On the potential of Life Cycle Assessment in water resources management: focus on groundwater

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Abstract In water resources management the environmental benefits and impacts of projects have to be assessed, a task that can hardly be achieved with the methodologies that are available in current practice. Life Cycle Assessment (LCA) is the standardised method for measuring the environmental impact of any product or service. After quantifying all associated emissions and the consumption of resources, this impact is expressed with respect to a few common impact categories. These are supposed to reflect major societal and environmental priorities. However, despite their central role in environmental processes, hydrological aspects are only rarely considered in LCA at present. One neglected aspect is groundwater; although groundwater is the most extracted raw material in the world, it is virtually ignored in LCA. To overcome this deficiency, an interdisciplinary approach is needed. This contribution reviews the rudimentary state of the art and develops the initial steps for approaching groundwater quality and quantity issues within a LCA framework. A major focus is the issue of whether, and how, a natural water system can be considered a safeguard object within impact assessment, assuming that it represents a separate receptor. Resulting enhanced LCA will complement integrated water resources management (IWRM) with a focus on processes within a life cycle perspective of specific products and services.

Key words groundwater; Life Cycle Assessment (LCA); environmental impact

BACKGROUND
Around the world, pressure on groundwater resources is escalating. Combined demands, such as an increasing human population and its associated needs, industrialisation, urbanisation, and irrigation requirements compound the problem (UN, 2006). The European Water Framework Directive recommends that we “provide for sufficient supply of good quality surface water and groundwater as needed for sustainable, balanced and equitable water use”. Gleick (2003), however, raises concerns that “the failure to meet basic human and environmental needs for water is the greatest development disaster of the 20th century”. Natural water bodies are dynamic systems that can be very resilient, but also very sensitive, to human impact as well as to climate changes that raise the probability of floods and droughts. The decreasing reliability of predictions about the availability of these freshwater resources augments the importance of the comparatively stable and huge groundwater reservoir in the subsurface. As groundwater is an elementary, but also sensitive and uncertain resource, there is a growing need to understand and sustainably manage it. Essentially, harmful effects of human activities and industrial processes must be minimised.

For a structured, quantitative estimation of environmental impacts from human activities and industrial processes, Life-Cycle Assessment (LCA) offers a standardised conceptual framework (ISO 14040 series). It provides a detailed “cradle-to-grave” examination of the life cycle of a product or service, so as to obtain a cumulative estimate of all the environmental burdens involved. In principle, such an approach needs to be capable of balancing potential damage and benefits to groundwater bodies resulting from all phases of a product’s life cycle.

Traditionally, hydrological impacts are of only minor concern to LCA practitioners. This may be attributed to the fact that LCA has its roots in the industrial sector. The inspected production processes are thought to have little influence on the subsurface (e.g. Heuvelmans, 2005). Emphasis is placed instead upon environmental issues that reflect expected societal priorities, such as global warming, land use, and/or acidification. Further so-called “impact categories” that LCA also typically considers include human health impacts (e.g. carcinogens) and depletion of natural resources (e.g. crude oil consumption). Interestingly, with a global annual withdrawal rate of about 700 km³, the world’s most extracted raw material is groundwater (Zekster & Everett, 2004).
In the following section, we will not only focus on the central role of groundwater as a “raw material”, but also as a receptor. A more detailed portrayal of common LCA practice will be provided, revealing that the hydro(geo)logical point of view on this matter is largely missing. This deficit leads us to a highly pertinent research need: more complete and realistic consideration of groundwater in LCA. We call for the development of a conceptual framework that consistently integrates the burdens and benefits for groundwater bodies into the LCA methodology. Subsequently, required fundamental working steps and recommendations based on a dialectic view from both LCA professionals and hydrogeologists are provided.

GROUNDWATER: THE HIDDEN SAFEGUARD ENVIRONMENT

Groundwater used as freshwater is commonly extracted from shallow aquifers within the upper 100 metres of the Earth’s crust. In fact, water is also found at much greater hydrogeological depths, and we are only using an estimated 15% of the entire global storage of groundwater that is in the range of several tens of million km$^3$ (Griebler & Mösslacher, 2003). Close-to-ground flow velocities are in the order of metres per day. In contrast, deep groundwater moves extremely slowly, can age for thousands of years, and hence represents a non-renewable resource. Among these resources, Margat et al. (2006) also count those groundwater systems with no, or very little, recharge. In EU countries, groundwater provides nearly 70% of piped water supply, indicating the central role it plays for the European community (Fig. 1).

![Fig. 1 Share of groundwater supplies (%) in Europe, excluding the Russian Federation (modified after Vrba & Lipponen, 2007).](image)

Groundwater is a major component of the hydrological cycle. In watersheds, it dynamically interacts with subsurface water bodies and, via the overlying topsoil by recharge and precipitation, with the atmosphere. The uppermost aquifers, which represent the most dynamic and important groundwater resources, are simultaneously most seriously exposed to anthropogenic impacts. Uncontrolled aquifer exploitation can significantly disturb the natural water balance. In many countries, groundwater quality is affected by coastal saltwater intrusion (e.g. Spain, Turkey) and by the discharge of pollutants from point and diffuse pollution sources (EEA, 2000).

Beyond its economic relevance as a resource and its connection to the visual, aboveground environment, the groundwater found worldwide supports unique and sensitive ecosystems. The habitat of micro-organisms is sustained by special physico-chemical conditions (absent sunlight,
low O₂ content, pore/fracture scale). According to Gold (1999), the total biomass in groundwater is even comparable to that above the ground. Subsurface organisms are crucial for triggering the chemical turnover (e.g. contaminant degradation, natural attenuation), for the generation of natural resources (e.g. methane hydrates), and are of central concern when considering underground deposition (e.g. radioactive waste, CO₂) (Griebler & Mösslacher 2003).

**LIFE CYCLE ASSESSMENT (LCA): CONCEPT AND CRITICS**

This standardised method allows for the recording, quantification, and evaluation of environmental damage intrinsically connected with a product, a procedure, or a service. It has been developed using the principles of material and energy balances to describe full resource usages and environmental impacts that are associated with the underlying supply chains. The four distinct procedural elements of LCA are structured, according to the ISO standard, as follows: (1) **goal and scope definition**, which determines the objectives and frame of the study, describes the system studied (and its boundaries), and the options that will be compared; (2) during the **inventory analysis** (LCI) the streams of resources, material, and energy of the respective process steps are recorded, and this step quantifies the inputs (e.g. raw material) and outputs (e.g. waste, pollution) that cross the boundary between product or service system and the environment; (3) **life-cycle impact assessment** (LCIA) sorts and assigns the data from the inventory analysis into predefined impact categories, in order to evaluate the magnitude and significance of the potential environmental impacts by category-specific indicators; and (4) during the final **interpretation** phase, the quantitative results, their meaningfulness and restrictions are comprehensively discussed to derive recommendations and conclusions (ISO 14040 and 14044, 2007).

![Fig. 2 LCA components (see ISO 14040, 2007; ISO 14044, 2007).](image)

LCA is a highly multidisciplinary, pragmatic approach that attempts to create a holistic, and thus simplifying, view of natural and industrial processes. Ordinarily, even the most detailed studies exhibit significant uncertainties and provide only ballpark figures of the real situation. This is due to incomplete data when describing elementary flows in industrial processes, as well as the impossibility of accurately explaining the spatial and temporal dynamics of natural systems (e.g. Hellweg et al., 2003). The method by which LCA is carried out for a specific product offers multiple degrees of freedom, so that there are several distinct concepts. When applied to a certain product, these may yield significantly different results. The scientific community has had
numerous open discussions that reveal great necessity for research into harmonising divergent LCA concepts in order to balance their different emphases and to bridge their pre-existing gaps. Critics refer to frequent use of subjective assumptions on industrial process chains, disputable system boundaries and, particularly, impact assessment (e.g. Guinee et al., 2002).

Naturally, both the pragmatic philosophy, as well as the perpetually immature character of LCA, hampers its credibility. In particular, rough approximations of natural processes and the crude blending of apparently irreconcilable aspects into single impact indicators are not acceptable to most natural scientists. However, LCA is the most widely accepted and modern method of quantifying, structuring, and comparing environmental impacts. The benefits relate to its ability to condense information to a level on which decision makers can absorb it. Consequently, LCA has its highest potential when it a priori integrates scientists from affected disciplines/sectors and clearly formulates its demands for inputs from the respective field.

GROUNDWATER WITHIN LIFE CYCLE ASSESSMENT

Groundwater quality and quantity issues are rarely addressed in LCA. If they are considered, we find different concepts depending on which of the numerous LCA studies, reports, and approaches is being examined. Only an overview of the most relevant ones which have so far been identified will be given here. During the last decade, the environmental assessment of agricultural activities in particular increased the awareness of the role of groundwater as a safeguard environment. However, groundwater is typically considered a component or transmission medium of other impact categories rather than as a self-contained impact category or receptor (e.g. Haas et al., 2000). Other studies, even when water supply is of central concern, simply place raw water extraction from aquifers beyond the system boundaries (e.g. Landu & Brent, 2006). Currently, an UNEP/SETAC Life Cycle initiative is dedicated to the use and depletion of water resources.

Groundwater quality

Of major concern has been potential damage to water quality. For example, leaching of pesticides or nitrate into the ground due to extensive farming is commonly assessed with respect to its significance to human health toxicity, ecotoxicity, and/or eutrophication. Although uncommon, inventory models in frameworks such as in the Swiss “ecoinvent database” (Frischknecht et al., 2007) distinguish the conditions of different aquatic systems. Agricultural emissions or pollutants from landfills enter soil, groundwater (emission media “deep subsoil”), or surface water. Such a distinction is of essential importance, since contaminants which may be degraded instantaneously in toxic surface water, for example, can spread in the subsurface over decades. Geisler et al. (2005) worked out an LCA methodology to assess the variability of pesticide leaching to groundwater in EU agriculture based on selected scenarios and presented a case study for the pesticide Atrazine. Their approach relies on a process-based model that accounts for site conditions, soil retention capacity, and agricultural use. Thus it is possible to account for the high spatial dependency of the impact of agricultural activities on groundwater. Recently, further efforts in this direction have been presented by Birkved & Hauschild (2006), reflecting the growing interest in this topic.

Besides pollutants from agricultural activities, there are further hazardous contaminants threatening water quality. These include the salinity increase from road de-icing salt, potential threats from sewage sludge or recycling materials in road construction. Hellweg et al. (2005b) introduced a site-dependent fate assessment box-model of heavy metals to the LCA context. They modelled steady-state transport of such compounds from landfills into the groundwater, which was tested at an exemplary site, but without further inspection of the parameter uncertainties. Ubiquitous distribution of heavy metals due to combustion, which is recognised as an increasing threat for soils, has not yet been found relevant in LCA. Even if atmospheric pathways and accumulation in soils are considered by rough models, transport to groundwater bodies has not been included.
Groundwater contamination from organic contaminants, such as chlorinated hydrocarbons or mineral oils, mainly arises from public, private, or industrial activities. Such contaminated sites are widely known in Europe. According to the EU Groundwater Directive, any new damage to the subsoil environment by such contaminants is not allowed. In principle, this means that direct groundwater contamination in or at the end of industrial process chains should not occur. However, improper or careless handling, accidents with raw materials containing hydrocarbons, and illegal dumping frequently happen within the EU (EEA, 2000), and are even more common in emerging economies. Although not consistently considered in LCA so far, mining activities and oil pumping seriously threaten groundwater bodies on a global level. Such pollutants can yield highly toxic contaminant plumes, which require long-term remediation activities to achieve a “good status” using criteria from the EU Groundwater Directive (2006). The application of such remediation technologies is associated with so-called “secondary impacts” (e.g. energy demand for continuous pumping at wells), which have been the subject of only a limited number of studies so far (e.g. Bayer & Finkel, 2006).

**Groundwater quantity**

Groundwater is threatened by any human activity that disturbs the hydrological water balance between aquifers and the coupled compartments of the hydrosphere. However, groundwater systems have an enormous buffer capacity. In dynamic, broad watersheds, local or short-term water shortages may easily be dampened. Variations of the groundwater level are essential factors for soil genesis, and can accelerate the conversion and transport of substances. Such circumstances complicate the establishment of generally valid criteria for evaluating the potential of hydrogeological interventions to cause damage.

One of the initial steps in emphasising groundwater quantity issues in LCA was made by van Ek et al. (2002), who discussed a new impact category, “desiccation”, to account for freshwater deficits. The objective of their approach, however, is closely related to other common baseline impact categories: examining the potential impacts of groundwater extraction on aboveground ecosystems. Strictly speaking, in this way groundwater systems are not considered to be safeguard objects, rather sinks or transmitters/factors for other ecological endpoints in the cause–effect chain (Hellweg et al., 2005a). Thus, potential damages to aquifers as a resource and their own ecosystem are ignored. One prominent example is seawater intrusion, which threatens coastal aquifers due to excessive pumping. It can lead to long-term threats to groundwater as a freshwater resource, as well as destroy its ecosystem. Further, in the approach used by van Ek et al. (2002), the consequences of groundwater extraction for irrigation or water supply are exclusively considered. Any other potential (in)direct negative consequences, such as decreased recharge by hardening/sealing of the surface or artificial drainage, are neglected. Impacts from dams for hydropower or irrigation water storage are also not included. Unfortunately, no additional work can be found that further develops van Ek’s approach, so that the impact category “desiccation” seems to still be in a premature stage.

Water quantity issues that consider groundwater as a resource are commonly included in the baseline impact category “(extraction/depletion of) abiotic resources” (SETAC Europe, 1999; Guinee et al., 2002). Many LCA studies, however, do not distinguish between water sources. This would be essential to distilling meaningful, compartment-specific indicators. Commonly, the underlying concept follows a “less is better” principle, that is, the less (ground)water industrial production processes consume, the better for the environment. However, in several countries (e.g. Switzerland, Germany, Iceland) the groundwater resource is not scarce, and thus groundwater consumption for industrial, agricultural, or drinking water does not inevitably lead to environmental harm. As mentioned above, anthropogenically accelerated groundwater flow may even yield higher subsurface mineralisation rates, improving the availability of nutrients and degradation of contaminants. In the context of abiotic resources, groundwater is treated either as a fund, which stands for a resource that can be replenished within the range of a human life, or as deposit, if it is fossil water (Guinee et al., 2002).
Owens (2002) recommends not only focusing on the quantity of water removed from the environment, but also incorporating the (clean) water that is returned (e.g. after treatment, for cooling). This is to obtain the net water quantity removed from the environment. Though his report focuses on water in general, it includes promising further categorisations, which can be applied to the processing of groundwater in LCA. Owens (2002) suggests distinguishing between water use and consumption. While the first describes the portion of water that is returned back into the water body it stems from, the latter is the quantity of water that is lost due to evapo(transpi)ration or product integration.

FRAMEWORK FOR CONVERGENCE

The environmental assessment of technical/industrial systems is increasing in importance due to modern environmental regulations. These regulations, which include the European IPPC or Water Framework Directive, require measures to prevent or, if this is not feasible, reduce emissions to achieve a high level of environmental protection. The actual inappropriateness of standard LCA in comprehensively assessing the impact to aquatic environments leads to numerous tasks which are required to achieve convergence of LCA practitioners and hydro(geo)logists. Only with a more consistent consideration of the safeguard environment groundwater in LCA will it be possible to compare products with respect to their direct and indirect hydrogeological effects. Decisions that are made based on such a comparison (e.g. preference of one product or service over the other; improvement of product to decrease potentially adverse affects to groundwater bodies in a life-cycle perspective), will ultimately govern groundwater management. This would allow for decision-making that includes groundwater issues in LCA and thus prevents unbalanced solutions for product or service provision.

A fundamental problem for incorporating groundwater issues into LCA is that no general metrics exist for evaluating impacts on water quality and quantity. None of the available hydrological or hydrogeological perspectives is consistent with the pragmatic objectives of LCA. Groundwater, like any other natural water resource, has to be considered as an element of the complex hydrological cycle, which has unique time- and space dependent features that are known only to a small extent. In fact, reliable description of actual and future status is highly uncertain, and, consequently, so is the prediction of potential effects. Uncertainty in characterising status and effects are adverse conditions for estimating and comparing impacts. So even if hydrological indicators have been developed, they are neither fully apposite for life cycle impact assessment, nor can they be exactly quantified.

Compared with the standard LCA approach for calculating air emissions (e.g. CO$_2$, photo-oxidants) used to derive estimations of impacts on global warming, ozone layer depletion, etc., the volume of water used during the life cycle of a product can not be just summed up. The related impacts will depend highly on the conditions of the aquifer from which the water is abstracted. This means that, for computing groundwater quantity and quality impacts, a sufficient spatial resolution of the natural conditions is first necessary. Also, during the inventory analysis in LCA, consumptions and emissions have to be recorded according to their space dependencies. Accordingly, it seems reasonable to refer to fixed time periods (e.g. per year). Recent research in the LCA-field includes the aspect of regionalization in inventory, impact assessment, and software development. This development meets the needs of regionalised groundwater impact assessment and allows future integration into common LCA-methods and software.

The UNESCO/IAEA/IAH Working Group, which was part of the Sixth Phase of the International Hydrological Programme, suggested so-called Groundwater Resources Sustainability Indicators which are interesting from the LCIA perspective (Vrba & Lipponen, 2007). Several indicators are formulated that describe particular aspects of the groundwater system and/or processes, and are based on quantitative and qualitative aggregation of selected descriptive variables. They are computed as relative, normalized values. For example, quantities of annually available or exploited groundwater volumes are scaled with respect to total available volumes. In
order to compare the degree of country-specific exploitation of groundwater, the total volume of groundwater abstracted is normalized by the annual recharge or by the total exploitable resources. Such sustainability indicators are crude but potentially valid for first step labelling of the situation, the actual hydrogeological stability or imbalance. Changes in indicator values, affected by human intervention, could be interpreted as impacts in the sense of LCIA. Given as relative values, changes of different selected indicators become comparable.

As another example, groundwater quality is not judged according to specific contaminant concentrations, but instead based on the question of whether remediation is required or not. This is a very general, potentially nebulous characterization but also much more suited for LCA than a pure hydrochemical description. In fact, comprehensive and reliable hydrochemical groundwater quality assessments are only available for case studies, as rough evaluations on a large scale, and can hardly be combined for the manifold existing contaminant types. Furthermore, groundwater quality can not be evaluated exclusively with respect to, for instance, unacceptably high contaminant concentrations, but must be determined with respect to the desired quality as well. A main factor is the cultural perspective of the local population regarding the extent of damages that are acceptable. The degree to which influence on groundwater quality improves or worsens the actual situation can best be considered from an economic point of view and evaluated in terms of the remediation effort necessary to restore an aquifer. However, this approach raises further questions: How are we to deal with the long timeframes of groundwater remediation? To what extent can we consider highly contaminated aquifers as “spoiled” and lost? And, on the other hand, how large is the resilience capacity of an aquifer for recovery?

These sustainability indicators are promising, but limited to a single-sided economic point of view. It is somehow presumed that (socio-)economic interferences reflect ecological effects. This is not the whole story. Ecological damages to dependent ecosystems can occur much earlier than direct threats to society are recognized, and potentially vice versa. Such indicators only consider groundwater as an abiotic resource which is prone to be depleted. As both terrestrial and aquatic ecosystems are in several cases directly linked to shallow groundwater levels, impacts of these effects have to be considered separately. Furthermore, groundwater bodies themselves host great ecosystems which have not yet been sufficiently studied. We see here one of the major research tasks fundamental to a more realistic consideration of groundwater in LCA. Emphasis has to be placed on the “safeguard environment groundwater”, with respect to both its central role for human and ecological users and its role as receptor. This follows the Groundwater Directive (2006, §2), which recognises that “Research should be conducted in order to provide better criteria for ensuring groundwater ecosystem quality and protection”.

In this first phase for incorporating a hydrogeological perspective in LCA, we identify three major criteria deemed suitable for quantifying and comparing impacts on different spatial scales. Impact can only be quantified according to relative changes which, naturally, depend on the actual situation. For example, threats to contaminated aquifers are considered less severe than to clean ones. The criteria represent a first categorization which is useful with respect to both quality and quantity issues.

1  **Resilience capability** This criterion is needed to characterise whether an aquifer is sensitive and/or can recover from human influences. For example, worst case scenarios include exploitation of fossil groundwater resources, which may also lead to compaction of the aquifer, and pollution by persistent, synthetic organic compounds. However, if (excess) water is extracted from highly dynamic and seasonably renewed reservoirs, low or no negative impacts can be expected. We propose a functional relationship between stress and damage (Fig. 3); there is a certain range within the buffer capability of natural systems in which the anthropogenic water cycle does not harm the hydrological cycle. If the pressure is increased to a certain degree, damage will result. Beyond a certain high pressure (e.g. level of over-use), this damage will, however, decrease and level off (e.g. in highly depleted or contaminated aquifers).
Ecological/socio-economic relevance  It is reasonable that, when comparing different aquifer systems, a criterion should be their overall relevance with respect to mainly dependent ecology and economy. For example, depletion of fossil groundwater resources will represent less threat to dependent aquatic and terrestrial ecosystems than in wetlands, while an aquifer in a metropolitan area will be much more relevant in a socio-economic perspective. Therefore, a ranking is needed to enable comparison among different subsurface environments.

Level of control  Even if we could much more accurately predict the conditions and responses of groundwater systems to human intervention, it still would be difficult to define one specific measure for adverse effects. They can be manifold and, what is more, are rated everywhere subjectively, according to social, technical, economic, ecological, and other considerations. Instead of amalgamating all kinds of supposed effects together to form a surrogate, the local, regional or country-specific level of control is suggested as a criterion. It is assumed that for a specific case, regulation mechanisms exist which realize “good” and sustainable practice and avoid adverse effects. The level of control depends on both the hydrogeological features of the aquifer as well as on knowledge and capacity for adequate management of the responsible actors. If these components are adverse, the risk of taking arbitrary and harmful actions is high. Considered within LCIA, this perspective will tell us whether using and consuming water in certain regions is preferable due to better control or not. The question of what subjective arguments underlie the control is not in the foreground. Instead, it is assumed that the communities most attached to and most dependent on the respective groundwater resources are best qualified to determine the control objectives themselves. In this case LCIA would profit from existing IWRM studies worldwide.

EXAMPLE  As an illustrative example, we shed some light on the European tomato market. In the study case, a Swiss retailer asks how to rank tomatoes of different origin with respect to the related environmental impacts. Of special concern in the life cycle of many agricultural products is the use of water during the cropping phase. This is most serious in water-scarce areas where irrigation consumes a bulk of the limited available (ground)water resources. Accordingly, this aspect is also in the fore of this assessment: The tomatoes stem from different climatic regions of different (ground)water availability, and also the cropping techniques may be distinct. For example, we obtain a water use of 25–30 L per kg tomato for countries such as The Netherlands and Switzerland, whereas those tomatoes that originate from Spain, Italy or Morocco carry a burden of about double this value. The reason for this difference is not directly the climate but rather the regional variability of cropping practice, as non-organic fresh tomatoes are mainly sourced from greenhouses: high-end greenhouses in the northern regions achieve higher water use efficiency than those in the southern regions.
For the impact assessment, we apply the method of Pfister et al. (2009). This method is designed to complement the LCA Eco-indicator 99 method (Goedkoop & Spriensma, 2001) by modelling the impact pathways of damages to three areas of protection (AoP): human health, ecosystem quality, and resources. A major task is to find a common ground, a reference metric that can be utilized to combine the different AoPs. Consumption of groundwater deposits or over-use of stocks can, for example, be assessed by attributing surplus energy to the unit of water consumed. This valuation enables the impact on future users to be accounted for. Surplus energy is the additional amount of energy required by a potential backup technology to provide the resource in future. Here, we select as the ultimate backup technology, desalination of seawater.

Impacts on the natural environment (“ecology”) are expressed by combining vegetation vulnerability to water shortage and regional water availability. The derived impact factors are measured as potentially damaged fraction of an area per unit of water consumed. This is in line with common approaches to quantifying impact caused by land use. Finally, damages to human health are assumed to be primarily caused by lack of water for agricultural production. Accordingly these are measured in disability adjusted life years lost (DALY). This impact pathway considers the population vulnerability to the lack of freshwater for agricultural production, the resulting health impacts, and a water stress index. Finally, the impacts from the three AoPs are aggregated to Eco-indicator points based on defined weighting schemes.

The results of the impact assessment of water use are shown in Table 1. The relevant production areas are plotted on the maps depicted in Fig. 4. The severity of water use in Fig. 4(b) is expressed in Eco-Indicator 99 (EI99HA) points/m³, which is compared to the characterization of groundwater resources based on WHYMAP (2008).

### Table 1 Impact assessment for example study on tomato production.

<table>
<thead>
<tr>
<th></th>
<th>EI99HA impact [points/ton]</th>
<th>% depletion</th>
<th>% ecosystem quality</th>
<th>% human health</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morocco</td>
<td>47</td>
<td>65</td>
<td>30</td>
<td>5</td>
</tr>
<tr>
<td>West-Sahara</td>
<td>11</td>
<td>–</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>Spain (Almeria)</td>
<td>30</td>
<td>93</td>
<td>7</td>
<td>–</td>
</tr>
<tr>
<td>Italy (Sicilia)</td>
<td>15</td>
<td>94</td>
<td>6</td>
<td>–</td>
</tr>
<tr>
<td>Netherlands</td>
<td>0.3</td>
<td>–</td>
<td>100</td>
<td>–</td>
</tr>
<tr>
<td>Switzerland</td>
<td>0.4</td>
<td>–</td>
<td>100</td>
<td>–</td>
</tr>
</tbody>
</table>

Fig. 4 (a) EI99HA-based regionalized impact assessment for tomato example; (b) WHYMAP-based delineation of groundwater-stressed areas in Europe (WHYMAP, 2008). In Spanish and Moroccan production areas WHYMAP indicates groundwater depletion.
The results in EI99HA indicate that in very water scarce regions such as Morocco and southern Spain the impact from water use is most critical. Accordingly, WHYMAP reports major groundwater depletion in these areas. The regional variability shows options to shift tomato production from the water scarce areas to, for instance, Eastern Europe where specific water impacts are lower. Clearly, LCA results can help to inform the hydrologist about the importance of water use in tomato production. It can aid supply chain managers to source tomatoes from environmentally better suited areas. This assessment also can be utilized by local water managers in Morocco or Spain as an argument for growing different crops or developing another industrial sector/economic activity, since tomato growing appears to be comparatively unfavorable in an international context. By assigning water volumes to favorable sectors, LCA could also be the basis for solving water allocation problems with different stakeholders, while also including other environmental aspects.

OUTLOOK AND CONCLUSIONS
LCA stands for indirect groundwater management by supporting goal-oriented consumer behaviour that aims to reduce pressure on natural groundwater systems. By developing a hydrologically-based assessment of potential impacts from human interaction with aquifers, “greener” products can be prioritised. More sustainable and environmentally friendly groundwater management is the result. When reviewing the state-of-the-art in consideration of water, and in particular groundwater, in LCA, however, it is revealed that substantial research is needed to develop a consistent methodology. Compared with standard impact categories within LCA, water, and especially groundwater, is extraordinary. In contrast to other abiotic resources such as crude oil, it can be replenished. In contrast to CO₂ emissions, there exists an immense spatial dependency of threats to natural water bodies. The total freshwater resources stored in the ground are immense, but not evenly distributed and often scarce in regions of high demand. Setting up functional relationships in order to derive a generally valid and practicable evaluation is tedious due to the complex, insufficiently understood, and uncertain natural processes involved.

The assessment criteria suggested here represent a first step to stimulate discussion and further research in this direction. Essential improvements are necessary within an interdisciplinary context that combines a pragmatic view of LCA and process-based hydrology. Existing inventories of production processes in LCA have to be extended with the inclusion of a distinctive representation of water and groundwater. It is clear that this can only be achieved step-by-step, for example starting with case studies on agricultural products where the role of groundwater due to irrigation, contaminant leaching, and nitrate is relatively high. While in the near future a generalized and practicable method will be necessary, the ultimate goal has to be a holistic assessment metric that is globally scaled.

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