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WATER USE IN LCA

Categorizing water for LCA inventory

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Abstract

Purpose As impact assessment methods for water use in LCA evolve, so must inventory methods. Water categories that consider water quality must be defined within life cycle inventory. The method presented here aims to establish water categories by source, quality parameter and user.

Materials and methods Water users were first identified based on their water quality requirements. A list of parameters was then defined, and thresholds for these parameters were determined for each user. The thresholds were based on international standards, country regulations, recommendations and industry standards. Three different water sources were selected: surface water (including seawater), groundwater and rainwater. Based on the quality and water sources, categories were created by grouping user requirements according to the level of microbial or toxic contamination that the user can tolerate (high, medium or low).

Results and discussion Seventeen water categories were created: eight for surface water, eight for groundwater and one for rainwater. Each category was defined according to 136 quality parameters (11 conventional parameters, 38 specific inorganic contaminants and 87 specific organic contaminants) and the users for which it can be of use.

Conclusions A set of elementary flows is proposed in order to support a water inventory method oriented towards functionality. This can be used to assess potential water use impacts caused by a loss of functionality for human users.

Keywords Life cycle inventory · Water classification · Water quality · Water resources · Water use

1 Introduction

1.1 Background

Water use impacts assessment is currently undergoing significant changes. Until recently (Frischknecht et al. 2008; Milà i Canals et al. 2009; Pfister et al. 2009; Boulay et al. 2011), there were no methods or guidelines to assess water use impacts in life cycle assessment (LCA), and only the volume of withdrawn water was listed in inventory databases. This impact assessment method development is therefore leading the evolution in water inventory requirements.

Inventory analysis involves collecting input and output data for all unit processes included in the scope of the assessment. From a water perspective, this translates into assessing the quantity, quality, type of resource (ground or surface water) and geographical location of the water that is withdrawn and released. These key characteristics will affect the functionality of the water—a loss of which would generate environmental impacts. Water functionality can be lost either through consumption (water is unavailable for use in the same watershed) or degradation (water is too contaminated to be used for a specific function) (Bayart et al. 2010). Current

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databases such as ecoinvent (Frischknecht and Jungbluth 2007) and LCA Food (Nielsen et al. 2003) only distinguish the water source, at best differentiating between lake, river, ground, sea, sole and cooling/turbine water, without any quality differentiation. The purpose of this article is therefore to advance a functionality-based regionalized inventory method allowing impact assessment associated with quality degradation and consumption.

Bayart et al. (2010) propose "that the inventory flows represent a set of water types each representing an elementary flow with its own characterization factors". They add that these water types should be differentiated based on their source and quality and should therefore be described by a set of quantitative values. However, the lack of quantitative methodology was highlighted in a recent assessment of water use in red meat production in Australia (Peters et al. 2010) where a qualitative classification of water of high, moderate, low or alienated quality is used. Bayart and colleagues mention two possible approaches to consider quality: either functionality-based or distance-to-target. The former "assesses to which users the water withdrawn and released is functional" and this should be based on international and accepted quality standards for each user. Water is considered functional if it can meet users' needs without generating adverse effects or a change in activities. For example, the need for an extra influent treatment because of quality degradation caused by human intervention changes the activity. The impacts of this change should be accounted for in LCA through boundary extension. The distance-to-target approach can either be based on dilution or the energy required to treat the water to reach a reference water quality. Stewart and Weidema (2005) state that water quality is multidimensional and should not be defined in a single indicator but rather as a vector of water quality characteristics.

Water quality indexes and classifications have been advanced in many fields outside LCA, especially to describe and categorize surface water. While these methods serve their purposes, they are mainly geared towards ecosystem quality needs and not human uses. When describing the existing classification schemes, the WHO states: "As a general rule, the orientation of the classification system towards aquatic life implies that the category limits are more conservative than they would be if targeted at other water uses" (Enderlein et al. 1997). Government agencies, however, have shown interest in a function-based classification, and partial guidelines have been advanced. The European Economic Community has presented quality standards for surface water with respect to domestic uses and required treatment (EEC 1975). The Environmental Agency of Japan (Overseas Environmental Cooperation 1998) and Taiwan's Environmental Protection Administration (Taiwan EPA 1998) have gone one step further and determined parameters and thresholds associated with several users, including domestic, industrial, aquaculture, irrigation, recreation and environmental conservation. Other classification schemes have been developed in India, Thailand and the UK (Enderlein et al. 1997). While these classifications can, at least partially, meet the needs of the LCA community, only a few parameters are defined and no information can be obtained on how the thresholds were determined. Moreover, the categories were created in a way that does not allow for much distinction between the users' quality requirements. It is therefore impossible to assess functionality loss for individual users.

1.2 Objectives

This paper aims to create an appropriate inventory scheme/classification that allows quality to be considered and evaluated in a subsequent impact assessment in LCA through a functionality-based approach. The objective of the method is to create water categories defined by source and quality parameters. There should be as few categories as possible, yet sufficient enough to cover and differentiate the different user needs based on quality.

2 Methodology

The main steps in defining the water category are illustrated in Fig. 1. They refer to the different parameters considered

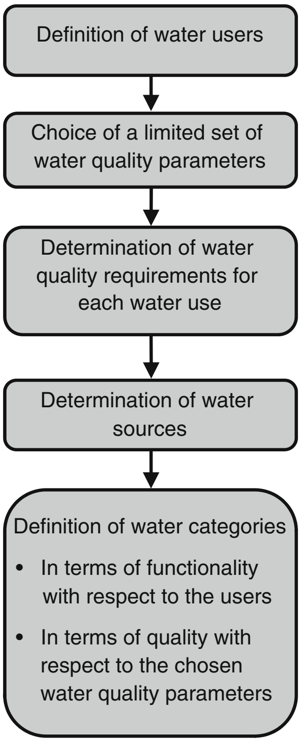

Fig. 1 General methodology

when defining water categories: the different users for which a category should be functional or not, the quality parameters that will define each category and their associated thresholds, and the sources of water to be considered. These steps are defined in detail in this section and led to the resulting water categories.

2.1 Definition of water users

The first step consists in defining the water users. Bayart et al. (2010) identified seven main water users: agriculture, domestic users (drinking water), industry, transport, fisheries, hydropower and recreational users. However, for some of these activities, the quality of water that can be used varies greatly. This is especially the case for domestic, industry and agriculture. Sub-categories were therefore created to account for this diversity. In total, 11 distinct users were set out (see Table 1).

Domestic users differ regionally and across the world in their use of different water-treatment technologies based on available water quality. Available water quality therefore dictates the necessary treatment. However, while an increase in water contamination may not affect a user that already applies an advanced water treatment, this isn't the case for a user that relies on a simple disinfection method. Therefore, three domestic users were differentiated according to their drinking water production mode based on the three water-treatment levels.

Table 1 Types of water users

Water user	Definition
Domestic 1	Domestic user performing no treatment or simple chemical disinfection to the water prior to use
Domestic 2	Domestic user performing a conventional chemical–physical treatment (coagulation or precipitation, solid removal process, disinfection) or equivalent treatment to the water prior to use
Domestic 3	Domestic user performing an advanced treatment (i.e. conventional treatment plus additional treatment (UV disinfection, adsorption, etc.)) or specific advanced treatment (reverse osmosis, nanofiltration, adsorption, ion exchange, desalination, etc.) or desalination to the water prior to use
Industrial	Industrial user (manufacturer) withdrawing available water and treating it to the required level
Cooling	Once-through cooling water for energy production
Agriculture 1	Agriculture that requires good quality irrigation water
Agriculture 2	Agriculture that requires only poor-quality irrigation water
Fisheries	Freshwater aquaculture and capture of fish
Hydropower	Hydroelectricity production
Transport	Transportation of goods through inland waters
Recreation	Recreational activities such as swimming and water sports

Two types of water users were considered for agriculture: agriculture 1 is the use of good quality irrigation water (needed to grow crops that are usually eaten raw) while agriculture 2 is the use of relatively poorer quality irrigation water (needed to grow crops that are not eaten raw, such as cereals, and non-food agriculture). It should be noted that even though international standards for irrigation water exist (Ayers and Westcot 1985), national and/or regional standards or practices may vary greatly from one part of the world to the next. This is particularly true for microbiological standards, namely faecal coliforms. The standard ranges from the very strict Washington State standard for water reuse (Washington State 1997) to the use of polluted streams in Europe (UNEP Global Environment Monitoring System (GEMS) Water Programme 2009) or the use of untreated wastewater in many less-developed countries (Van der Hoek 2004; WHO and UNEP 2006). This translates into a wide range of infection risks for the populations that eat the crops and the agriculture workers who are more directly exposed. The descriptions of the users considered in this method are summarized in Table 1.

This definition of water users can be compared to the similar approaches of the Environment Agency of Japan (Overseas Environmental Cooperation Center 1998) and the Environmental Protection Agency of Taiwan (Taiwan EPA 1998) in their respective definitions of surface water quality standards. Japanese standards include three water supply categories, three fishery categories, three industrial water categories, one irrigation water category and one environmental conservation category. Taiwanese standards define three public water categories, one swimming category, two aquaculture categories, two industrial categories (manufacture and cooling) and one environmental conservation category. The European Communities (1975) also set out three domestic user types according to the treatment required to obtain drinking water. This distinction for users such as domestic and agriculture is important to avoid major misconceptions when later identifying the quality requirement for each user.

2.2 Choice of quality parameters

The second step consists in choosing the water quality parameters. This is not an easy task for two main reasons. The first is obviously the large number and diversity of parameters that can characterize the quality of a water stream, either natural or not. For example, the United Nations Global Environment Monitoring System (GEMStat) database (UNEP

Global Environment Monitoring System (GEMS) Water Programme 2009), which aims at improving water quality data access and monitoring by providing quality data on surface and groundwater for 104 countries, includes 155 water quality parameters distributed as follows: physico-chemical characteristics (22), microbiology (four), organic matter (eight), nutrients (24), major ions (19), metals (56) and organic contaminants (22). Also, the Environmental Protection Agency of the United States (USEPA 1982) lists 126 priority organic and inorganic pollutants, and the United States Geological Survey (2006) lists 95 emerging contaminants.

The second challenge lies in the fact that water quality characterization parameters may differ depending on the type of contamination, measurement methodologies or other field-specific issues (e.g. sodium adsorption ratio, SAR, in irrigation). For example, in the wastewater field, suspended particles are directly measured whereas, in the drinking water field, the relatively low concentrations of particles are indirectly measured through turbidity. Organic matter is usually measured in terms of biochemical oxygen demand (BOD) and chemical oxygen demand in the wastewater field, but these parameters are rarely used in the drinking water field because they would lead to values below the detection limit.

In order to define a workable list of parameters, choices had to be made according to the objectives of the water classification, as outlined by Owens (2002), to define the functionalities of a water body. Except for transport and hydropower, for which quality is not an issue, the relevant parameters were based on international standards and guidelines. Table 2 is a sample of Table A2 provided in the Supplementary Information (SI) which lists the water quality parameters that define the functionality of water for irrigation, fisheries, drinking water production, recreation and cooling. Three parameter categories are set out: general parameters (which include microbial parameters), inorganic compounds and organic compounds. For each water use and quality parameter, the reference of the standard or guideline is indicated. In several cases, more than one reference is listed. The data was taken from different sources, namely WHO (WHO and UNEP 2006) for agriculture, Food and Agriculture Organization (FAO; Svobodová et al. 1993) for fisheries, WHO (WHO 2008) and the European Economic Community (EEC 1975) for drinking water, WHO (WHO 2003) and the government of Québec (MDDEP 2010) for recreation, Electric Power Research Institute (EPRI; EPRI 2003) for cooling water and Taiwan EPA (Taiwan EPA 1998) for several users.

In the last column of Table 2 (and Table A2 in the Electronic supplementary material), the distinction is made between the parameters retained to define water categories and those that were not. The rationale behind each selected or discarded parameter is also briefly described. Toxicity (humans, plants or fish) is the main justification for parameter selection based on the guidelines for each user and which therefore define water functionality. Other selected parameters include indicators for scaling or clogging potential and aesthetic parameters for drinking water. The latter are indirectly related to human health issues since an aesthetically unpleasant source of water may favour risky behaviours such as the use of a

Table 2 Sample of references and parameter selection rationale (complete in Table A2, Electronic supplementary information)

Parameter	Agriculture	Fisheries	Drinking water	Sources for drinking water	Recreation	Cooling	Parameter selection/Rationale
General parameters							
Faecal coliforms		TAI98	WHO08	EEC75, TAI98	QUE10, TAI98, WHO06		Retained because it is a good indicator for faecal pollution
Suspended solids	WHO06, TAI98	TAI98		EEC75, TAI98	TAI98	EPRI03	Retained (aesthetic parameter for drinking water, indicator for clogging potential)
Total dissolved solids	WHO06		WHO08	EEC75			Retained (aesthetic parameter for drinking water, indicator for scaling potential); correlation with electrical conductivity
Inorganics							
Arsenic	WHO06	FAO93	WHO08	EEC75, TAI98			Retained (toxicity)
Cadmium	WHO06	FAO93	WHO08	EEC75, TAI98			Retained (toxicity)
Organics							
Benzene			WHO08				Retained (human toxicity)
Atrazine			WHO08				Retained (human toxicity)

contaminated water source or long and inadequate water storage.

Not all microbial parameters were considered in this study. Microbial indicators such as faecal coliforms were preferred to reflect the reality of microbial monitoring. Also, there does not appear to be any established parameters pertaining to organic compounds for irrigation. This is because the WHO and UNEP (2006) have defined thresholds for several inorganic compounds but none for organic compounds. This may be explained by the fact that, despite the concern over chemicals, most known illnesses relate to microbial contamination, and surveillance systems seem to solely focus on potential causes of human illness (Todd 2008). Phosphorus was not retained to evaluate drinking water functionality since it does not appear in drinking water standards. The microcystin-LR (cyanobacterial toxin) concentration was selected instead because it is part of the WHO guidelines for drinking water quality (WHO, 2008). However, it has been shown that relatively high concentrations of phosphorus in water (among other factors) favour the growth of cyanobacteria. Regional correlations between microcystin-LR and phosphorus concentrations may be established, as shown by Giani et al. (2005) for southern Québec. This type of relationship could be used to estimate the microcystin-LR concentration from the phosphorus concentration—the latter being more readily available. However, the exclusion of dilution effects would here strongly affect the results.

2.3 Determination of water quality thresholds per user

The selection of water quality thresholds was mostly based on those provided by the aforementioned references. WHO standards define most thresholds for domestic 1 since this type of water must meet drinking water quality standards after disinfection. The faecal coliform threshold was set according to North American mandatory filtration regulations (USEPA 2004; MDDEP 2006), which are also in line with EEC guidelines (1975).

For domestic 2, thresholds for specific inorganic and organic contaminants are equivalent to WHO drinking standards since conventional treatments do not remove these contaminants. There are two exceptions to this rule: Fe and Mn, which can easily be removed through conventional treatments (Crittenden et al. 2005). The faecal coliform limit is consistent with that of the EEC guidelines (EEC 1975). From a drinking water perspective, the limit also corresponds to what is considered to be moderately to highly contaminated water, since this parameter is not normally the treatment limiting parameter but rather an indicator of microbial contamination (Payment et al. 2000).

For domestic 3, thresholds for specific inorganic and organic contaminants are ten times higher than those of the WHO drinking standards. This is based on the assumption that an advanced water-treatment system may remove 90% of inorganic and organic contaminants. There are three exceptions to this rule: Na, Cl and SO_4, for which the seawater concentrations are considered limiting values. The same approach was applied for total dissolved solids (TDS), alkalinity and hardness. This recognizes that desalination is part of the advanced treatments available for Domestic 3. As for Domestic 2, the faecal coliform limit is consistent with that of the EEC's guideline (1975) as well as what is considered to be highly contaminated water from a drinking water perspective (USEPA 2004; MDDEP 2006). It also corresponds to well-treated wastewater (secondary treatment with disinfection), which is generally considered to be the highest contamination level water that can be used as a water source (MDDEP 2006).

For the three domestic users, all of the parameters that were not considered in the WHO standards were based on EEC guidelines (EEC 1975) and the Taiwanese classification (Taiwan EPA 1998). For the three domestic users, the threshold for oil and grease content was set as the detection limit of the partition-gravimetric method, which is 1.4 mg/l (APHA AWWA and WEF 1998), even if lower values than this detection limit are mentioned in EEC guidelines (EEC 1975).

For agricultural uses, thresholds for specific inorganic contaminants and for most conventional parameters were set according to WHO and UNEP (2006) criteria. Plant toxicity, which occurs under very specific conditions or for very specific plant species, was not considered since it has very limited impacts in terms of water functionality for agriculture (Ayers and Westcot 1985). Regarding microbiological contamination, thresholds for agriculture 1 and 2 categories were set from the risk reduction goals proposed in the WHO guidelines for wastewater use in agriculture (WHO and UNEP 2006), for unrestricted irrigation and restricted irrigation, respectively. These guidelines define the acceptable risks for crop consumers and agricultural workers and the minimal treatment that should be done on wastewater in order to reuse it for irrigation purposes. It therefore indirectly sets the quality requirements for irrigation water. This indirect approach was chosen because, to our knowledge, there is no international consensus on microbial contamination thresholds for irrigation water, as confirmed by the experts consulted during this study.

The water requirements for industry are assumed to be equal to the thresholds for the domestic 2 water category. While water quality needs for industry vary greatly, one can suppose that industries have adapted to the available water quality. This therefore implies two assumptions: (1) surface water used by industries around the world is of functional quality for domestic 2 users or better; and (2) industries have adapted to a water quality that meets their needs. This can be justified by considering that a water-consuming industry would not likely settle in an area where desalination is required. Cooling processes are excluded from this hypothesis and 1998 industrial standards from the EPRI were used to identify the few thresholds that apply to cooling water (EPRI 2003). However, some were adjusted based on typical seawater composition, which can also be used for cooling purposes.

Thresholds for water use in fisheries were mostly defined by reviewing the factors affecting fish health, as published by the FAO (Svobodová et al. 1993). The Taiwanese surface water quality standards (Taiwan EPA 1998) were also used to set these thresholds when not specified, such as the faecal coliform threshold for Aquaculture. Whenever a maximum concentration range is recommended by the FAO (1993) and the lower limit for this range is extremely low (2×10^{-4}mg/l for cadmium, for example), the functionality criterion becomes the absence of this contaminant. This is the case for cadmium, chromium, lead and zinc, which can be highly toxic to fish. The same approach was used for pesticides, which can be extremely toxic to fish. The threshold for oil and grease content was set as the detection limit of the partition-gravimetric method, which is 1.4 mg/l (APHA AWWA and WEF 1998), even if lower values are stated in FAO guidelines (Svobodová et al. 1993).

WHO guidelines for safe recreational water environments (WHO 2003) were used to set thresholds for recreational use. As per the WHO's risk analysis-based suggestion, thresholds for specific inorganic pollutants were set at ten times the thresholds for drinking water. These guidelines specify that the faecal coliform count is a very good indicator of fresh water microbial contamination. Because of its common use in many fields, this indicator was therefore preferred over intestinal enterococci, which is a very good indicator of fresh and marine water contamination but is less common in other applications such as drinking water or irrigation.

2.4 Determination of water sources

Bayart et al. (2010) and Owens (2002) suggest including surface and groundwater as distinct sources. This distinction is important since the two types of water do not necessarily serve the same users and are not available in the same amounts throughout the world. They therefore represent different scarcities—an important factor in water use impact assessment (Bayart et al. 2010). In addition, we propose the inclusion of rain as an extra source of water to enable the life cycle inventory accounting of rainwater harvesting. This would prevent the water from reaching ground and surface water bodies as well as its potential subsequent extraction. Sea water was not categorized since it can be classified as poor-quality surface water, as described below.

2.5 Definition of water categories

Eight water quality categories were created from all the quality thresholds obtained for each user. User functionalities were identified as either sensitive to microbial contamination (represented by faecal coliforms) and/or toxic contamination (most other parameters). Users were then grouped based on the level of contamination they could handle (low, medium and high). While agriculture 1 and recreation are more sensitive to microbial contamination, toxic contamination is more crucial for fisheries. Domestic 1 is very sensitive to both types of contamination, while agriculture 2 and domestic 2 (and consequently Industrial as well) are moderately sensitive to both. Finally, domestic 3 and cooling are the least sensitive, except for transport and hydropower, which do not present any quality restrictions. For each group, the more critical value was chosen for each parameter, ensuring that all user thresholds are respected within a group. This is important to ensure that all users can safely use a water category that is functional for them. However, it may also be restrictive for some users who could actually use lower-quality water for certain parameters. The consequences of this are discussed below. The quality categories were then associated with water sources to create 17 categories (see Table 4). Quality parameters have not been set for rainwater since rain is considered to serve all users. Categories were created in such a way that all the quality parameters of a given water stream must be below the thresholds for a given water category in order to be put in a category. When one parameter of the water to be categorized does not meet the specified limit for a water category, the category is no longer relevant, since only one excess contaminant can severely restrict a user functionality (high faecal coliforms, high lead content, etc.). However, while many parameters are defined for each category, it is not necessary to know the values for all parameters before categorizing a water stream. This is discussed in Section 3.

2.6 Application

To show applicability, the water category was evaluated for the world's main surface waters using available data. Specific values are presented for the Amazon basin, but all watersheds with available data were characterized. Data from the GEMStat database (UNEP Global Environment Monitoring System (GEMS) Water Programme 2009) was used. This database is currently the only available international water quality database. Although data frequency in both time and space is not fully consistent (countries report quality parameters of their choice), data is available for several countries or at a watershed scale. Only parameters with a minimum of ten samples were considered in the characterization, and the median of all samples was used for each parameter. This value was then compared to the resulting category thresholds (Tables 3 and Table A3 in the Electronic supplementary material), and possible water categories were identified for each parameter. The overall category for a water type corresponds to the best quality common to all parameters.

3 Results and discussion

3.1 Determination of water quality thresholds for each water use

The chosen thresholds are reported in Table A3 in the Electronic supplementary material (a sample of which is presented in Table 3). Each threshold is referenced, and a short rationale or comment was added whenever necessary. When no clear standard, guideline or recommendation was provided, no threshold was retained.

The procedure described above, based on the available references, was used to select the thresholds for each value, with four exceptions described herein. First, the limiting value for BOD_5 was set at 5 mg/L even though Taiwan EPA (Taiwan EPA 1998) adopted a lower value for its Domestic 1 and Swimming categories. This is based on the fact that BOD_5 less than 5 mg/L is very difficult to measure because of the uncertainty associated with the BOD analysis. Second, one exception was made to the Cooling thresholds of EPRI guidelines for the $CaxSO_4$ threshold, which is instead based on typical seawater composition. The value of this parameter is indeed equal to $10^6(mg/L)^2$ for seawater, whereas the value recommended by EPRI is $5\times 10^5(mg/L)^2$. Third, whereas iron could be regarded as an aesthetic parameter for domestic 1 due to the taste and colour it can give to drinking water, no limit was assigned in the WHO guidelines. It was therefore omitted from drinking water requirements. Lastly, the WHO's (2006) proposed agriculture pH requirements are between 6.5 and 8.4, but, the lower value was extended to 4.5 to include naturally occurring rainwater pH range (Charlson and Rodhe 1982), since it would be incoherent to characterize water as being too acidic for irrigation if it has the same pH as natural rainwater.

The selected approach favoured the use of an exhaustive list of parameters, since no rationale would support limiting the proposed thresholds to fewer parameters. While it is obvious that not all of the parameters are known for any one water use, it is best to provide a threshold for when they become available to ensure that the characterisation is as exhaustive and robust as possible (i.e., based on as many available quality parameter as possible to describe water quality). While a characterisation is possible with only a few parameters, the more parameters are used, the more relevant the water category becomes.

3.2 Determination of water categories

The 17 resulting water categories (eight surface water, eight groundwater and one rainwater) are presented in Tables 4 and 5. The different categories based on quality, associated sources and users for which each category is functional are identified in Table 4. Table 5 presents a sample of Table A5 in the Electronic supplementary material, providing an exhaustive list of thresholds for each water category.

While these categories were created by grouping user's quality thresholds and choosing the lowest value, as explained above, certain parameters were adjusted to avoid incoherence. These adjustments are described below.

The coliform parameter was adjusted to 200 CFU/100 mL for agriculture 1, instead of the 100 mg/L value previously identified, to harmonize it with recreational uses. This is justifiable as there is no solid or uniform international guideline for good quality irrigation water and the limit of 200 UFC/100 mL faecal coliforms for agriculture 1 comes from British Columbian standards (2003). The WHO presents its information based on a debatable risk assessment based on the acceptable risk of illness—a definition that may differ from one country to the next.

The sodium adsorption ratio is an important parameter for irrigation, but its guideline is a function of the conductivity or TDS parameter. At this point, it is recommended to refer to the WHO and UNEP (2006) for the threshold assessment of the sodium adsorption ratio. The relation between these parameters and the acceptable zone for agriculture functionality is presented in the Electronic supplementary material.

Cooling water guidelines are proposed for aluminium, copper and iron but are more severe than for most other users and were therefore omitted. This is based on the fact that Cooling is for once-through cooling water with a large range of water qualities. The specialists consulted as part of this study agree that a higher than recommended metal concentration is likely to, at worse, shorten the service life of the cooling equipment or require more frequent cleaning. This was considered to be within the limit of functionality for cooling purposes (Klvana 2010, personal communication). This hypothesis seems acceptable if one agrees that drinking or irrigation water can be used for once-through cooling in power plants.

Lastly, dyes were excluded since little information was found on thresholds requirements, aside from the qualita-

Table 3 Sample of quality thresholds for each user: values and detailed reference (complete in Table A3 in the Electronic supplementary information)

Parameter	Units	Agriculture 1	Agriculture 2	Fisheries	Domestic 1	Domestic 2	Domestic 3	Recreation	Cooling
General parameters									
Faecal coliforms	UFC/100 ml	100 (based on risk analysis in WHO6)	10,000 (based on risk analysis in WHO6)	10,000 (TAI98)	20 (EEC75; it also corresponds to a threshold for mandatory filtration in the Province of Québec, Canada)	2,000 (EEC75)	20,000 (EEC75)	200 (QUE10 & WHO06; TAI98's threshold for swimming is 50)	
Suspended solids	mg/l	100 (WHO06, TAI98)	100 (WHO06, TAI98)	40 (TAI98)	25 (TAI98 & EEC75)			25 (TAI98)	300 (EPRI03)
Total dissolved solids	mg/l	2,000 (WHO06; threshold for severe effect)	2,000 (WHO06)		500 (EEC75)	500 (EEC75)	40,000 (seawater is considered as a limiting case)	40,000 (seawater is considered as a limiting case)	
Inorganics									
Arsenic	mg/l	0.1 (WHO06; wide toxicity range from 0.05 to 12)	0.1 (WHO06; wide toxicity range from 0.05 to 12)	3 (FAO93; lower limit of the toxicity range)	0.01 (drinking water standard of WHO08)	0.01 (drinking water standard of WHO08)	0.1 (ten times the WHO08 standard; EEC75)	0.1 (ten times the WHO08 standard)	
Cadmium	mg/l	0.03 (WHO06: conservative limit due to its potential for accumulation)	0.03 (WHO06: conservative limit due to its potential for accumulation)	Absence (FAO93 toxicity range from 0.0002 to 0.001)	0.003 (drinking water standard of WHO08)	0.003 (drinking water standard of WHO08)	0.03 (ten times the WHO08 standard)	0.03 (ten times the WHO08 standard)	
Organics									
Benzene	mg/l			Absence (FAO93 consider the lighter oil fractions as more toxic than heavier fractions)	0.01	0.01	0.1	0.1	
Atrazine	mg/l				0.002	0.002	0.02	0.02	

Table 4 Water category functionalities per user (S=Surface water, G=Groundwater)

Quality	1	2a	2b	2c	2d	3	4	5	Rain
Sources	S or G	S or G	S or G	S or G	S or G	S or G	S or G	S or G	Rain
Quality level	Excellent	Good	Average	Average-Toxic	Average-Biologic	Poor	Very poor	Un-usable	
Contamination	Low microbial low toxic	low microbial medium toxic	Medium microbial medium toxic	Low microbialhigh toxic	High microbial low toxic	High microbial medium toxic	High microbial high toxic	Other	N/A
Domestic 1	√	X	X	X	X	X	X	X	√
Domestic 2	√	√	√	X	X	X	X	X	√
Domestic 3	√	√	√	√	√	√	√	X	√
Agriculture 1	√	√	X	√	X	X	X	X	√
Agriculture 2	√	√	√	√	√	√	X	X	√
Fisheries	√	X	X	X	√	X	X	X	√
Industry	√	√	√	X	X	X	X	X	√
Cooling	√	√	√	√	√	√	√	X	√
Recreation	√	√	X	√	X	X	X	X	√
Transport	√	√	√	√	√	√	√	√	√
Hydro	√	√	√	√	√	√	√	√	√

√ functional, X non-functional

tive toxicity information associated with malachite green (Svobodová et al. 1993).

3.3 Application

From the example described above, the water category for the Amazon watershed is classified as S3. As shown in Table 6, the combination of high faecal coliforms and suspended solids drive this classification. Results for all available watersheds worldwide are presented in Fig. 2 and the associated data and sources supporting this classification are presented in the SI. While data for all watersheds was not available, hypotheses were set out to use the closest available data, whenever possible. This classification can be used to determine the water quality entering a process (withdrawn). Similarly, the water released from a given process into the environment (e.g. an industrial effluents), can be classified combining the amount of chemicals "released to water" as reported in existing life cycle inventory (LCI) databases with the volume of water being released. This latter information is traditionally not given by LCI databases. If no primary data on the released volume are available, a hypothesis could be made on the fraction of withdrawn water that is evaporated based on industrial standards. For example, Shiklomanov and Rhoda (2003) propose a range of 5–20% evaporation in industry.

Not all parameters may be available when categorizing an industrial effluent and, it is therefore important to make an expert decision to determine the parameters that are most likely to be affected by the industry. US EPA guidelines on effluent limitations may be used to identify the sensitive parameters per industrial sector (2010). For example, when evaluating a pulp and paper effluent, parameters such as BOD and suspended solids will be more important than faecal coliforms. The effluent quality is highly dependent on the industry and national legislation, and, while industrial effluents may often correspond to category 5 as sampling has demonstrated in Pakistan and Malawi (Phiri et al. 2005; Sial et al. 2006), it may be otherwise in other regions or for other industries. For example, the pulp and paper industry in Québec, Canada, reports BOD and MES averages that meet water category 3 criteria (18.4 and 30 mg/L, respectively) making the water functional for domestic 3, agriculture 2 and cooling if the other contaminants also conform. A simple Excel tool that evaluates the resulting water category based on input parameters is provided in the Electronic supplementary material.

Water quality regulations and guidelines vary from one country to the next, and while this study attempts to advance widely accepted functionality-based categories, it is clear that certain parameters may be subject to discussion. Moreover, as with any threshold-based methodology, one should exercise good judgment when faced with a value that is close to the

Table 5 Sample of water category threshold values (complete in Table A5 of the supplementary information)

Parameter	Units	1	2a	2b	2c	2d	3	4	5
	General parameters								
Faecal coliforms	UFC/100 ml	20	200	2,000	200	10,000	10,000	20,000	
Suspended solids	mg/l	25	25	100	25	40	100	300	
Total dissolved solids	mg/l	500	500	500	2,000	2,000	2,000	40,000	
	Inorganics								
Arsenic	mg/l	0.01	0.01	0.01	0.1	0.1	0.1	0.1	
Cadmium	mg/l	0	0.003	0.003	0.03	0	0.03	0.03	
	Organics								
Benzene	mg/l	0	0.01	0.01	0.1	0	0.1	0.1	
Atrazine	mg/l	0.002	0.002	0.002	0.02	0.02	0.02	0.02	
…									

threshold. In cases of doubt, referring to the original source used to determine the threshold may help.

When creating a limited number of categories that group different combinations of eight users with specific requirements, gaps that will sometimes misrepresent the actual users for which a category is functional are unavoidable. For example, one parameter may cause a much lower-quality category to be chosen and lead to an overly restrictive list of users for which the water is functional and eventually to the overestimation of the impacts for the process effluent or an underestimation for an influent. Such cases are especially prone to occurring when guidance is not provided for some parameters for a specific user when grouped in the same category as one for which guidance is provided. However, a lack of guidance does not necessarily mean a high tolerance to a parameter but rather a lack of consensus or information on the toxic effect. Other cases are generated from threshold differences between users that are considered to have the same sensitivity to toxicity (e.g. domestic 1 and fisheries). These gaps are unavoidable with a water category strategy, unless a number of categories as large as 256 (2^8, for eight users with different quality requirements) is applied.

In order to implement this approach in LCI databases, quality and quantity information on water entering and leaving each process is necessary. Elementary flows are defined as each corresponding to a water class. While this may seem insurmountable, much of this information is actually already available. In most disaggregated ecoinvent processes (Frischknecht and Jungbluth 2007), the inventory already indicates the volume and source of water entering the process, and the amount of chemical emitted into water. The quality of water entering the process can be taken from the classification proposed in this paper through Fig. 2 and based on GEMStat data (2009). Therefore, only the released quantity of water must be collected to make the approach operational. When not available, hypotheses can

Table 6 Classification of available water in the Amazon basin

Parameter	Median value	Number of samples	Units	Lowest accepted threshold (identified from Table A5)	Accepted water category
Nitrites	0	434	mg/l	3	All
Nitrates	0.073	734	Mg N/l	50	All
Ammonia	0.2	37	mg/l	0.3	2b, 2d, 3,4,5
pH	7.9	37		4.5–8.4	All
Suspended solids	64	45	mg/l	100	2b, 3
Phosphorus (total)	0.030947	491	mg/l	0.1	All
Sulfate	5.243	259	mg/l	500	All
Zinc	0.0042	290	mg/l	2	2a, 2b, 2c, 3, 4, 5
Arsenic	0.0007	332	mg/l	0.01	All
Faecal coliforms	3,500	33	UFC/100 ml	10,000	2d, 3, 4, 5
Resulting water category					3

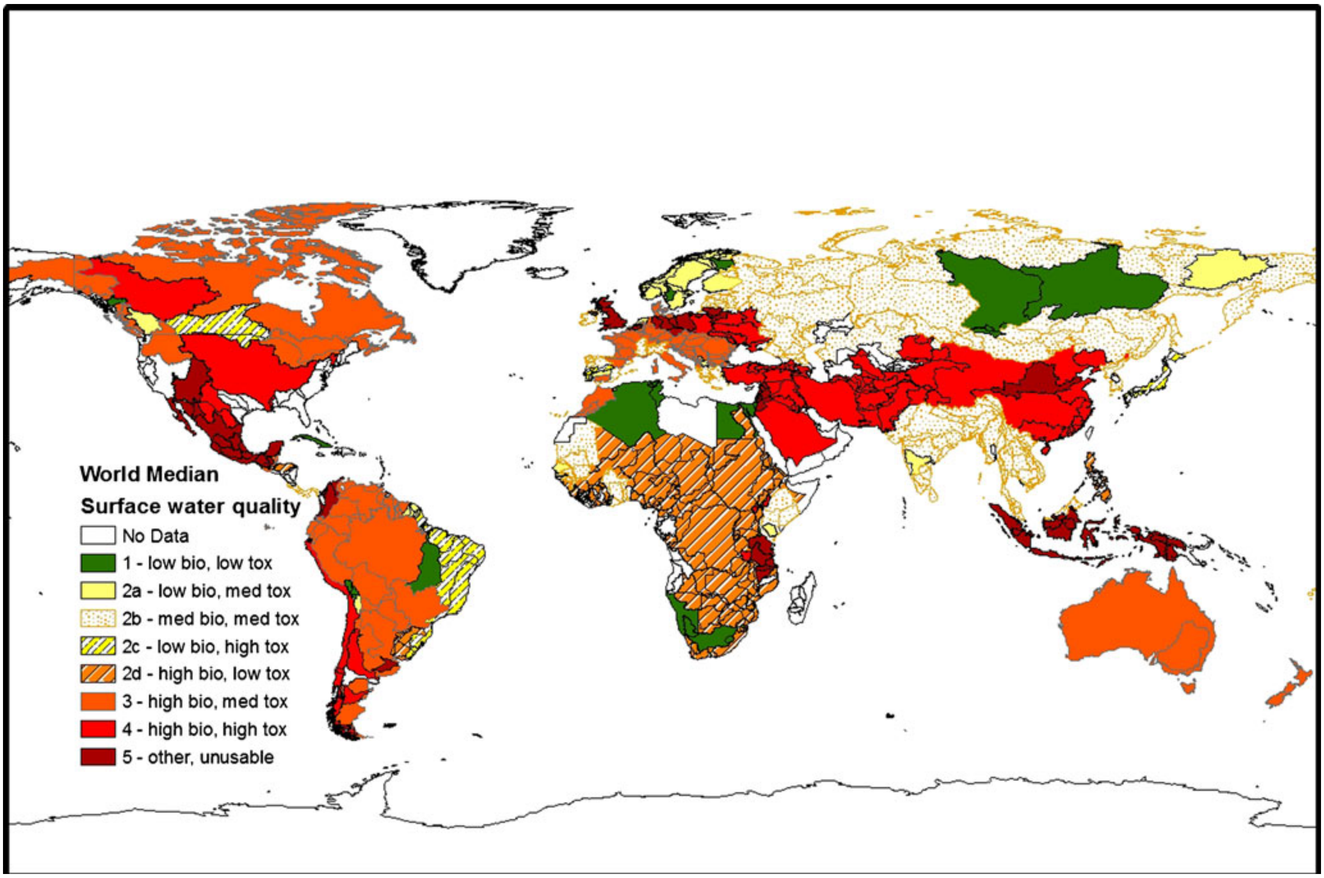

Fig. 2 Classification of the world's surface water

be formulated on the percentage of water evaporated from a process and then deducted from the water withdrawn. Alternatively, we suggest collecting generic industry data on effluent quality and assessing a default water category for each industry type. However, as previously discussed, even within an industry, the effluent quality can vary depending on geographical location and the level of regulation. Effluent regionalization could be carried out by allowing the user to choose between good, average or bad quality effluents, each representing the extremes and the average of worldwide practices for a specific industry.

These water categories can serve as elementary flows in a database such as ecoinvent (Frischknecht and Jungbluth 2007) and enable the quantification of the functionality loss associated with withdrawn and consumed water or the water released at a lesser quality. This functionality loss should also consider scarcity and the distribution of the different users sharing the same resource in order to assess the actual cubic meter of water whose function has been lost, as carried out in (Boulay et al. 2011), whose methodology assesses impacts on human health based on a loss of functionality. One interim use for this approach would be to apply the categories as a quantitative enhancement in LCI reporting instead of just total water use or the relatively qualitative categories in the Australian example cited above. Such results of water withdrawn and discharged by category can be used in a MCDA decision making framework until such time as the mechanistic linkages and data necessary for full integration in proposed endpoint models are established.

4 Conclusions

This method first determined 11 different human users based on the difference in water quality each of them require. In total, 136 quality parameters and their associated thresholds were then used to guide the creation of 17 distinct water categories based on the source, quality and potential users. These categories were created in an attempt to operationalize the functionality-based water categories proposed by Bayart et al. (2010). The resulting inventory method fills the existing gap in LCA associated with the assessment of the potential impacts of the degradative use of water by providing the elementary flows necessary to evaluate a loss of functionality for human users. The result constitutes a step forward in extending these classifications for worldwide acceptance as compared to existing classifications (EEC 1975; Overseas Environmental Cooperation Center 1998; Taiwan EPA 1998). Moreover, it was found that only one additional data is required to operationalize this methodology in existing databases: the volume of water that is released. This latter parameter could, however, be approximated based on industrial evaporation hypothesis.

While this article has explored water category development, limitations regarding the feasibility of grouping the quality requirements of different users into a manageable amount of categories were determined. Along with the simplicity of water categories, choices and simplifications have to be made and may lead to the overestimation or underestimation of impacts when used with an impact assessment method. These limitations could be overcome if functionality-based inventory flows were to be considered directly, avoiding the water category simplifications. Inventory information would then provide a volume of water, the source and the different users it can be functional for. This information would be obtained from a quality parameter comparison assessment with the user thresholds proposed here, resulting in a functionality vector in which each element represents the functionality or not (1 or 0) of the water type for a particular user. The functionality comparison between influents and effluents could then enable impact assessment from functionality loss, as already advanced by Boulay et al. (2011), but avoiding the error associated with modelling gaps from water categories.

Another limitation associated with assessing user functionality is the lack of internationally recognized thresholds for many users and parameters. While there is generally good guidance for domestic users and fisheries, agriculture quality requirements remain few and inconsistent throughout the world. Moreover, the threshold approach can always be criticized at values near the threshold, since reality is rarely black or white when it comes to water functionality for a specific use. However, at this point, method developments do not capture the subtleties of the impacts associated with quality degradation, apart from functionality loss.

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