Open access • Journal Article • DOI:10.1021/ES1039634

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Published on: 16 May 2011 - Environmental Science & Technology (American Chemical Society)

Topics: Greenhouse gas, Greenhouse effect, Global warming, Freshwater fish and Freshwater ecosystem

Characterization factors for water consumption and greenhouse gas emissions based on freshwater fish species extinction

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Abstract

Human-induced changes in water consumption and global warming are likely to reduce the species richness of freshwater ecosystems. So far, these impacts have not been addressed in the context of life cycle assessment (LCA). Here, we derived characterization factors for water consumption and global warming based on freshwater fish species loss. Calculation of characterization factors for potential freshwater fish losses from water consumption were estimated using a generic species-river discharge curve for 214 global river basins. We also derived characterization factors for potential freshwater fish species losses per unit of greenhouse gas emission. Based on five global climate scenarios, characterization factors for 63 greenhouse gas emissions were calculated. Depending on the river considered, characterization factors for water consumption can differ up to 3 orders of magnitude. Characterization factors for greenhouse gas emissions can vary up to 5 orders of magnitude, depending on the atmospheric residence time and radiative forcing efficiency of greenhouse gas emissions. An emission of 1 ton of CO_2 is expected to cause the same impact on potential fish species disappearance as the water consumption of 10-1000 m^3, depending on the river basin considered. Our results make it possible to compare the impact of water consumption with greenhouse gas emissions.

Keywords: water consumption, global warming, life cycle assessment, freshwater ecosystems

Brief: Development of a life cycle impact assessment method to address effects of water consumption and greenhouse gas emissions on freshwater fish species disappearance.

Introduction

Life cycle assessment (LCA) is a technique used to assess the environmental impacts associated with a product, process or service.[1] This paper focuses on life cycle impact assessment (LCIA), the phase where inventory data are assessed in terms of environmental impacts. Impact categories in LCIA can be associated with areas of protection (AoPs), such as natural resources, ecosystem quality and human health.[2] The relationship between inventory data and the magnitude of impacts on the AoPs in LCIA are expressed in terms of characterization factors.[3]

Global freshwater biodiversity is one of the AoPs which has experienced large adverse effects.[4] Although freshwater fish species losses due to anthropogenic impacts have been addressed in earlier studies,[5-7] less attention has been paid to assessing these impacts in an LCA perspective.[8] At present, freshwater-related studies using LCA techniques have mostly focused on toxicological effects.[3,9-11] The environmental impacts of water consumption on terrestrial ecosystems has only recently been conducted by Pfister et al.[12] Impacts of water consumption and greenhouse gas emissions in relation to freshwater biodiversity have so far not been addressed in LCA context.

Global warming and increases in water consumption can significantly affect freshwater ecosystems.[13,14] For example, reduced river discharge (the volume of water flowing through a river per unit time) due to water consumption and greenhouse gas emissions could lead to freshwater fish species losses.[15] In lotic freshwater ecosystems, river discharge can be used as a surrogate of habitat space to generate species-discharge relationships similar to terrestrial species-area curves.[15-17] Because climate warming and water consumption is expected to reduce river discharge in many parts of the world,[18] these species-discharge relationships have been used to forecast species diversity losses associated with reductions in freshwater. In addition, river discharge reduction can, for instance, lead to a higher concentration of nutrients and pollutants in freshwater[15] thus compounding the negative effects of water quantity reductions alone on biodiversity. Changes in temperature and precipitation associated with global warming can also adversely affect water availability. It is expected that river discharge reduction due to global warming can negatively influence the distribution and occurrence of many fish species (Figure 1).[7,19,20]

The aim of this paper is to derive characterization factors related to freshwater ecosystem damage for water consumption and greenhouse gas emissions. The present study focuses on the occurrence of freshwater native fish species in global rivers. In order to put our results into LCA perspective, we also calculate normalization factors for water consumption and global warming as input for overall normalization factors that represent biodiversity impacts in freshwater. Normalization factors provide information about the relative importance of each impact category considered, such as impacts on freshwater biodiversity. .

Methods

Framework. Figure 1 gives an overview of the cause-effect chain regarding the disappearance of freshwater fish species caused by greenhouse gas emissions and water consumption. In this study, water consumption refers to water used for human activities, (e.g. communal, agricultural and industrial) that is not returned to the river. The influence of reduced flow rates on fish species numbers can be quantified with the global species-discharge model, an index of habitat space, feeding and reproductive opportunities. This model was developed on the basis of information on native fish species and river discharges in various river basins (Xenopoulos et al.).[14] This model assumes a positive correlation between the number of freshwater fish species and average river discharges at the mouth of river basins.

$$R = 4.2 \cdot Q_{mouth,i}^{0.4} \tag{1}$$

where R is the freshwater fish species richness and Q_{mouth} is the annual average river discharge at the river mouth of basin i ($m^3.s^{-1}$).

The species-discharge relationship can be used as a basis to calculate characterization factors for water consumption that specify freshwater fish species extinction per unit of reduced river discharge for river basins in different regions of the world.[14] This has been done in a river basin-specific way. Using the data provided in Xenopoulos et al.,[14] information of the average river discharge for 326 river basins was considered. These 326 rivers include well-known river basins in the world, representing a wide geographical distribution of rivers around the various continents. However, we excluded 83 river basins which are located at latitudes higher than 42°, because these river basins were recently (in geological time) glaciated, i.e. covered by ice. As such, these rivers have not had enough time to evolve to their maximum species richness potential. It follows that the species-discharge relationship for these river basins is weak as they have much fewer species per unit discharge than the rivers below 42°. This indicates that most of the world's river basins located in the high latitudes including Northern Europe, Northern America and Canada were not taken into account. In addition, due to data limitations in the river volume and length calculations, 29 river basins were also excluded. Thus, a total of 214 river basins were used in our final models.

The species-discharge relationship can also be used to derive characterization factors that quantify the potential extinction of freshwater fish species per unit of greenhouse gas emission. The endpoint modelling for global warming further includes the influence of greenhouse gas emissions on global mean temperature and subsequent effects on river water discharge (see Figure 1). The calculation of the characterization factors for water consumption and global warming is explained below.

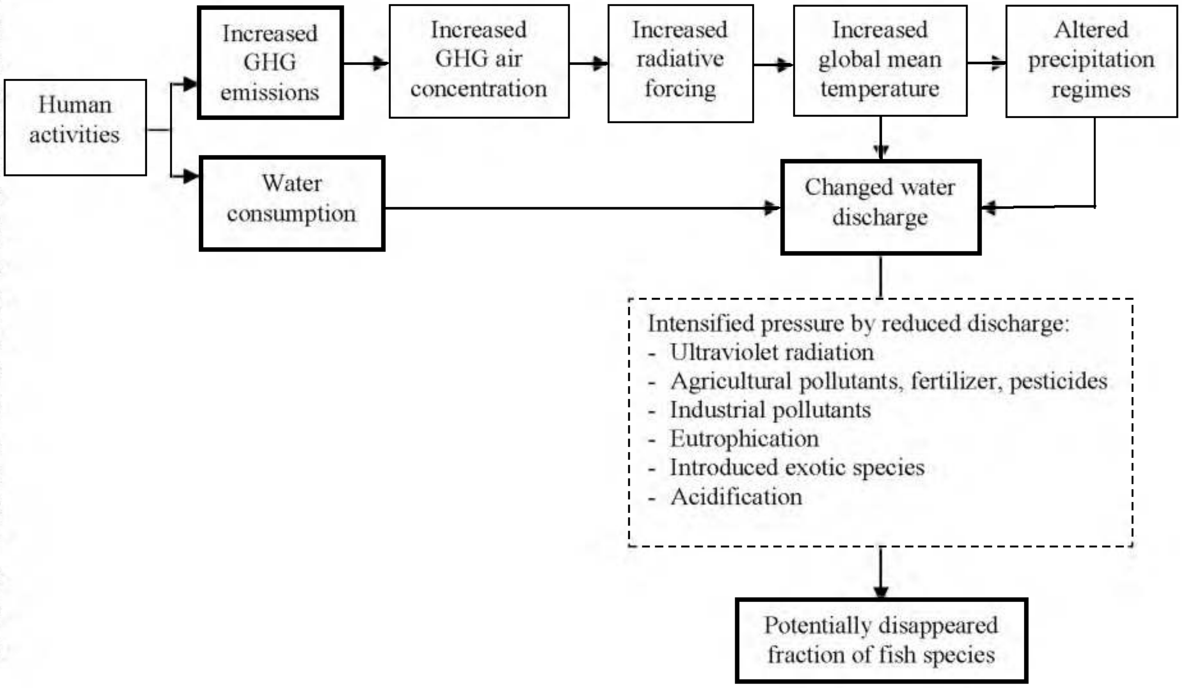

Figure 1. Cause-effect chain for impact of greenhouse gas emissions and water consumption on freshwater fish species.[14,15]

Water Consumption. Characterization factors for water consumption reflect the impact of water use due to human activities on freshwater fish species richness, expressed in units of $PDF \cdot m^3 \cdot yr \cdot m^{-3}$. The river basin-specific characterization factors for water consumption ($CF_{wc,i}$) were calculated by:

$$CF_{wc,i} = FF_i \cdot EF_i = \underbrace{\frac{dQ_{mouth,i}}{dW_i}}_{fate} \cdot \underbrace{\left(\frac{dPDF_i}{dQ_{mouth,i}} \cdot V_i \right)}_{effect} \qquad (2)$$

where FF_i is the fate factor of river basin i, EF_i is the effect factor of river basin i ($PDF \cdot m^3 \cdot yr \cdot m^{-3}$), $dQ_{mouth,i}$ is the marginal change in water discharge at the river mouth in basin *i* ($m^3 \cdot yr^{-1}$), dW_i is the marginal change in water consumption by human activities in river basin *i* ($m^3 \cdot yr^{-1}$), $dPDF_i$ is the marginal change in the potentially disappeared fraction of the freshwater fish species due to the marginal river discharge change $dQ_{mouth,i}$ and V_i is the volume of river basin *i* (m^3). The $dQ_{mouth,i}/dW_i$ was assumed to be equal to one, indicating that a change in water consumption ($m^3 \cdot yr^{-1}$) is fully reflected in a change in water discharge at the mouth for that river basin ($m^3 \cdot yr^{-1}$).

The effect factor for each river basin was calculated by:

$$\frac{dPDF_i}{dQ_{mouth,i}} = \frac{dR_i}{R_i \cdot dQ_{mouth,i}} = \frac{4.2 \cdot 0.4 \cdot Q_{mouth,i}^{0.4-1}}{4.2 \cdot Q_{mouth,i}^{0.4}} = \frac{0.4}{Q_{mouth,i}} \tag{3}$$

where $dPDF_i$ is the marginal change in the potentially disappeared fraction of the freshwater fish species for river basin *i*, $dQ_{mouth,i}$ is the marginal discharge change at the river mouth in basin *i* ($m^3 \cdot yr^{-1}$) and dR_i is the marginal change of the freshwater fish species richness in river basin *i*. River basin-specific discharges at the river mouth $Q_{mouth,i}$ were derived from the WaterGap model[21].

The river volumes (m^3) for all river basins were calculated by:

$$V_i = \frac{Q_{mouth,i}}{2} \cdot \tau_i \tag{4}$$

where V_i is the water volume in river basin *i* (m^3), $Q_{mouth,i}$ is the discharge at the river mouth in basin *i*, and τ_i is the average residence time of water in river basin *i* (s). Assuming a linear increase of river flow over the distance, we estimated that the average river discharge was half of the discharge at the river mouth. Derivation of the river volume was based on data from various sources.[14,21-25] Further details of the derivation of the river volume can be found in the Supporting Information (estimation of river volumes).

Greenhouse Gas Emissions. Characterization factors for greenhouse gas emissions quantify the fraction of freshwater fish species that potentially disappear due to a change in emission of greenhouse gases. The characterization factors for 63 greenhouse gas emissions (in PDF·m^3·yr·kg^{-1}) were calculated by:

$$CF_{ghg,x} = FF_x \cdot EF = \underbrace{\frac{dTEMP}{dGHG_x}}_{fate} \cdot \underbrace{\left(\sum_i \frac{dQ_{mouth,i}}{dTEMP} \cdot \frac{dPDF_i}{dQ_{mouth,i}} \cdot V_i \right)}_{effect} \qquad (5)$$

Where FF_x is the fate factor for greenhouse gas emission x (°C·yr·kg^{-1}), EF is the effect factor (PDF·m^3·°C^{-1}), $dGHG_x$ is the change in greenhouse gas emission x (kg·year^{-1}), $dTEMP$ is the change in global mean temperature (°C), $dQ_{mouth,i}$ is the change in water discharge at the river mouth in basin i (m^3·yr^{-1}), $dPDF_i$ is the marginal change in the potentially disappeared fraction of freshwater fish species in river basin i and V_i is the volume of river basin i (m^3).

Temperature factors were taken from De Schryver et al.[26] and consist of three calculation steps. The first step resembles the change in air concentration of greenhouse gases due to a change in emission and reflects the atmosphere life time of a greenhouse gas. The second step represents the change in radiative forcing due to a concentration change. The third step reflects the change in global mean temperature due to the change in radiative forcing. The climate sensitivity and heat absorption rate by the oceans determine the relation of global mean temperature change and radiative forcing change.[27] A time horizon of 100-year was applied in the present study. The indirect cooling effect of ozone depleting substances was not included in the greenhouse gas calculations due to the high uncertainties involved (see De Schryver et al.).[26]

Freshwater effect factors related to climate change require river basin-specific information on the change in PDF due to a change in global mean temperature. The effect factor was derived by:

$$EF = \sum_i \frac{dQ_{mouth,i}}{dTEMP} \cdot \frac{dPDF_i}{dQ_{mouth,i}} \cdot V_i \approx \sum_i \frac{\Delta Q_{mouth,i}}{\Delta TEMP} \cdot \frac{0.4}{Q_{mouth,i}} \cdot V_i \qquad (6)$$

where $dQ_{mouth,i}$ is the change in the water discharge at the river mouth in basin i ($m^3 \cdot yr^{-1}$) and $dTEMP$ is the change in global mean temperature (°C). It is not possible to derive $dQ_{mouth,i}/dTEMP$ analytically, thus, data from IPCC[28] and Millennium Ecosystem Assessment[29] as described in Xenopoulos et al.[14] and Sala et al.[30] were used for the derivation of $\Delta Q_{mouth,i}/\Delta TEMP$ for five global climate scenarios in the year 2100. For every scenario, we divided the modelled change in river discharge from the WaterGap model[21] by the predicted temperature change for the year 2100. Further information on the five global climate scenarios can be found in the Supporting Information (Table S1).

River discharge is predicted to increase in some areas of the world due to increased precipitation[31]. Without human accidental or intentional fish introductions, it is unlikely that increasing river discharge will have a positive effect on fish species richness, particularly at the current time scale as related to local scale and isolated river basins.[14] Therefore, river basins with increased discharge were excluded in the calculation of the effect factor for global warming.

Normalization. Normalization factors provide information about the relative importance of each impact category and were expressed as the potentially disappeared fraction of species over a certain river volume per capita. Normalization factors for water consumption refer to the year 1995,[21,32,33] while normalization factors for global warming were based on greenhouse gas emissions in year 2000.[34] The population numbers were taken from the U.S. Census Bureau.[35] Due to lack of data, we were only able to derive the normalization factors for water consumption and global warming for 112 river basins and 21 greenhouse gas emissions, respectively.

Results

Water Consumption. River basin-specific characterization factors for water consumption differs 3 orders of magnitude (Figure 2). Most of the river basins (57%) have characterization factors for water consumption between $10^{-4} – 10^{-3}$ PDF·m^3·yr·m^{-3}. The characterization factors for the largest river basins in the world, such as the Nile, the Amazon and the Yangtze Rivers are between $10^{-3} – 10^{-2}$ PDF·m^3·yr·m^{-3}. Characterization factors for all 214 river basins can be found in the Supporting Information (Table S4).

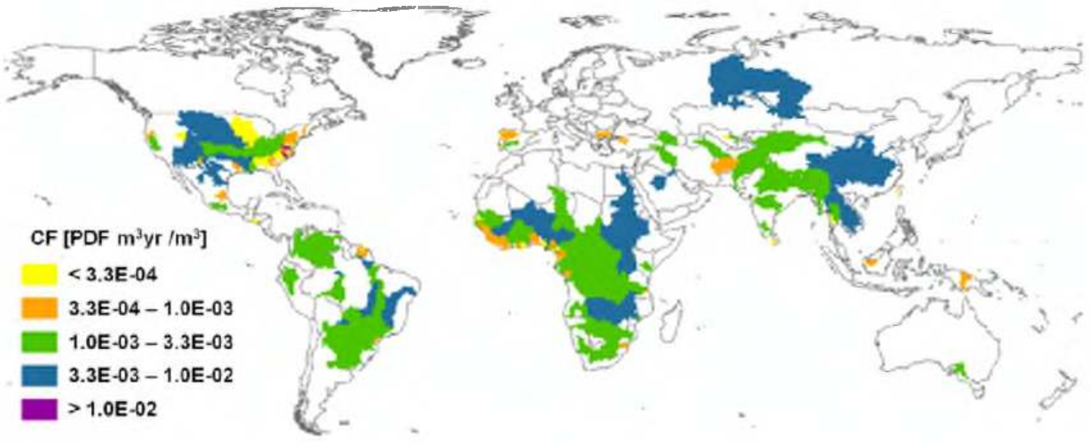

Figure 2. Characterization factors for water consumption (PDF·m^3·yr·m^{-3}).

Greenhouse Gas Emissions. Characterization factors for CO_2, CH_4, N_2O, CFC-11, SF6 and HFC-125 emissions are shown in Figure 3 (ranges from $8.5 \cdot 10^{-5}$ to 2.1 PDF·m^3·yr·kg^{-1}). The largest characterization factor is found for SF6 (around 4 orders of magnitude larger than CO_2). The differences between the greenhouse gases are determined by the differences in atmospheric residence time and radiative forcing efficiency. The rivers with the largest contribution to the characterization factors for global warming are the Amazon, Madeira, Orinoco, Purus and Brahmaputra. These rivers explain together 65% of the freshwater ecosystem impact per unit of greenhouse gas emission. The river basin-specific effect factors and the characterization factors of 63 greenhouse gases are listed in the Supporting Information (Tables S2 and S5 respectively).

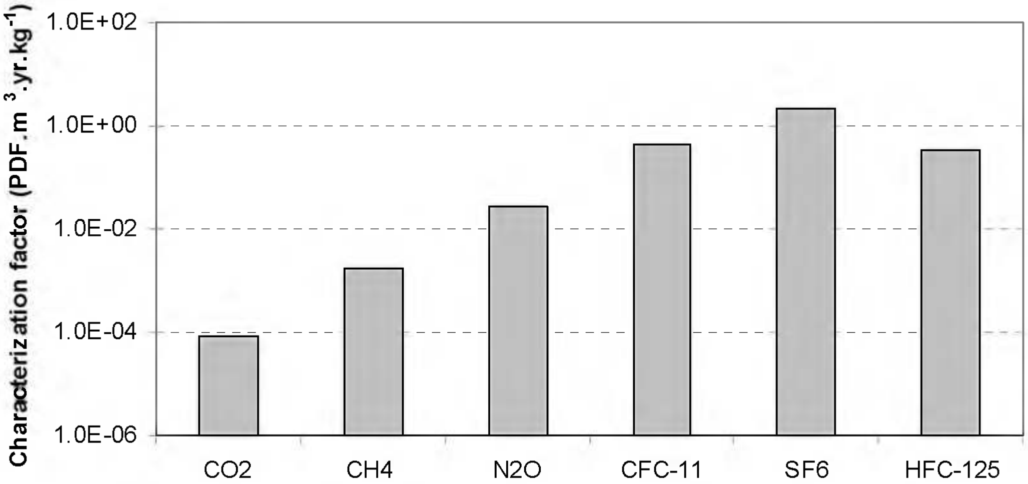

Figure 3. Characterization factors of six greenhouse gas emissions (PDF·m^3·yr·kg^{-1}) from a 100-year time horizon.

Normalization. The normalization factors per capita for water consumption and global warming are approximately equal (respectively 0.54 and 0.57 PDF·m^3/capita). For water consumption, the highest normalization factor is found for the Ganges River, which constitutes 22% impact of the river basins considered (Figure 4A). The normalization factor based on emissions in year 2000 shows that CO_2 contributes most to global warming, with 70% of the total greenhouse gas emissions included (Figure 4B). Normalization factors for river basin-specific water consumption and greenhouse gas emissions are given in the Supporting Information (Tables S4 and S5 respectively).

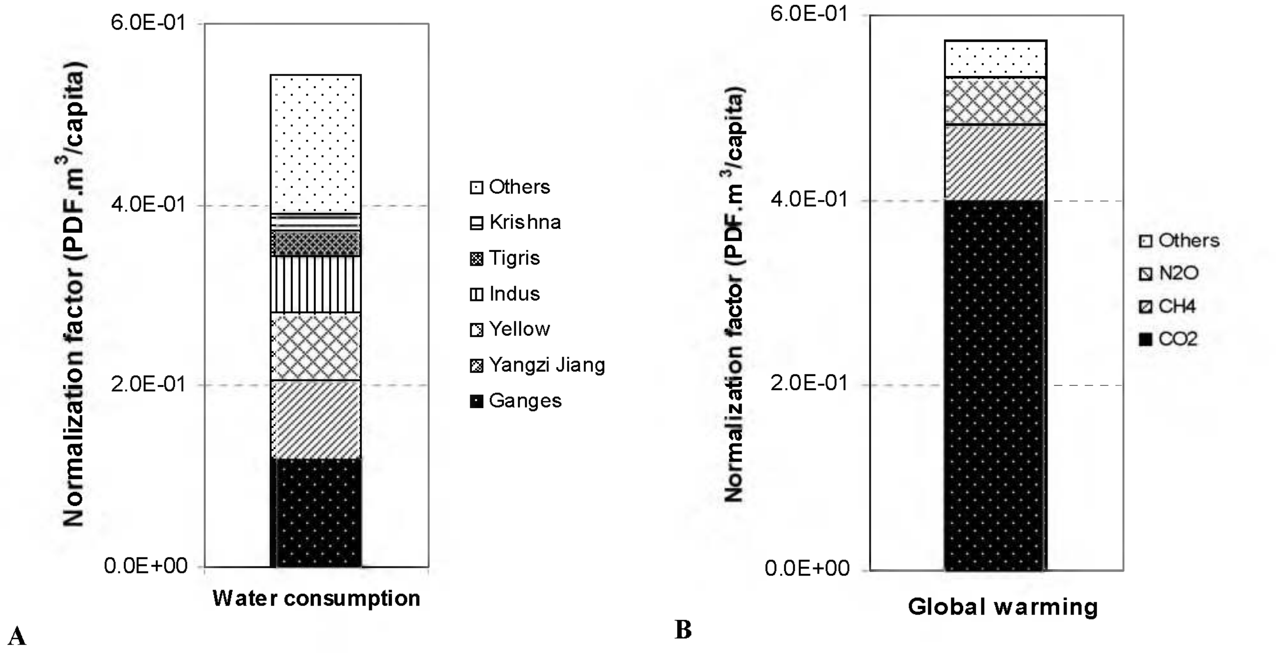

Figure 4. River basin-specific normalization factors (PDF·m^3/capita) for water consumption in year 1995 (4A) and normalization factors for global warming based on emissions in year 2000 (4B).

Discussion

We were able to derive characterization factors for water consumption and global warming based on information of potential freshwater fish species disappearance for 214 river basins worldwide. Below we discuss the uncertainties related to our calculations and provide the implications of our study.

Fate factors. The estimation of river volumes, based on the average river discharge and the average water residence time in river, affects both the fate factors for water consumption and greenhouse gas emissions. We assumed as a first approximation that the average river discharge was half of the discharge at the river mouth and that the average travel time was half of the total length of river. Furthermore, integration of data from multiple data sources in the water volume calculation of the rivers will lower the degree of data consistency. A complete data for worldwide river characteristics is however, not available. Therefore, we had to combine heterogeneous data sources for deriving river volumes (see Table S2 in the Supporting Information).

Second, an uncertainty specifically related to the calculation of fate factors for global warming, is the arbitrary selection of a 100-year time horizon. For a number of greenhouse gases, particularly with a relative long lifetime in the atmosphere such as SF6, the results are sensitive to the choice of time horizon.[26,36] For instance, the characterization factor of SF6 will increase with about 2 orders of magnitude if an infinite time horizon is chosen instead.

Finally, we excluded in our global warming calculations the indirect influence of ozone depleting chemicals, such as cholorofluorocarbons and halons, on radiative forcing. The indirect effects of ozone depleting chemicals can result in net negative radiative forcing and therefore negative fate factors.[26,37]

Effect factors. A number of uncertainties are also related to the effect factor calculations of water consumption and global warming. First, due to recent geological glaciation, we had to exclude river basins in the effect factor calculations that are located at the latitude higher than 42°. Applying the current species-discharge curve would lead to overestimation of effect factors for water consumption and global warming in these rivers, as the rivers above 42° have much fewer species per unit discharge. In order to consider river basins above 42°, a specific species-discharge curve need to be built for these river basins. For global warming we conducted a sensitivity analysis by including other river basins (> 42°) as well in the calculation of the characterization factors. As shown in the Supporting Information (Figure S1), including all river basins (297 river basins in total) in the calculation of the characterization factors for global warming increases the effect factor by 1.5%. This uncertainty is considered low compared to the uncertainties in the calculation from emission to global mean temperature increase (see De Schryver et al.).[26]

Second, we used a global fish species-discharge model as opposed to basin-specific fish species-discharge curves which may be more accurate.[14] However, global data sets of fish species are often not available to build watershed-specific species-discharge models.

Third, the modification of the flow regime at a range of spatial scales that affects fish species may also affect the associations between aquatic macroinvertebrates and their habitat.[38-40] However, other aquatic freshwater taxonomic groups could not be included in this study because of insufficient data on the global scale. This implies that our characterization factors do not fully represent all the lotic aquatic ecosystems.

Fourth, the influence from building dams and abstractions was not considered in the study (see Xenopoulos et al.).[14] The absence of dams allowed us to model more accurate species-discharge curves without any human influences, as dams are known to reduce the average downstream river discharge.[41,42] In future research, the species-discharge curve as employed in this paper, could also be used to provide river-specific characterization factors for the construction of dams to produce hydropower.

Fifth, we estimated the river basin specific dQ/dTEMP for global warming based on five future scenarios. Uncertainty in the calculation of dQ/dTEMP is associated with the future scenario chosen. Future climate change projection is difficult and uncertain to define because changes in the future economic growth, technology and policy-making processes concerning human actions are unknown.[43] In the present study, the dQ/dTEMP can be a factor of 2 higher or lower, depending on the scenario chosen. This uncertainty can particularly influence the relative importance of impacts of greenhouse gas emissions compared to other stressors.

Finally, we compared our effect factors for global warming with effect factors reported in a previous study on direct temperature effects towards aquatic organisms.[44] Our volume-weighted effect factor for the impact of climate change on fish species is typically $7\cdot10^{-3}$ and ranges between $3\cdot10^{-3}$ and $2\cdot10^{-2}$ PDF·°C^{-1}. This implies that an increase in global mean temperature of 1°C would typically result in 0.7% (0.3-2%) fish species loss. Verones et al.[44] calculated effect factors for freshwater ecosystems due to direct water temperature increase of cooling water discharge in the river Rhine. They found that the effect factor is significantly higher in summer than in winter time (5 orders of magnitude), with a yearly average effect factor of around 1% species loss per °C increase and a highest monthly effect factor of 4% species loss per °C increase. The results from Verones et al.[44] imply that including direct temperature effects on freshwater species occurrence could significantly increase the characterization factors for greenhouse gas emissions. The river basin specific information, required to calculate the effect factors according to Verones et al.[44] in a meaningful way, is, however, currently not available. For generalization, river-specific data for the ambient water temperature over the seasons, key river characteristics for heat exchanges and information on species pools, based on the susceptibility of species in different climatic zones, should be gathered.

Implications. We developed regionalized characterization factors for water consumption and generic characterization factors for global warming related to freshwater ecosystem impacts on the global scale. Regionalized inventory data of water consumption is required to apply the new characterization factors in practice. With this information, comparison between the new characterization factors of water consumption and greenhouse gas emissions with other stressors for freshwater biodiversity are now possible.

Acknowledgements. We thank An de Schryver for her useful suggestions in the preparation of normalisation data for water consumption. Marlia Hanafiah was financed by the Ministry of Higher Education Malaysia and the National University of Malaysia. Stephan Pfister and Mark Huijbregts were partly funded by the European Commission under the 7th framework program on environment (ENV.2009.3.3.2.1: LC-IMPACT – Improved Life Cycle Impact Assessment methods (LCIA) for better sustainability assessment of technologies).

Supporting Information available. Information on the river volume estimation, derivation of $dQ_{mouth,i}/dTEMP$, summary of the five global climate scenarios (Table S1), influence of including river basins located above 42°, normalization factors for water consumption and global warming, river characteristics data – below 42° (Table S2), river characteristic data – above 42° (Table S3), characterization factors and normalization factors for water consumption (Table S4) and characterization factors and normalization factors for global warming (Table S5). This information is available free of charge via the Internet at http://pubs.acs.org.

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