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

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Abstract

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

Method—Considering the current scope of the AoP natural resources, the complex nature of freshwater resources and its important dimensions to safeguard safe future supply, a definition of freshwater resource is proposed, including water quality aspects. In order to clearly define what is to be protected, the freshwater resource is put in perspective through the lens of the three main

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safeguard subjects defined by Dewulf et al. (2015). In addition, an extensive literature review identifies a wide range of possible impact pathways to freshwater resources, establishing the link between different inventory elementary flows (water consumption, emissions and land use) and their potential to cause long-term freshwater depletion or degradation.

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

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

Keywords

Life cycle impact assessment; Freshwater resources; Water use; Long-term depletion; Long-term pollution

1. Introduction

Effective management of water resources is required to enable long-term sustainable development outcomes. Given the life-supporting function that freshwater provides in sustaining ecosystems, society’s agriculture and human consumption (UNEP, 2009), as well as the other functions of water in industry, its management is recognized as being vitally important for both the environment and the economy. Currently, freshwater resources in many regions are at risk of being overexploited. Most of the major aquifers in the world’s arid and semi-arid zones are experiencing rapid rates of groundwater depletion (Famiglietti, 2014), which has increased worldwide from 126 km^3a^{-1} in 1960 to 283 km^3a^{-1} in 2000, and is potentially large enough to contribute measurably to sea-level rise (Konikow and Kendy, 2005; Wada et al., 2010). Surface water systems in many regions are also being overexploited, like the Colorado River (Wildman, Jr. and Forde, 2012), with many river systems subject to river basin closure (Falkenmark and Molden, 2008), and most global freshwater withdrawals occurring in watersheds already experiencing extreme water stress (Ridoutt and Pfister, 2010). At the same time, water quality degradation is occurring in many river, lake and groundwater systems. For instance, in Latin America, Africa and Asia, it has been estimated that organic pollution has increased between 1990 and 2010 in almost twothirds of all rivers, while severe and moderate salinity pollution already affects around one-tenth of all river stretches in these three continents (UNEP, 2016). Observed pollution can sometimes be persistent, as is the case of PCB contamination in the Hudson river (The Hudson River Natural Resource Trustees, 2013). In addition, significant groundwater pollution has also widely occurred, although this is difficult to quantify globally since many groundwater resources have no adequate water quality monitoring programs (Foster et al., 2013; Lemming et al., 2010; Sampat, 2001). Given the importance of freshwater as a resource and the unsustainable overexploitation and degradation occurring in many regions, approaches are required to facilitate understanding of environmental impacts to freshwater resources in a decision-making context.

Previous work in water footprinting and virtual water assessments has described freshwater resources in terms of *green* and *blue water* (terms written in italics throughout the manuscript are defined in table S1 of Electronic Supplementary Material, ESM). In this terminology, soil moisture regenerated by precipitation (green water) is differentiated from run-off and percolation (blue water), and serve as two separate resources managed differently the water cycle (Falkenmark and Rockström, 2006). The differentiation of green and blue water resources was adopted early on with guidelines on how to include them in volumetric water footprint assessments (Hoekstra et al., 2011) with the main goal of addressing water management in supply chains by considering global sustainable resource limits (Hoekstra and Wiedmann, 2014). This terminology is not used in the ISO standard on water footprinting, which is based on life cycle assessment (LCA) (ISO 14046, 2014) where the water flows from different media compartments (e.g. soil and groundwater) are separately accounted for in the inventory (Pfister et al., 2015) with respect to the provision of a functional unit (ISO, 2006). Thus, the impact assessment methods can be applied to the specific inventory flows, which has resulted in mainly blue water consumption impacts having been addressed thus far. The two approaches for LCA and water footprinting are similar in principle and both quantify water use, but they differ in the communication of their results (Boulay et al., 2013), which requires proper declaration of applied methods when reporting footprint results (Pfister et al., 2017).

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

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

2. Aligning freshwater resources with the AoP natural resources

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

2.1. Current scope of the AoP natural resources

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

2.2. Freshwater: a complex natural resource

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

- In addition to being a resource for human economic activities (e.g., hydropower, cooling, industry …), freshwater is above all a non-substitutable support for (human and ecosystem) life. “Freshwater is a vital resource in sustaining both ecosystem health and human survival” (Bayart et al., 2010). This is an important point because it may lead to double-counting among the three AoPs (natural resources, human health and ecosystem quality). Indeed, once a freshwater resource is affected by human intervention, the users (human and ecosystems) dependent on this resource may be impacted. Bayart et al. (2010) therefore recommended that “natural resource damage categories may be disregarded if the cause-effect chain is modeled up to the human health and ecosystem quality categories”. Thus, it is required to determine whether and how the freshwater resource may be impacted beyond those pathways affecting its users. In other words, are there any potential impacts that are not covered by the AoPs human health and ecosystem quality which should be included in the AoP natural resources?
- The freshwater resource has a particular status as it is both a withdrawal compartment for consumption (source function) and a receiving compartment for emissions (sink function). “Lakes, for example, are sinks for inputs of water, and the materials and pollutants carried in the water, thereby being sensitive barometers of human activities in their surrounding watersheds” (UNEP, 2009). Both types of elementary flows (emissions and water consumption) should be linked to a damage indicator for freshwater as a resource. However, the way the AoP natural resources has been approached so far reflects the fact that only extraction and consumption (or dissipation) can impact natural resources (Sonderegger et al., 2017). Today, water degradation due to emissions is only considered in impacts on ecosystem quality and human health (e.g. toxicity or eutrophication), and more generally there is no existing approach linking polluting emission flows with potential damage to natural resources.
- Natural resources can be classified according to their renewability rate. Three categories are considered in function of their renewability rate: (1) *stock resources* are finite resources, not regenerated within a human lifetime (2) *fund resources* are regenerated within a human lifetime and (3) *flow resources* are continuously (re)generated (Dewulf et al., 2015; Sonderegger et al., 2017). The particularity of freshwater resources is that they can satisfy each of these categories (Koehler, 2008; Milà i Canals et al., 2009), with a renewability rate ranging from a few days to several thousand years (Fig. 1), and even a flow resource such as a river can undergo irreversible impacts (Pfister et al., 2009). Biospheric, atmospheric and solid freshwater (e.g., ice caps, glaciers, and permafrost) may not be considered a “usable” resource because they generally cannot be harnessed (see Fig. S1 in ESM), and are thus excluded from the scope of freshwater resources as part of the AoP natural resources.

2.3. Safeguard subjects and dimensions of freshwater resources

In order to define what is to be protected, freshwater resources are considered through the lens of the three safeguard subjects defined by Dewulf et al. (2015) (Fig. 2). The first safeguard subject (S1) is the asset of natural resources as such, regardless of how they might be used and/or the purpose they serve. This refers to the different *specific assets* (also called *resource categories* in Sonderegger et al. (2017)) constituting the natural resources. Freshwater is clearly one of these specific assets, however, it is essential to recognize and integrate the temporal nature of this concept, i.e. freshwater resources for future generations. The second safeguard subject refers to their provisioning functions for humans (S2), and the third one concerns their global function relative to more global interactions and regulation between the natural and human-industrial environment (S3). In other words, S2 focuses on the functions directly provided to humans such as domestic, industrial, agricultural, hydroelectric and transport functions, whereas S3 addresses regulatory, cultural and supporting services, as exhaustively described in Aylward et al (2005). Fig. 2 illustrates these safeguard subjects and highlights the importance of the quality and quantity of water. Indeed, to maintain most of these provisioning and global functions, two dimensions of freshwater resources must be preserved: the quantity (physical availability) and the quality These two dimensions are defined as per FAO/HLPE (2015): (1) the physical availability (quantity) “through rainfall, rivers and aquifers in a particular region” and (2) the quality of water: “in terms of Food Security and Nutrition (FSN) has different implications according to its uses; water quality needs for irrigation vary by crop, are high for food processing, food preparation and drinking, and are important for health and hygiene.” (FAO/HLPE, 2015). We consider that stability of water, i.e. limiting the quantity and quality fluctuations through time, is implicitly covered by how impacts on water quantity and quality are (or will be) characterized in LCIA. Freshwater quantity and quality are properties of the physical resource and so can be interpreted as assets to protect (i.e. S1), which by proxy will lead to the protection of many aspects of the S2 and S3 safeguard subjects.

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

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

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

3.1. Existing methods

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

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

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

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

3.2. Which stressors for freshwater resources?

This section describes the different causality chains and related environmental interventions (water consumption and emissions), identified as stressors, that can irreversibly impact the two dimensions of the freshwater resources (quantity and quality). We thus distinguish long-term freshwater depletion from long-term freshwater degradation impacts. An overview of these stressors is presented in Fig. 3. The description of this wide range of possible threats to freshwater resources highlights the fact that stock, as much as flow and fund freshwater resources are subject to irreversible changes.

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

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

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

In addition to depleting the local freshwater reservoir, overexploitation may also have other indirect consequences (depending on local conditions) on freshwater resources in the broader sense. Excessive groundwater pumping and aquifer depletion can cause the aquifer system to compact, resulting in permanent loss of groundwater storage volume in the aquifer system. Extensive subsidence of aquifers due to groundwater extraction around the world has been well documented (Galloway and Burbey, 2011). This issue has been widely recognized (Galloway and Burbey, 2011), but is currently neglected in LCA and should find its place in the framework of freshwater resources impacts. Furthermore, over-exploiting groundwater resources in coastal areas may potentially lead to marine intrusion and salinization effects (Amores et al., 2013). The latter is discussed in Section 3.2.2, dedicated to long-term freshwater pollution.

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

> Changes in water flows caused by land use change: Land use change refers to the transformation of one land use into another in a transition that carries significant changes to land properties (e.g., soil, above and belowground carbon content, etc.) (Koellner et al., 2013). Changes in land use affect the water cycle, which is reflected by the partitioning of precipitation and solar radiation at the soil and vegetation surfaces, and can affect long-term freshwater availability. The descriptions of these effects typically follow a water yield or atmospheric water supply approach to the water cycle (Ellison et al., 2012). Land use change can affect surface permeability and soil conditions that favor runoff over infiltration and percolation of precipitation under new land use conditions. For instance, cropland and pasture have shallower root systems, smaller leaf area index and greater albedo than forests, thereby reducing evapotranspiration and favoring percolation (local freshwater availability) and runoff (downstream water availability). These effects have typically been observed in paired-catchment studies (Ellison et al., 2012) and may be observed in regions of recent and intense land use change activity. For example, soybean-dominated watersheds in the Amazon region showed greater streamflow than forested watersheds, mainly due to stream dependency on baseflow and high soil infiltration rates (Hayhoe et al., 2011).

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

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

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

> Future Freshwater Contamination: Future freshwater contamination refers to processes that release pollutants into the environment over several hundreds or even thousands of years, such as landfills and mine tailings. Freshwater resources can potentially be impacted by these long-term pollutants. In fact, acid drainage of abandoned mines can be a source of both surface and groundwater pollution for decades, as illustrated by the gold mining activities in South Africa (Tutu et al., 2008; Winde and Sandham, 2004) or the Rio Tinto system in Spain, where mining activities (mainly copper, silver, gold, pyrite) that began at the Copper and Bronze Age and ended in 1998, generated 5,000 years of pollution (Davis et al., 2000). P. Younger (1997) studied the longevity of minewater pollution and showed that the poorest water quality discharged from abandoned mines can be expected to occur within the first 40 years, after which an on-going generation of acidity will persist for several hundred years until mineral sources are depleted. The case of uranium contamination is also a classic example of water/sediment long-term pollution due to mining (Winde and Sandham, 2004). This issue requires a dynamic inventory. The case of long-term metal emissions from landfills, and how to handle them, are well-known topics of discussion in LCA (Bakas et al., 2015; Hellweg and Frischknecht, 2004; Hischier et al., 2010).

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

- *Heavy metal contamination (the expression “heavy metals” in LCA can include metals such as lead, metalloids such as arsenic or nonmetals such as selenium):* These trace elements are naturally present in surface or groundwater, with concentrations dependent on local geological and climatic conditions. However, because of their use in various human activities (industry, building, agriculture), they are also discharged into freshwater or soil from point or diffuse sources. Their toxic properties impact ecosystems and humans, and their presence degrades freshwater quality. The bio-physicochemical conditions of a given freshwater compartment can induce changes in metallic forms (e.g. oxidation levels or complexation), favoring precipitation and thus immobilization, or solubilization and thus mobilization of these elements. However, metals are never degraded but remain in the environment in different dissolved or particulate forms.
- *Persistent organic pollutants (POPs) contamination*: Persistent organic pollutants are not naturally occurring in the environment. These molecules have been

synthetized by humans and are characterized by a long lifetime in the environment. They have been widely used by various human activities such as industry (due to their chemical stability) or in agriculture (as pesticides). POPs are mainly hydrophobic compounds, and although their concentrations in water remains very low, due to low solubility constants, they may be present on particulate matter or sediments, and may bio-accumulate within the aquatic food web. They slowly degrade via physical, chemical or biological processes. The massive use of certain organochlorine pesticides, such as Chlordecone in the French Antilles, is a good example of persistent freshwater pollution. In the French Antilles, this insecticide was banned in 1993, and recent studies reveal its frequent presence in soils, rivers, spring water, but also in drinking water and food crop produce (Cabidoche et al., 2009). It is assumed that only lixiviation is able to slowly reduce soil contamination, and thus increase aquifer contamination and ultimately affect springs and rivers over hundreds of years (Cabidoche and Lesueur Jannoyer, 2011). Another well-known example of a highly persistent chemical is polychlorinated biphenyl (PCB) with many sites in the world revealing high levels of environmental PCB contamination, even 40 years after having been banned. The case of the Hudson River PCB contamination (The Hudson River Natural Resource Trustees, 2013) attests that freshwater resources, including sediments and the aquatic food web, can be polluted for decades. Most of these persistent and toxic substances were introduced in the middle of the twentieth century.

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

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

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

3.3. Trade-offs with other AoPs and freshwater depollution

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

3.3.2. Freshwater depollution—As shown in Fig. 3, impacts of freshwater use can result from long-term freshwater depletion or pollution. However, some processes may withdraw polluted water, purify it to a level required for the operation, and discharge water that is of higher quality than the water withdrawn initially. The question of if and how this freshwater depollution should be credited depends on several aspects. In most of the cases, depolluted water will be discharged into a flow freshwater compartment (e.g. a river). In such cases, the depollution is not considered beneficial from a resource perspective but can cause benefits for human users and ecosystems, if the water is cleaner than the receiving compartment. Thus, the benefit can be considered by means of impact assessment methods for water use considering quality aspects (e.g. Boulay et al., 2011), or as negative emissions in traditional, emission-oriented impact categories (e.g. human- or eco-toxicity.) However, this approach raises two issues of consistency. First, this is equivalent to crediting the whole potential impact of a removed pollutant molecule, without considering that this molecule may have already caused impacts before its removal. This leads to an overestimation of the benefit from the removal. For a correct implementation, the potential impact to credit must be the integration of its (avoided) impacts from the moment when the pollutant is removed to its final degradation or sequestration (i.e. it is no longer bioavailable) instead of integrating over its entire environmental lifetime from its emission onwards. The latter is how a pollutant characterization factor is (usually) calculated. For persistent pollutants, this overestimation may be substantial due to their prolonged presence and activity in the environment. Secondly, we raise the question of hysteresis of impact assessment models. The cause-effect chains of LCIA models are not necessarily reversible, or at least have neither been developed nor tested for an application assuming an inverse logic of the pathway, even though that is how they are used when applying credits (calculated as avoided impacts).

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

4. Operationalization and consequences on methodological choices

4.1. Definition of a recovery period for freshwater resources

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

Some of the long-term impacts affecting freshwater resources could naturally revert, and quantitative and/or qualitative properties of freshwater resources may be restored. Typically, such processes occur over long periods of time, if at all (e.g. consumption of fossil groundwater). The time required to restore freshwater resources quality or quantity is called *recovery period*, and, according to Chapman (1996), can be defined as the restoration time needed for an aquatic environment to recover, once the cause of water quality degradation or consumption has ended. In Fig. 4, the recovery period (t_{Rec}) is defined by the following two main impact pathways (i.e. consumption and emissions) as: the *duration of water absence* which follows freshwater consumption (i.e. the time required by the freshwater compartment to naturally re-establish its level prior to consumption), or the *duration of pollution presence* following the emission of a pollutant (i.e. the time required to naturally decontaminate, also called natural attenuation). Reversibility and irreversibility are concepts intrinsically linked to a time-scale and so it is the distinction and classification of impacts between short or long-term, as processes may be reversible in very long time-horizons but irreversible in the human time-scale. When the recovery period lasts longer than an arbitrarily selected period (t_{Rev} in Fig. 4), changes in the properties of the aquifer are considered ‘irreversible’ and fall into the concern of the AoP natural resources. The selection of the time horizon (t_{Rev}) distinguishing between reversibility and irreversibility is a normative choice which typically depends on how the concept of future generations is quantitatively operationalized. Several options could be considered, e.g. current life expectancy, average life span, or 100 years as suggested by UNESCO/WHO/UNEP (1996) as the time horizon for irreversible freshwater degradation. None of these choices is necessarily right or wrong but they are indeed more or less appropriate in different contexts. It is therefore advisable to test alternative time-horizons when modeling in order to assess the sensitivity of this choice, after having clearly defined its rationale.

4.2. Operationalization of the recovery period

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

4.3. What should a freshwater resource impact indicator reflect?

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

- A midpoint indicator should expresses the consumptive use of freshwater going beyond the renewability rate during a given time period and could be expressed in cubic meters of freshwater equivalent depleted;

- An endpoint indicator could in theory express the environmental damage due to future scarcity, however “modeling future scenarios of depletion and environmental damage due to scarcity will be complex, especially with regard to current and future human use” (Bayart et al., 2010), the reasons being: (i) “the choice between a deficiency or compensation scenario depends on socio-economic parameters that are extremely difficult to predict”, (ii) “future technological innovations are uncertain” and (iii) “some potential freshwater uses for which water depletion would be an impediment have likely not been identified yet” (Bayart et al., 2010).

Finally, Bayart et al. (2010) end their discussion by suggesting the quantification of these impacts using the concept of surplus energy required for future resource extraction, which is in line with a compensation scenario. Since the framework presented in this paper encompasses a much wider range of possible impact pathways to freshwater resources, including the qualitative aspect, more general recommendations are required, although the same reasoning applies. That is, freshwater resource indicator(s) should express potential irreversible changes in both availability (quantity) and degree of usability (quality) of freshwater remaining for future human needs. Then, in theory, such indicator(s) may address the impacts on future generations due to the loss of provisioning functions of freshwater resources (S2) as well as their global functions (S3). However, Sala et al. (2017) have discussed the feasibility of adopting S2 and S3 perspectives, and assessing losses of global functions (S3) “looks to be unfeasible for the time being as there is currently insufficient modeling that can capture the complexity fully, as there is a lack of quantitative factors to characterize it, and also they can be seen as going beyond ‘classical environmental LCA”. This is particularly true when the potential impacts assessed occur in a future scenario, and within this future context, the same applies for S2, also in consideration of the fact that any arbitrary selection of one particular scenario could hardly be justified. Thus, a freshwater resources indicator(s) should not attempt to predict future potential human behavior with regard to water depletion or pollution, but should rather stay as close as possible to biophysical parameters so as to flag potential long-term impacts. This means that in a first step, the freshwater depleted or degraded needs to be quantified, and only in a second step, additional modeling such as the potential future efforts to compensate for depletion and remediate degradation may be modeled. In case the user intends to aggregate into AoPs it is useful to consider the endpoint indicators and whether the units, representativeness, and underlying assumptions and methods of calculation are consistent enough to allow such aggregation.

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

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

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

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

5. Conclusions

This paper provides a conceptual framework for assessing potential impacts to freshwater resources as part of the AoP natural resources. Freshwater differs from other resources in LCA (e.g. fossil fuel) in that it is a vital resource on which ecosystems and humans depend. It therefore appears to be an absolute necessity to protect this resource with a view to intergenerational equity. In light of the findings of this work, we recommend that the freshwater resources indicator(s) capture impacts that are not currently being covered by human health or ecosystem quality indicators and therefore evaluate the irreversible reduction of freshwater availability (depletion) or its degree of usability (degradation) for future generations. The definition of a time horizon distinguishing between reversibility and irreversibility is a normative choice that needs to be done with respect to a careful interpretation of the concept of “future generations”. If recovery time occurs before the defined timeframe, potential impact of water use should be considered reversible and linked to the human health and ecosystem quality AoP. Conversely, if beyond this timeframe, potential impacts should be considered irreversible and be linked to biophysical parameters connected to the AoP natural resources, thus refraining from predicting future (and unknown) potential impacts on humans and ecosystems. The proposed framework also identifies the different stressors to freshwater resources with the aim to highlight the methodological gaps and challenges for future LCIA development. Finally, this approach and logic could be extended to other life-supporting/ecosystem relevant resources, such as soil, that are also potentially exposed to irreversible changes affecting availability and degree of use in the future.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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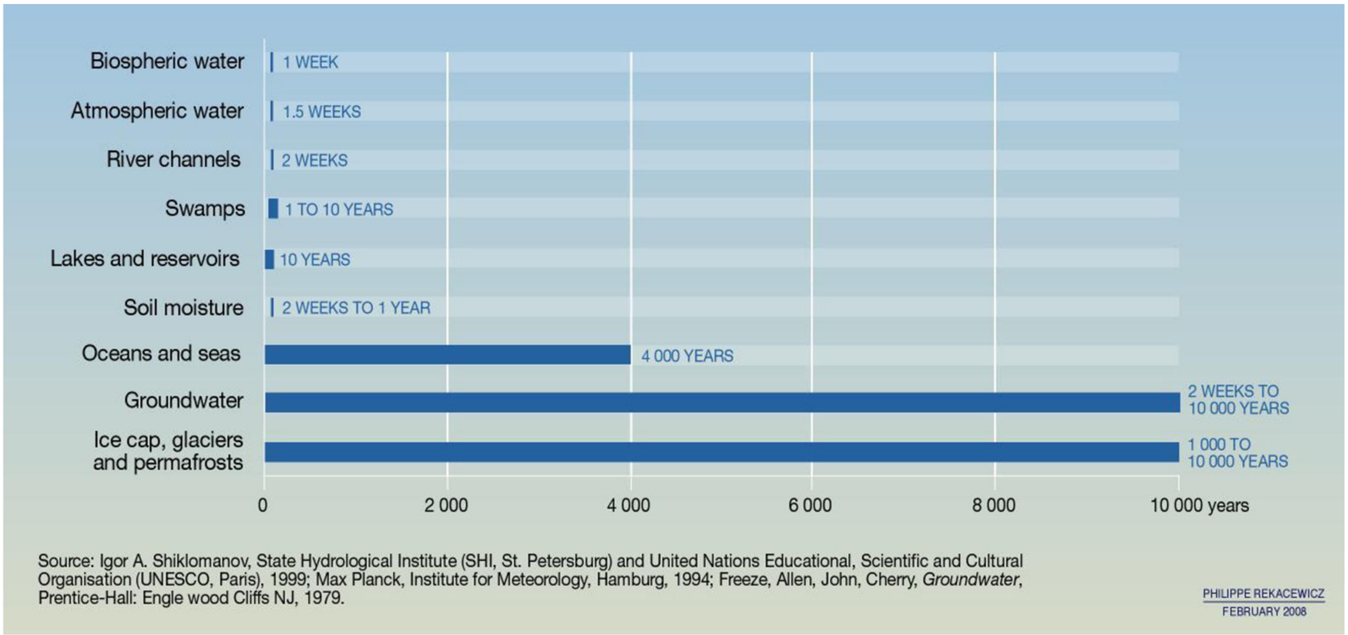

Source: Igor A. Shiklomanov, State Hydrological Institute (SHI, St. Petersburg) and United Nations Educational, Scientific and Cultural Organisation (UNESCO, Paris), 1999; Max Planck, Institute for Meteorology, Hamburg, 1994; Freeze, Allen, John, Cherry, *Groundwater*, Prentice-Hall: Engle wood Cliffs NJ, 1979.

Fig. 1:

Estimated average residence time of water resources - from Virtual Water Graphics report of UNEP (2008)

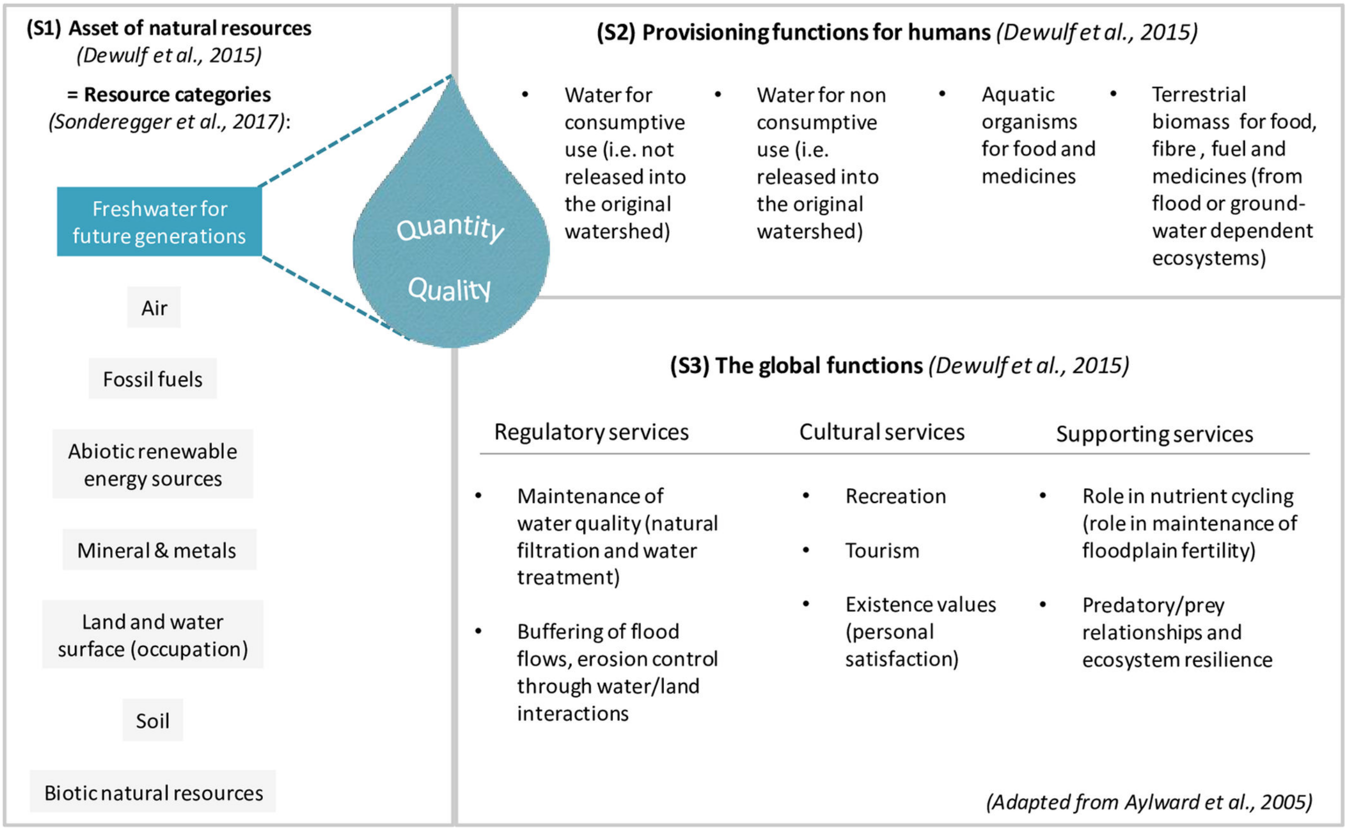

Fig. 2:

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

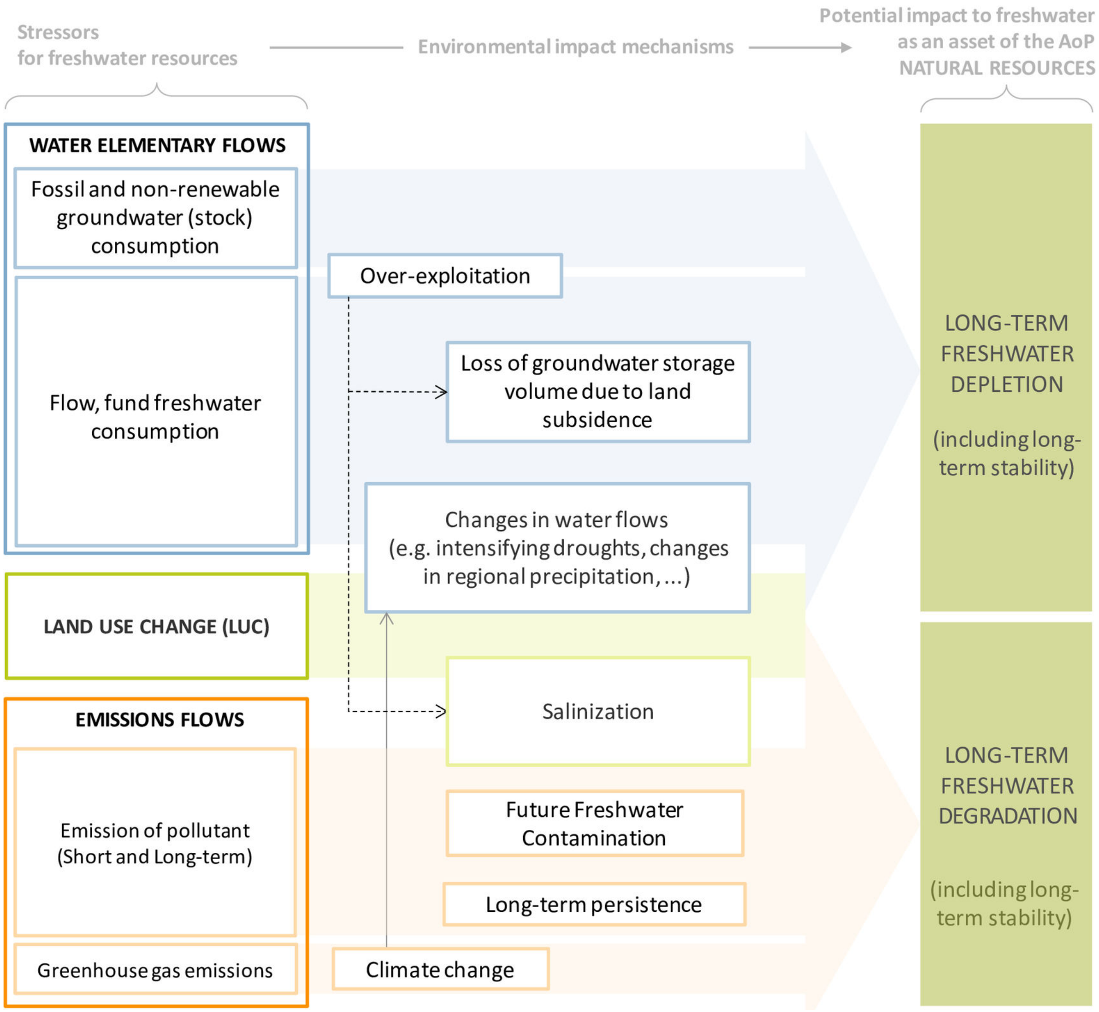

Fig. 3:

Identification of the stressors involved in the freshwater resources cause-effect chains. Boxes in the middle of colored two arrows express that two causes (arrows) lead to the same impact (box).

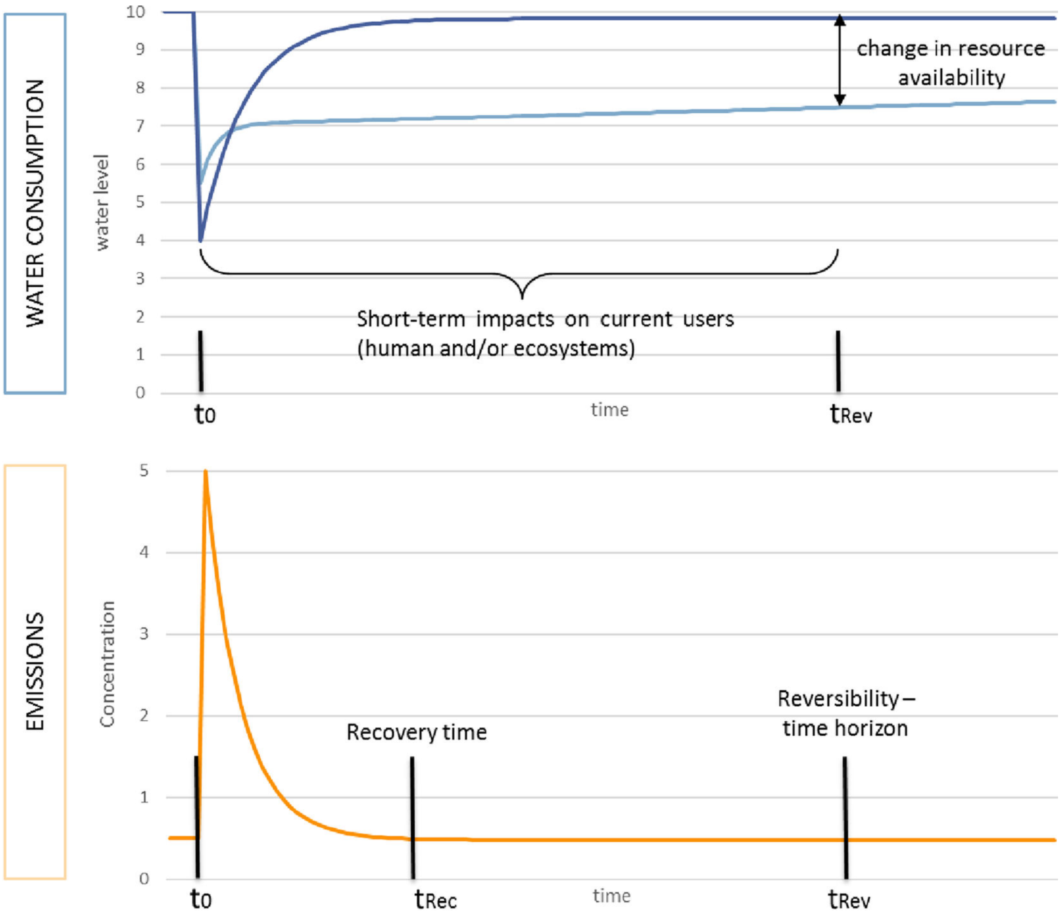

Fig. 4:

Illustration of water consumption (light and dark blue) and a pulse emission (orange), where t0 = time at which the intervention occurs, t_{Rec} = recovery time, and t_{Rev} = reversibility time horizon, distinguishing the boundary between short and long-term, potential impacts. The curves are drawn for illustrative purposes only and show different ideal patterns i.e. full recovery within the time horizon (orange), almost complete recovery (dark blue) and partial recovery (light blue)

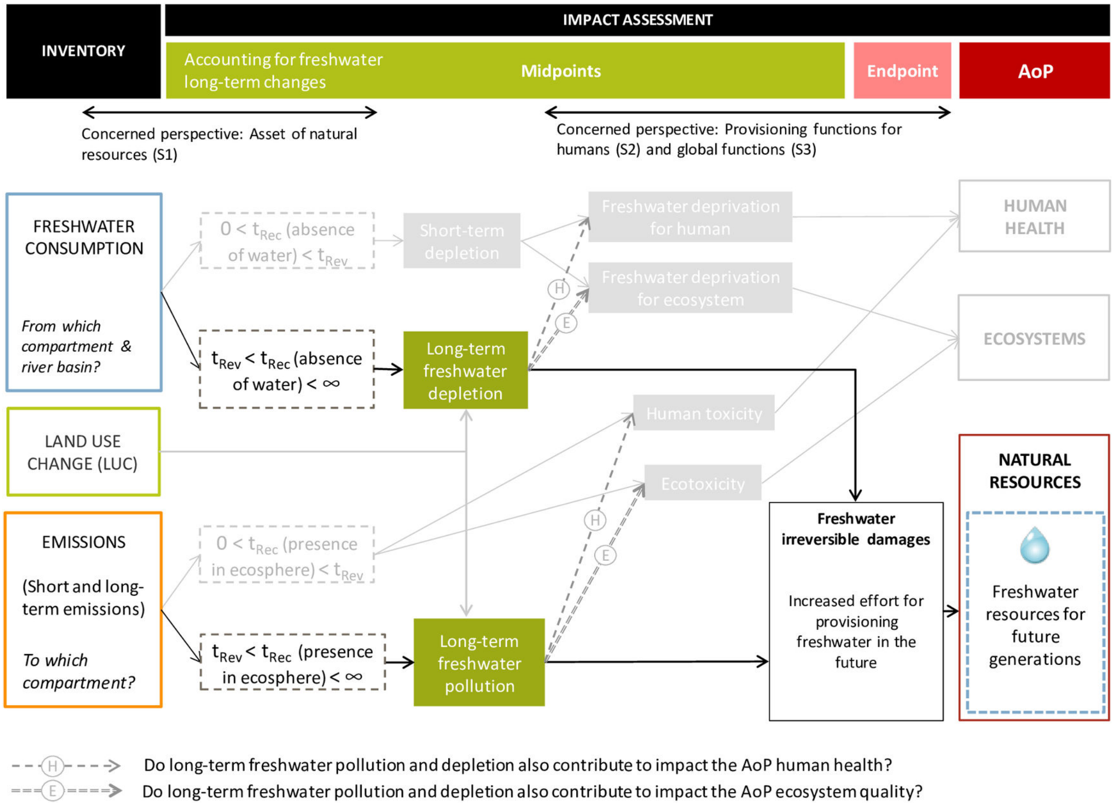

Fig. 5:

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