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Implementing groundwater extraction in life cycle impact assessment: characterization factors based on plant species richness for the Netherlands

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Abstract

An operational method to evaluate the environmental impacts associated with groundwater use is currently lacking in Life Cycle Assessment (LCA). This paper outlines a method to calculate characterization factors that address the effects of groundwater extraction on the species richness of terrestrial vegetation. Characterization factors (CF) were derived for the Netherlands and consist of a fate and an effect part. The fate factor equals the change in drawdown due to a change in groundwater extraction and expresses the amount of time required for groundwater replenishment. It was obtained with a grid-specific steady-state groundwater flow model. Effect factors were obtained from groundwater level response curves of potential plant species richness, which was constructed based on the soil moisture requirements of 625 plant species. Depending on the initial groundwater level, effect factors range up to 9.2% loss of species per 10 cm of groundwater level decrease. The total Dutch CF for groundwater extraction depended on the value choices taken and ranged from 0.09 to 0.61 $m^2 \cdot yr/m^3$. For tap water production, we showed that groundwater extraction can be responsible for up to 32% of the total terrestrial ecosystem damage. With the proposed approach, effects of groundwater extraction on terrestrial ecosystems can be systematically included in LCA.

Introduction

Groundwater accounts for more than 98% of available freshwater resources. Approximately one-fifth of the total amount of water used for drinking purposes, for industrial cooling, for agricultural purposes, or as process water comes from groundwater (1). Excessive groundwater withdrawal results in a lowering of the groundwater level, causing phreatophytic stress for both natural and agricultural vegetation (2). This, in turn, may have a significant impact on the number of terrestrial plant species that could occur within the vegetation communities affected (3-6).

Until recently, an operational method to evaluate the environmental impacts associated with water use was lacking in Life Cycle Assessment (LCA). Therefore most case studies left out water use as an impact category, even if water withdrawal was identified as a large inventory flow (e.g. 7,8). If water use was incorporated in the impact assessment, it was usually addressed by simply taking the inventory data, i.e. the total amount of water used (e.g. 9,10).

Recently, efforts have been made to incorporate water use in LCA, firstly by means of reviewing possibilities and setting up frameworks (11-14). Milà i Canals et al. (15) provide a midpoint approach relating water use to the availability of freshwater resources for further human use after 'reserving' the necessary resource for ecosystems (water stress indicator). Van Ek et al. (16) investigated various hydrological models and a groundwater level-effect curve to predict the change in nature-value as an effect of desiccation due to groundwater extraction. Specific characterization factors were, however, not provided. Pfister et al. (17) introduced a method to address effects of freshwater consumption on biodiversity, expressed as the vulnerability of vascular plant species, and calculated impact indicators to be used in life cycle impact assessment (LCIA). They assumed that any water that is used can directly be replaced by precipitation, disregarding dynamic soil interaction processes. Furthermore they used the net primary production which is limited by water availability as an indicator for ecosystem quality, and related this to the potentially disappeared fraction of species (PDF).

The aim of the current study is to develop a method to address the effects of groundwater extraction on the species richness of terrestrial vegetation in an LCIA context. Characterization factors, expressing the change in potentially not occurring fraction of plant species (PNOF) due to a change in extraction of groundwater, are derived with the intention to be incorporated in LCA. We apply a method comparable to the one applied by Van Zelm et al. (18) for acidification, where forest plant species loss was determined by coupling a fate model with multiple regression equations that predict plant species occurrence. In the context of groundwater extraction, the fate model, applicable for the Netherlands, deals with the lowering of the average groundwater level per unit of groundwater extraction, and includes processes such as precipitation, evapotranspiration, and soil permeability. Plant species richness is linked to the lowering of the groundwater table by means of a response curve based on the occurrence of 625 plant species in relation to various abiotic variables, including soil moisture content, in the Netherlands. To assess the applicability of the characterization factor derived, we determine the contribution of groundwater extraction to the total terrestrial ecosystem damage resulting from tap water production.

Methods

Characterization factor. The characterization factor for groundwater extraction (CF in $m^2 \cdot yr/m^3$) in the Netherlands is defined as the change in the number of plant species due to a change in extraction of groundwater over a certain area. The CF consists of a fate factor (FF in $m^3 \cdot yr/m^3$) and an effect factor (EF in 1/m). To account for spatial variation in FF and EF, a spatially explicit grid-based approach was followed whereby FF and EF were multiplied per grid cell and then summed over all grid cells *i*:

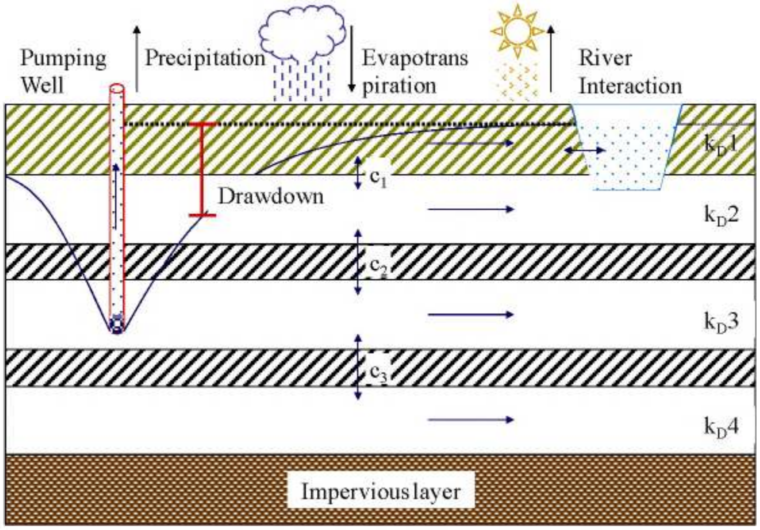
$$CF = \sum_i FF_i \cdot EF_i \tag{1}$$

Fate factor. The fate factor, describing the drawdown in relation to the change in groundwater extraction, expresses the time that is needed for groundwater replenishment. The fate factor was determined with the National Hydrological Instrumentation (NHI), which is a national hydrological model for the Netherlands developed by the Dutch Institute for Applied Natural Science Research TNO (19). With a resolution of 250x250m, NHI covers 95% of the country, excluding the islands in the north and the southernmost part (See supporting information). Grid-specific partial fate factors (FF_i in years) were calculated as follows

$$FF_i = \frac{A_i \cdot \Delta AG_i}{\Delta q} \tag{2}$$

where A_i is the area of grid cell *i* (m^2), ΔAG_i is the change in yearly average groundwater level in grid cell *i* (m), and Δq is the change in extraction rate set at 1% increase of the current extraction rate (m^3/year).

For saturated zone calculations, NHI uses the United States Geological Survey's MODFLOW code (20-22). A schematic representation of the NHI groundwater module is shown in Figure 1. The geohydrological structure is defined by an impervious basis underlying four aquifers separated by three semi-pervious layers. The horizontal flow through the aquifers depends on the transmissivity (kD in m^2/day) of the corresponding layer and the vertical flow through the semi-pervious layers depends on the vertical resistance (c in days) of the corresponding layer. The NHI describes the groundwater regime in the Netherlands, as surveyed in the year 2000. River interaction is included by a total drainage flux per junction. Anisotropies and sheet pilings are included as well, by indicating place and amount of barriers (19). A constant recharge value was used, representing the net recharge from precipitation and evapotranspiration. Groundwater extraction was parameterized with average extraction data for the year 2000 for each of the 872 major groundwater wells in the Netherlands, with extraction depths of up to ca. 300 m. Yearly average groundwater levels were modelled by running MODFLOW to a steady-state. The location of each major well in the Netherlands is shown in the supporting information.



c = vertical resistance (days); k_D = (horizontal) transmissivity (m^2/day)

Figure 1. Simplified representation of the NHI saturated zone model.

Effect factor. The effect factor in grid cell *i* (1/m) describes the change in potentially not occurring fraction of plant species (PNOF) due to a change in AG:

$$EF_i = \frac{dPNOF_i}{dAG_i} \tag{3}$$

The effect factor was determined with groundwater level response functions, following the procedure outlined by Van Zelm et al. (18). The PNOF was derived from the probability of occurrence of individual plant species (P_s). Statistical model MOVE was applied to predict the occurrence of plant species with a range of environmental parameters as input (23). As measurements on abiotic parameters are scarce, MOVE uses Ellenberg indicator values of plant species to assess environmental conditions (23). Ellenberg (24) summarized the ecology of the Central-European vascular plants by assigning to each species indicator values for environmental variables, such as moisture, salt, nitrogen, and acidity. Site conditions in MOVE are determined as the average of the Ellenberg indicator values of all species present at a site. Multiple regression equations are used to express the occurrence probability of individual species as a function of the site-specific average Ellenberg values:

$$\begin{aligned}\ln\left(\frac{P_s}{1-P_s}\right) &= b_0 + (b_1 \cdot n + b_2 \cdot n^2) + (b_3 \cdot f + b_4 \cdot f^2) + (b_5 \cdot r + b_6 \cdot r^2) + \\ &(b_7 \cdot s) + (b_8 \cdot tox) + (b_9 \cdot PGR) + (b_{10} \cdot VEG) + (b_{11} \cdot r \cdot n) + (b_{12} \cdot r \cdot f) + (b_{13} \cdot n \cdot f)\end{aligned} \tag{4}$$

where n, *f*, r and s, are Ellenberg values describing nitrogen-, moisture-, acid-, and salt-content, tox is the potentially affected fraction of plants due to heavy metals, and PGR and VEG describe the influence of the physical-geographical region, and the vegetation type, respectively. The last three terms in Equation 4 describe the interactions between r, n, and *f*. Finally, b_0 to b_{13} are regression coefficients (25).

Equation 4 was simplified in order to relate species occurrence P_s specifically to the moisture indicator *f*.

$$\ln\left(\frac{P_s}{1-P_s}\right) = a_s + b_s \cdot f + c_s \cdot f^2 \tag{5}$$

where a_s describes the situation of all environmental variables except *f*, relevant for plant species s, and b_s and c_s are species specific regression constants related to *f*.

Within the MOVE model κ-values are provided, which express the probability of occurrence related to the model predictors. When $P_s > \kappa$ a plant species is assumed to be present, and when $P_s < \kappa$ a plant species is assumed not to occur (26). The κ-values were used to predict the occurrence of 625 terrestrial plant species (see supporting information). In order to determine whether a plant species could occur at a specific *f* (Eq. 5), variability in the other site conditions had to be accounted for. By varying r, n, s, tox, PGR, and VEG, Equation 5 was parameterized 500 times for each plant species at each *f*. If at least one of the realizations yielded $P_s > \kappa$, it was assumed that the plant species could occur at that *f*. The site conditions were varied according to measurement data in the MOVE model, with r values between 4 and 8; n between 3 and 7; s between 0 and 3; and tox between 0 and 0.4. These numbers correspond with pH between 3 and 9, N stock of 2 to 500 kg/ha/yr, chloride concentrations between 3 and 10,000 mg/L, and a potentially affected fraction of plants due to heavy metals between 0 and 0.4 (23,27-28). The physical-geographical regions (PGR) included were North Sea area, tidal area, closed estuaries, rivers, hills, urban area, sea clay, peat, higher sand grounds north, higher sand grounds south, and dunes. The vegetation types (VEG) included were nutrient-poor grassland (low herbaceous vegetation), pine forest, spruce forest, deciduous forest, and heath. A region-vegetation combination was judged to be likely, and therefore taken into account, when at least 100 records were available in MOVE (23). The resulting 27 combinations are provided in the supporting information. Subsequently, a groundwater level-response curve was obtained, based on the potentially not occurring fraction of plant species (PNOF) at each *f* value:

$$PNOF_f = 1 - POF_f \tag{6}$$

with $POF_f = \dfrac{N_f}{N_{\max}}$ (7)

where POF_f represents the potentially occurring fraction of plant species at a certain *f*, N_f is the number of species that can occur at a certain *f*, taking into account varying r, n, s, tox, PGR, and VEG, and N_{max} is the maximum number of co-occurring species within the range of moisture values. N_{max} is lower than the total number of species (N_{tot}), because interspecific variation in moisture requirements prevents the co-occurrence of all plant species at a single f. We do not consider N_{tot} but rather N_{max} as background situation (zero stress, independent of groundwater level).

To ensure an appropriate connection between the fate factor and the effect factor, the Ellenberg value *f* was linked to average groundwater level (AG) with the regression found by Schaffers and Sýkora (29):

$AG = -2.55 + 0.26 \cdot f$ (8)

The derivative at each point of the response curve, showing the PNOF in relation to AG, represents the effect factor at each AG. Average groundwater levels AG_i were calculated with NHI and effect factors could then be allocated to each grid cell *i*. Groundwater level-response curves were created based on all plant species (n = 625) and for the species that are on the red list in the Netherlands (n = 141; (30)). This red list is based on the IUCN criteria. A full species list is provided in the supporting information.

Cultural Perspectives. To handle value choices in the modeling procedure in a consistent way, we applied the cultural perspective theory (31-32). Three cultural perspectives, i.e. individualist, hierarchist and egalitarian were used. The individualist coincides with the view that mankind has a high adaptive capacity through technological and economic development and that a short time perspective is justified. The egalitarian coincides with the view that nature is fragile, with many factors to damage it, that a long time perspective is justified, and a worst case scenario is needed (the precautionary principle). The hierarchist perspective coincides with the view that impacts can be avoided with proper management, and that the choice on what to include is based on the existence of evidence. Table 1 provides an overview of the value choices that can be included within groundwater modeling.

Time perspective can be applied by considering effects within a certain time horizon, emphasizing long term or short-term processes. In general time horizons of 20, 100 and infinite years are applied for the individualist, hierarchist, and egalitarian respectively (9). As no delay of over 10 years is expected in the lowering of the groundwater table due to extractions (19), time horizons are not included in the perspectives.

An assumption regarding ecosystem damage is the inclusion of species. For the individualist and hierarchist perspectives, all plant species were assumed equally important. For the egalitarian perspective high importance was given to species that are already threatened in their existence and therefore red list species were included only.

The individualist is risk seeking, the hierarchist accepts a high level of risk as long as the decision is made by experts, and the egalitarian perspective is risk adverse (32). Based on these attitudes towards risks, the individualist perspective only includes empirically proven effects. The hierarchist perspective includes scientifically accepted effects, while the egalitarian perspective includes all potential effects that may occur.

Potential positive effects were included for the individualist perspective as they have a positive attitude towards environmental benefits (31), and if they are not uncertain for the hierarchist as well.

Table 1. Value choices for groundwater extraction for three different perspectives

Value choice	Individualist	Hierarchist	Egalitarian
Time Horizon	-	-	-
Species protection level	All	All	Red list
Likelihood of effects	Proven effects	Likely effects	All known effects
Positive effects	Yes	Yes	No

LCA application. To assess the applicability of the characterization factors for groundwater extraction, we calculated the relative contribution of groundwater extraction compared to other terrestrial ecosystem impact categories for tap water production. Inventory data were taken from the ecoinvent database v2.2 (33) and characterization factors for land use, ecotoxicity, acidification, and climate change were applied according to the individualist, hierarchist, and egalitarian perspectives of the ReCiPe method (9).

Results

The partial fate factors over the Netherlands range from $-1.2 \cdot 10^{-5}$ to $2.7 \cdot 10^{-2}$ yr and are shown in Figure 2.

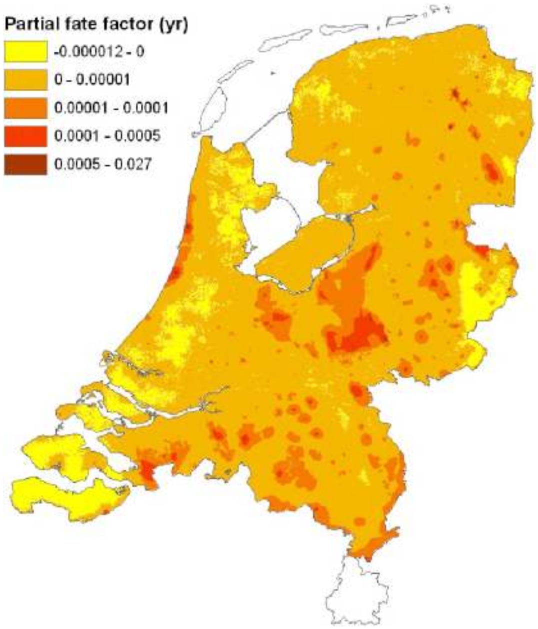


Figure 2. Partial fate factors (yr) for the Netherlands.

Figure 3a shows the groundwater level response curve, depicting the PNOF at various AGs, for the Netherlands. From AG of -2.30 m up to -1.25 m the PNOF decreases as the groundwater level increases. In the shallower groundwater range the PNOF increases when the groundwater level increases. The groundwater level response curve was divided in four parts and for each an effect factor ($\frac{dPNOF}{dAG}$) was calculated. EFs are 0.24 m^{-1} ($-2.30 < AG < -1.98$ m), 0.92 m^{-1} ($-1.98 < AG < -1.25$ m), -0.23 m^{-1} ($-1.25 < AG < -0.83$ m), and -0.85 m^{-1} ($-0.83 < AG < 0$ m) respectively. Figure 3b shows the groundwater level-response curve for the red list species only. A similar trend is observed and the curve for red list species can be divided in four parts as well. EFs are 0.25 m^{-1} ($-2.30 < AG < -1.95$ m), 1.18 m^{-1} ($-1.95 < AG < -1.21$ m), -0.05 m^{-1} ($-1.21 < AG < -0.72$ m), and -1.01 m^{-1} ($-0.72 < AG < 0$ m) respectively. For lower groundwater levels, effects on red list species are 4 to 28 % larger. Figure 3c shows curves for nutrient poor grassland, pine forest, deciduous forest, and heath separately. It can be seen that the variation in effect factor among vegetation types is relatively small (around a factor of 1.5).

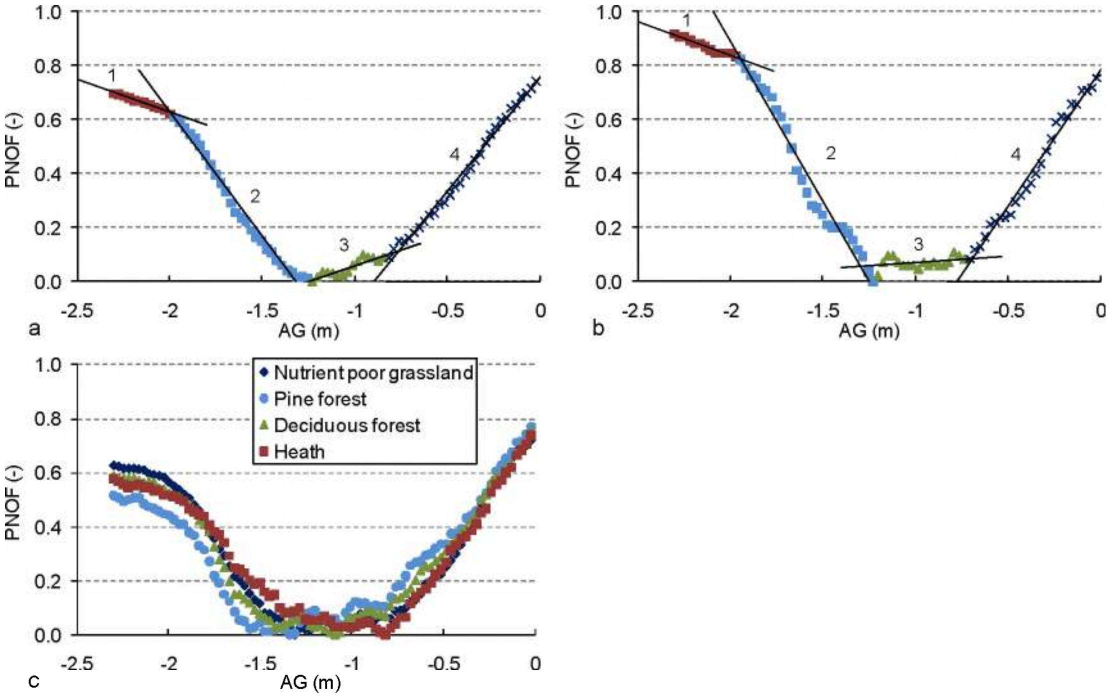


Figure 3. Groundwater level-response curves representing the potentially not occurring fraction of plant species (PNOF) as a function of the yearly average groundwater level (AG). (a) shows the overall curve with fitted linear functions that follow (1) PNOF = -0.24*AG + 0.14 with an explained variance $R^2 = 0.99$; (2) PNOF = -0.92*AG - 1.21 with $R^2 = 0.98$; (3) PNOF = 0.23*AG + 0.29 with $R^2 = 0.82$, (4) PNOF = 0.85*AG + 0.75 with $R^2 = 0.99$. (b) shows the curve for 141 species that are on the red list in the Netherlands with fitted linear functions that follow (1) PNOF = -0.25*AG + 0.34 with an explained variance R2 = 0.96; (2) PNOF = -1.18*AG - 1.48 with R2 = 0.97; (3) PNOF = 0.05*AG + 0.11 with R2 = 0.12, (4) PNOF = 1.01*AG + 0.78 with R2 = 0.99. (c) shows curves per vegetation type.

The groundwater level-response curve for all species can be extrapolated from AG = -2.30 m to AG= -3.58 m. Grid cells with AGs of -2.30 to -3.58 m will then be assigned the EF for the AG-range of -2.30 m to -1.98 m. For AG < -3.58 m, the PNOF equals 1, implying that these areas do not contain groundwater-dependent vegetation. Therefore, the EF was set to 0 m^{-1} for an AG < -3.58 m. For the red list species the same extrapolation strategy was applied.

For the calculation of the characterization factor CF, the response curve for all species is included for the individualist and the hierarchist perspective, while the egalitarian perspective takes into account the red list species only. The effects likely to occur in the groundwater level range below -2.3 m where the effect curve is extrapolated are included in the hierarchist and egalitarian perspective, but excluded from the individualist perspective due to the relatively high uncertainty of this part of the response curve. The individualistic and hierarchist perspective include positive effects, while the egalitarian perspective does not include positive effects from a precautionary point of view. Figure 4 shows the three CFs for the Netherlands.

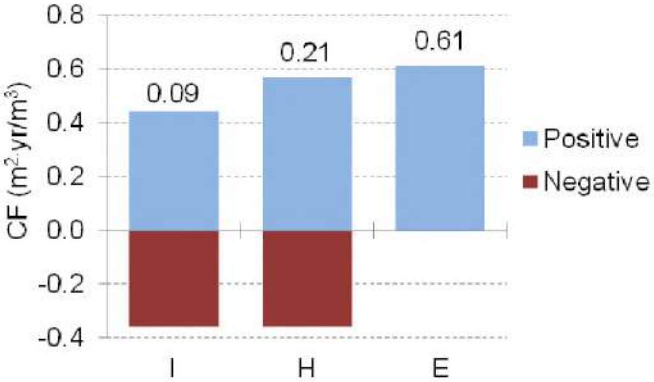


Figure 4. Characterization factors for the individualist (I), hierarchist (H), and egalitarian (E) perspectives, consisting of a positive and a negative part.

Application of our calculated CF shows that groundwater extraction causes 2.2 to 13.2% of the total ecosystem damage resulting from the production of tap water, depending on the perspective taken (Figure 5).

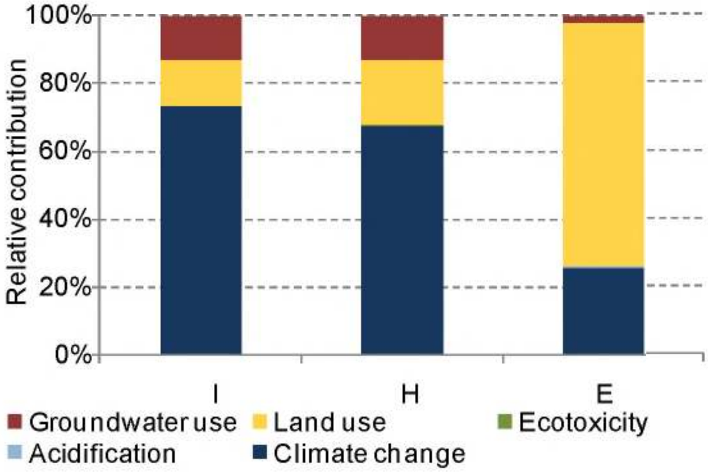


Figure 5. The relative contribution of five impact categories to the terrestrial ecosystem damage of tap water production following the individualist (I), hierarchist (H), and egalitarian (E) perspective.

Discussion

This paper described the development and application of a method that predicts the change in plant species richness, modelled as the potentially not occurring fraction of plant species, per unit of groundwater extraction. The characterization factor derived provides the opportunity to combine the ecological consequences of groundwater extraction with the effects of other types of stressors, such as land use and acidification, in the Life Cycle Assessment of products. Below, we discuss the benefits and limitations of the modelling procedure and provide an interpretation of the results obtained.

Fate factors. To obtain fate factors for groundwater extraction, the MODFLOW model was run to steady-state and yearly average changes in groundwater levels were derived. A steady-state approach seems appropriate for groundwater wells where water is being pumped constantly, thus having a permanent effect on the groundwater level. In the Netherlands, 75% of the extracted groundwater is used for drinking water (34), which is extracted with continuously pumping wells (35). Therefore, the effects of an intermittently pumping well were not taken into account in our study. More research on the effects of intermittently pumping wells is needed in order to include these wells in LCA studies.

Current European policy aims at a sustainable use of groundwater, which would mean a decrease of groundwater extraction in the future (36). As a reference situation, we used the amount of extraction as it was in the year 2000. To account for possible future decreases in extraction a different reference situation can be assumed for calculating fate and effect factors. When more information is available on future scenario's, these can be included in the three perspectives as well, as future optimistic, baseline, and pessimistic views correspond to the individualist, hierarchist, and egalitarian perspective, respectively (31).

Using the ecohydrological DEMNAT model, Van Ek et al. (16) derived a typical factor for dAG/dq of 0.02 mm lowering of the groundwater level per Mm^3/yr of extracted groundwater, whereas our total factor ($\sum_i FF_i$) was 0.14 mm per Mm^3/yr. Extractions from wells located near the borders with Germany and Belgium cause a drawdown in these countries as well. These effects are not included by the NHI, which causes a small underestimation of the full drawdown over the affected area and thus of the fate factor.

Next to regional variation caused by diverging extraction rates, the fate factor can vary due to variation in hydro-geological parameters: soil permeability, recharge, ground pack around the extraction (e.g. is it mainly clay, sand, or peat) and depth of extraction. For LCA purposes it would be interesting to derive fate factors as a function of these varying parameters to account for location-specific conditions. Our fate model provides the possibility to link grid-specific groundwater table lowering to environmental variables, such as the vertical resistance and transmissivity of the soil layers, and precipitation and evapotranspiration. Further research is required to quantify the influence of variation in hydro-geological model parameters on the fate factor.

Effect factors. To obtain effect factors for groundwater level change, the MOVE model was applied. The DEMNAT model also provides response curves for plant species pools, showing a decline in species diversity for dropping groundwater levels (37). Runhaar et al. (37) found a maximum of 13.5% species richness decrease per 10 cm decrease of Average Spring Groundwater level decrease which corresponds well with the maximum of 9.2% species richness decrease per 10 cm groundwater level decrease found in our research.

Laidig et al. (38) showed that it depends on the vegetation type and species included whether there is a positive or negative relationship between species occurrence and groundwater level change, corresponding to the increase in species diversity for higher groundwater levels found in our research.

For the connection between fate and effects, we applied the relationship between Ellenberg moisture value f and average groundwater level as derived from Schaffers and Sýkora (29). As shown by Ertsen et al. (27), there is also a good correlation between Average Spring Groundwater level and f. The relationship between ASG and f could have been used as well, but would have required dynamic calculations with the MODFLOW model to derive fate factors related to ASG.

We showed that the effect factors for our full list of terrestrial plant species did not largely differ from the effect factors for the red list species only. The response curves showed similar trends and both curves could be divided into four parts. It was also shown that the effect factors hardly differ between different vegetation types. These findings indicate that the variation in effect factors among vegetation types occurring in a temperate maritime climate is relatively small, suggesting that our generic response curve can be used in other regions with comparable vegetation types. However, it should be stressed that our method predicts responses of species richness irrespective of species composition, as we used one generic groundwater level response curve based on the total plant species pool in the Netherlands. Specific response curves for vegetation types characteristic of, for instance, wet or dry circumstances will facilitate more location-specific assessments of the effects of groundwater extraction on plant species richness. This should be subject to further research.

The groundwater level-response curve showed that the point of departure is relevant in the derivation of the effect factor. For yearly average groundwater levels lower than -1.25 meters, a decrease in species richness is expected if groundwater levels are lowered (maximum 9.2% per 10 cm of groundwater level decrease). In contrast, for groundwater levels higher than -1.25 meters, a lowering of the groundwater level is expected to increase species richness (maximum 8.5% increase per 10 cm of groundwater level decrease). It should, however, be stressed that our work should not be used as an argument to lower groundwater levels in ecosystems where groundwater tables are naturally high. In these cases, a shift towards a different vegetation community with higher species diversity should not be automatically interpreted as beneficial, especially because the increase in species diversity might go on the expense of particular species that rely on high groundwater levels. Natural heterogeneity in landscape characteristics, including natural variability in groundwater levels, is an important driver for maintaining overall species diversity.

Application in LCA studies. Characterization factors were derived for the generic Dutch situation. Effect factors were based on data on the occurrence of plant species, and therefore expressed as potentially not occurring fraction of plant species (PNOF). This, in contradiction to effects caused by for example, toxic compounds, for which data are available on the effect and lethal dose for species (39). On an endpoint level, the PNOF can be considered equal to the potentially affected or potentially disappeared fraction of species.

For LCAs, the Netherlands is a relatively specific spatial context. This brings up the question whether the current research can be applied outside the Netherlands. Provided that the required geohydrological data are available, as is the case for e.g. China (40), Canada (41), and Italy (21), the U.S. Geological Survey model MODFLOW can be parameterized for every region of the world to calculate fate factors according to the method outlined in this paper. The effect factors apply to temperate maritime climates with similar vegetation types as the Netherlands. The Ellenberg numbers were based on observations of realized niches of plant species in Central Europe. As the ecological behavior of species can be different in other regions, calibration of the Ellenberg values is needed according to regional deviations. This was successfully done for several other European areas, e.g. the Faroe islands (42), Britain (43), Sweden (44) and Greece (45).

Our research is among the first to include the impacts of groundwater extraction on terrestrial ecosystems in LCA context. For the production of tap water we showed that groundwater extraction contributes to terrestrial ecosystem damage up to 32%. We recommend to further elaborate on the inclusion of groundwater extraction in LCA by developing CFs for regions outside the Netherlands as well.

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Supporting information available

Information on groundwater wells, terrestrial plant species included, their κ-values, and physical-geographical region–vegetation types included is in the supporting information. This material is available free of charge via the internet at http://pubs.acs.org.

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