to the AoP ecosystem quality and human health? (2) Do long-term freshwater pollution
548 and depletion also contribute to impacts on the AoP ecosystem quality and human health, as represented by the
549 dotted arrows in **Fig. 5**?

550 Currently, water deprivation impact models (e.g. AWARE (Boulay et al., 2017)) only consider current users since
551 the issue under consideration is local or temporal freshwater unavailability leading to deprivation of current users.
552 Thus, including an additional impact pathway on the AoP natural resources that reflects the freshwater depletion
553 over a long-term should not overlap with impacts already assessed with current models. However, models for
554 toxicity (as for example the USEtox model (Rosenbaum et al., 2008)) estimate the impacts over the whole life time
555 of the pollutant, potentially implying several generations of users if the pollutant life time is about several hundred
556 years, as for metals. In that case, adding an impact which reflects the long-term pollution on resources may partly
557 overlap with toxicity impacts.

558 With the development of freshwater resource indicators, long-term changes in both availability (quantity) and degree
559 of usability (quality) of freshwater remaining for future human needs will hence be taken into account by the AoP
560 natural resources. Therefore, long-term freshwater pollution and depletion should not contribute to the impacts
561 assessed on the AoP human health; otherwise these environmental issues would be double counted. For instance,
562 once a freshwater resource has been depleted, (future) problems of water deprivation for humans and the (future)
563 consequences of remedying the problem, such as desalinization, cannot be counted at the same time. On the other
564 hand, species will most likely always be sensitive to these problems and do not have technological means to evade
565 or avoid impacts. Therefore, in **Fig. 5**, the dotted arrow (E), which refers to freshwater long-term impacts on
566 ecosystems, indicates a pathway that should always be considered, while the pathway which refers to long-term
567 freshwater impacts on human health (H) must be reconsidered according to what is already considered by the AoP
568 natural resources. Furthermore, it should be noted that reconsidering the time horizon for human toxicity impacts

569 would allow, as a secondary effect, to improve the consistency between impacts of water deprivation (assessed for
 570 current users) and toxicity related impacts.



571
 572 **Fig. 5:** Global impact pathways linking irreversible changes in freshwater resources to the AoP natural resource and their
 573 distinction from short-term impacts on the AoP human health and ecosystems, according to the recovery period (t_{Rec}) duration;
 574 T_{Rev} is the time horizon distinguishing between reversibility and irreversibility

575 **5. Conclusions**

576 This paper provides a conceptual framework for assessing potential impacts to freshwater resources as part of the
 577 AoP natural resources. Freshwater differs from other resources in LCA (e.g. fossil fuel) in that it is a vital resource
 578 on which ecosystems and humans depend. It therefore appears to be an absolute necessity to protect this resource
 579 with a view to intergenerational equity. In light of the findings of this work, we recommend that the freshwater
 580 resources indicator(s) capture impacts that are not currently being covered by human health or ecosystem quality
 581 indicators and therefore evaluate the irreversible reduction of freshwater availability (depletion) or its degree of
 582 usability (degradation) for future generations. The definition of a time horizon distinguishing between reversibility

583 and irreversibility is a normative choice that needs to be done with respect to a careful interpretation of the concept
584 of “future generations”. If recovery time occurs before the defined timeframe, potential impact of water use should
585 be considered reversible and linked to the human health and ecosystem quality AoP. Conversely, if beyond this
586 timeframe, potential impacts should be considered irreversible and be linked to biophysical parameters connected
587 to the AoP natural resources, thus refraining from predicting future (and unknown) potential impacts on humans and
588 ecosystems. The proposed framework also identifies the different stressors to freshwater resources with the aim to
589 highlight the methodological gaps and challenges for future LCIA development. Finally, this approach and logic
590 could be extended to other life-supporting/ecosystem relevant resources, such as soil, that are also potentially
591 exposed to irreversible changes affecting availability and degree of use in the future.

592 **6. Disclaimer**

593 The views expressed in this article are those of the authors and do not necessarily represent the views or policies of
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