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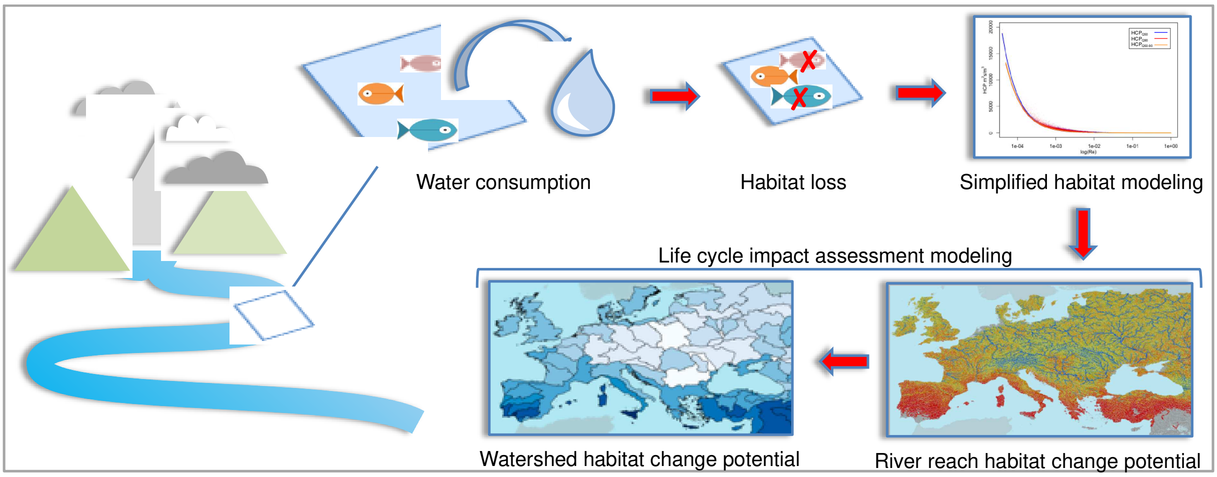
ABSTRACT

Global value chains and climate change have a significant impact on water resources and increasingly threaten freshwater ecosystems. Recent methodological proposals for life cycle impact assessment (LCIA), evaluate water use impacts on freshwater habitats based on river hydraulic parameters alterations. However, they are limited to French rivers due to lack of global data and models. On this basis, this article proposes an approach to compute regionalized characterization factors for modeling river habitat change potential (HCP) induced by water consumption, potentially applicable worldwide. A simplified model is developed for fish guilds and invertebrates. Based on French datasets, it establishes a relationship between HCP and river hydraulic parameters. A methodology to derive discharge and hydraulic geometry at the reach scale is proposed and applied to European and Middle Eastern rivers below 60°N latitude. Regionalized HCPs are calculated at the river reach scale and aggregated at watershed. Then, the impact of agricultural water use in contrasted European and Middle Eastern countries is evaluated comparing the outcomes from the HCP and the Available Water Remaining (AWARE) models at the national scale, considering water supply mix data. The same analysis is carried out on selected river basins. Finally, result consistency, uncertainty and global applicability of the overall approach are discussed. The study demonstrates the reproducibility of the impact model developed for French rivers on any hydrographic network where comparable ecological, hydrological and hydraulic conditions are met. Furthermore, it highlights the need to characterize impacts at a higher spatial resolution in areas where HCP is higher. Large scale quantification of HCP opens the way to the operationalization of mechanistic LCIA models in which the habitat preferences of freshwater species are taken into account to assess the impacts of water consumption on biodiversity.

GRAPHICAL ABSTRACT



KEYWORDS

Life cycle impact assessment, water consumption, freshwater habitat, biodiversity

ABBREVIATIONS

LCA, life cycle assessment; LCIA, life cycle impact assessment; CF, characterization factor; FF, fate factor; EF, effect factor; HCP, habitat change potential; Q, river discharge; CWU, consumptive water use; HS, habitat suitability; WUA, weighted usable area; Re, Reynolds number; W, river width ; HB, HydroBASINS; WSmix, water supply mix.

1. INTRODUCTION

Human interaction with water systems in the Anthropocene is being expressed through the pervasive alteration of the global water cycle. This stimulated the contextualization of watershed scale management paradigms under a global-scale perspective leading to the production of an increasing amount of knowledge about worldwide freshwater resource availability and exploitation (Vörösmarty et al., 2013). Water use for human activities and the exportation of water-hungry products in globalized supply chains (Dalin et al., 2017; Moran and Kanemoto, 2017), besides the consideration of the geopolitical implications of global water cycle modification, call for a better understanding of effective and potential consequences on water-dependent ecosystems.

More than 50% of the major river basins on Earth are threatened by pollution and disturbance of natural flow regimes, with damming, river fragmentation and consumptive water use among the main causes of biodiversity loss (Vörösmarty et al., 2010). Notwithstanding, estimations of global river threats and biodiversity status are often partial, since small streams are barely captured by global statistics, despite being generally more sensitive to anthropic pressures. High resolution global surface water availability models are nowadays of great importance (Pekel et al., 2016) and the refinement of methods to assess freshwater requirements of ecosystems and biodiversity is needed (Janse et al., 2015; Pastor et al., 2014).

Life cycle assessment (LCA) is a service and product-oriented approach to global-scale analysis of supply chains for various impact categories, including water use. Impact indicators can quantify damage on the environment at the end of a cause-effect chain (i.e. endpoint impact on resources, human health, and ecosystem quality), or describe environmental mechanisms occurring prior to the endpoint (i.e. midpoint). Characterization factors are developed to convert inventory data (e.g. m^3 of water consumed per unit of product) to the corresponding impact indicators. Depending on the type of impact, characterization factors may consider physical change of local environmental conditions caused by a stressor (fate factor), the exposure of sensitive targets (exposure factor), and any related adverse effects (effect factor).

AWARE, a consensus model for water use impact assessment in LCA, proposed by the UNEP-SETAC Life Cycle Initiative working group on water use in LCA (WULCA), includes environmental water requirements (EWR) in the quantification of available water remaining for life cycle impact assessment (LCIA) midpoint characterization (Boulay et al., 2018). Pfister et al. (2009) developed endpoint characterization factors for freshwater consumption impacts on net primary productivity (NPP) of vascular plants as a proxy for species loss. The model proposed by Verones et al. (2017, 2013a, 2013b) quantifies potential biodiversity impacts for birds, amphibians, reptiles and mammals in wetlands. Existing LCIA models for riverine species based on species-discharge relationships (Hanafiah et al., 2011; Tendall et al., 2014) have limitations in capturing changes in river communities because they do not consider the different responses that species adapted to different habitats have to river flow reduction or increase (Damiani et al., 2019, 2018). All these models address furthermore the need for regionalized characterization factors, further raised, for instance, with recent LCA application at the territorial scale (Loiseau et al., 2018; Nitschelm et al., 2016), and should ultimately be coupled with spatially explicit information on water supplies (Leão et al., 2018).

Modeling at watershed spatial resolution is consistent with widely employed water management practices for river ecosystems protection (Palmer et al., 2009). LCIA should therefore aim at providing global, regionalized models based on mechanistic approaches applied at watershed and sub-watershed levels. At present, no operational mechanistic model to assess water consumption impacts on stream ecosystems is available at the global scale (Damiani et al., 2018; Núñez et al., 2016). A high-resolution midpoint impact indicator of habitat change potential (HCP) based on freshwater physical habitat suitability for fish species, fish guilds and benthic macroinvertebrates has recently been proposed (Damiani et al., 2019). HCP quantifies the potential change in available habitat quantity on a river and watershed scale as a result of water consumption, taking into account the habitat preferences of freshwater fish and invertebrate species. However, the model is only applicable to the French river network and a worldwide extension needs to be investigated. The present study builds on this approach proposing a method for the development of characterization factors for water consumption impacts on freshwater instream ecosystems, to be implemented worldwide.

The availability of global data required to apply the habitat suitability equations adopted in the local French mechanistic approach is first evaluated. Based on available databases, missing variables are identified, namely topographical, hydrological and hydraulic. The high-resolution HCP model is then simplified to reduce complexity of input variables and to adapt to their availability. Variables are subsequently calculated from existing models to allow implementation outside France. An application of the new HCP model (referred to as generalized or global HCP throughout the article) on the European continent and the Middle East is then demonstrated and discussed. Characterization factors are calculated at the river reach scale and then aggregated at watershed scale. Results are compared with those of the original local model applied in France and a case study on European agricultural production is presented to show potential similarities and dissimilarities between the generalized HCP model and the AWARE model, since it is the only (proxy-) midpoint method actually including water demand for river ecosystems in the characterization and providing regionalized characterization factors for watersheds worldwide.

2. MATERIALS AND METHODS

2.1 Habitat change potential at river reach scale

Characterization factors based on HCP were computed from Equation 1 (taken from Damiani et al., 2019), where CF_i is the characterization factor at river reach i. FF is the fate factor calculated as the ratio between the difference in river discharge dQ (m^3/s) for each cubic meter of consumptive water use dCWU and it is assumed to be equal to 1 (Hanafiah et al., 2011). EF is the effect factor represented by habitat change potential HCP in $m^2\,s/m^3$ (change in m^2 suitable habitat quantity induced by river discharge alteration in m^3/s), then CF = HCP. In Damiani et al. (2019), the authors calculated HCP from seventeen multivariate habitat suitability equations corresponding to four fish guilds with different habitat preferences, eight fish species where some of them at different stage of development (i.e. alevin, juvenile, adult; Lamouroux and Capra, 2002), and a generic equation for benthic macroinvertebrates.

$$\mathrm{CF_i} = \mathrm{FF_i} \cdot \mathrm{EF_i} = \frac{\mathrm{d}Q_\mathrm{i}}{\mathrm{d}CWU_\mathrm{i}} \cdot \mathrm{HCP_i} \qquad (1)$$

HCP values were aggregated at reach scale to facilitate their use in LCIA, resulting in two indicators, one of which gathers guilds and invertebrates HCPs. For a global application of the model, we adopted the latter since we assume it summarizes a sufficiently large spectrum of habitat preferences without referring necessarily to particular species for which the distribution would be uncertain (see Table S1 in Supporting Information – SI – for guilds characteristics). Nevertheless, in the aggregated characterization factor, fish species favoring shallow and running waters dominate the overall characterization factor since their habitat is more sensitive to water quantity alteration.

Data availability at the global scale is a major constraint for a worldwide application of the HCP model. In Table 1 input variables of the local HCP model are listed.

Table 1. Variables required to run the HCP model of Damiani et al. (2019)

Reach Variable	**Unit**
Upstream catchment area (*A*)	km^2
Slope (*S*)	%
Strahler order (*O*)	
Width (calculated from *Q*, *A*, *S* and *O*)	m
Depth (calculated from *Q*, *A*, *S* and *O*)	m
Substrate particle diameter	mm
Inter-annual average discharge ($\bar{Q}$)	m^3/s
Inter-annual natural Median daily discharge (*Q50*)	m^3/s
Inter-annual low flow discharge daily percentile (*Q90*), over which daily discharge is 90% of the time	m^3/s

The model applied in France in Damiani et al. (2019) is based on the French theoretical hydrographical network (RHT, Pella et al., 2012) which has a resolution of the order of meters and provides all input variables needed to quantify habitat change potentials. Data in Table 1 with the same spatial precision are currently not available globally. The products derived from the HydroSHEDS database at 15 arc-sec (≈ 500 m at the equator) represent, to our knowledge, the best available option in terms of spatial resolution of river segments and global coverage (Lehner and Grill, 2013), but hydrological, hydraulic and topographical information are seldom associated to such datasets with the same accuracy as in the RHT network.

2.2 Modeling regionalized HCPs worldwide

The difficulty in deriving data at the river reach scale for substrate composition and especially for flow magnitudes hinders the global parameterization of HCP (e.g. flow exceedance probability for *Q50* and *Q90* was calculated from daily streamflow data in the RHT network). For this reason, a generalization of the local HCP model was developed to reduce the data requirements shown in Table 1. Subsequently, input variables of the simplified model were calculated for European and Middle Eastern river segments and the results of HCP characterization at reach were aggregated at watershed scale (Figure 1).

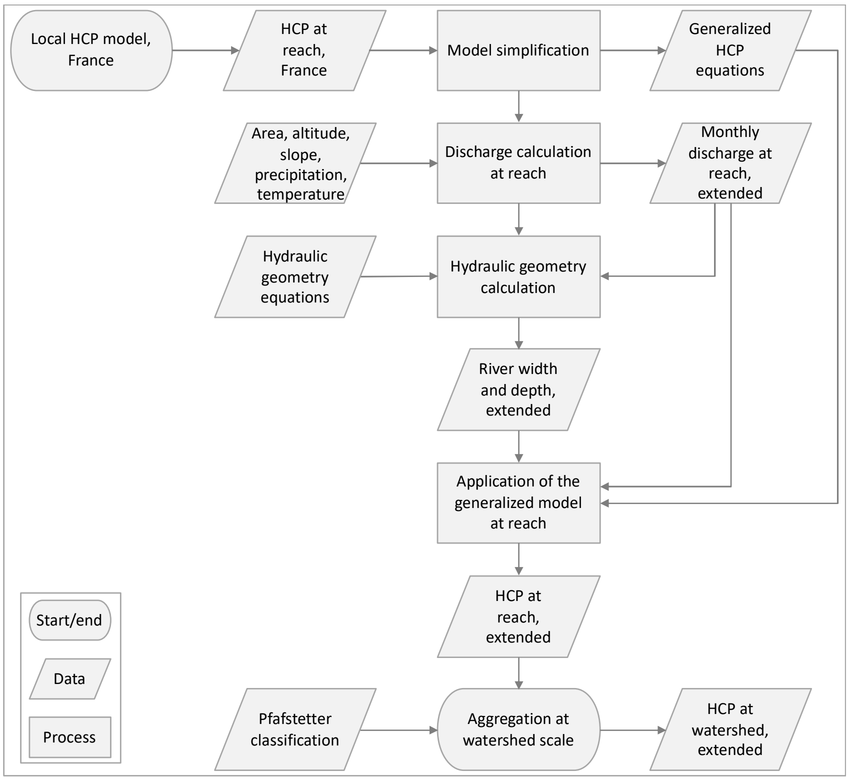


Figure 1. Logical approach for the characterization of habitat change potential at the global scale, demonstrated on European and Middle Eastern rivers

2.3 Extrapolation of a generalized HCP model

Habitat change potential was quantified on French rivers for *Q50* and *Q90*, representing median and low flows respectively. The discharge-dependent input variable of the LCIA model, which is directly altered by water consumption, is the Reynolds number *Re*, calculated as the ratio between river discharge *Q* and the product of water viscosity *v* (considered equal to 10^{-6} m^2/s) and river width *W*. To avoid working with high values, *Re* is multiplied by 10^{-7} (Damiani et al., 2019; Lamouroux and Capra, 2002; Lamouroux and Souchon, 2002). Non-linear least squares analysis was used to fit a power model to HCP results for *Re* at *Q50* and *Q90* (Equations 2 and 3). Model fitting was carried out in R (R Core Team, 2016; RStudio Team, 2016). When modeling HCP for the world's rivers, defining where and in which period of the year median and low flow conditions occur is not straightforward. To solve this, an equation was derived by fitting the model on *Q50* and *Q90* HCPs together, ranging from -1.8 to 22 396.3 m^2 s/m^3 (Equation 4). The residuals root-mean-squared errors (RMSE) indicate that the average spread of sample data around the regression line is lower than 0.5% of the HCP range for the three equations and can thus provide a measure of the goodness of fit of the simplified models.

$$HCP_{Q50} = 0.439 \cdot \left(\frac{Q50}{v \cdot W50}\right)^{-1.053} \qquad \text{RMSE} = 50 \qquad (2)$$

$$HCP_{Q90} = 0.669 \cdot \left(\frac{Q90}{v \cdot W90}\right)^{-0.998} \qquad \text{RMSE} = 108 \qquad (3)$$

$$HCP_{Q50-90} = 0.614 \cdot \left(\frac{Q}{v \cdot W}\right)^{-1.008} \qquad \text{RMSE} = 86 \qquad (4)$$

In case precise determination of flow exceedance probability is available at the scale of a river segment, Equation 2 and 3 are preferable, otherwise, and for the present study, the HCP_{Q50-90} equation was used to calculate characterization factors in Europe and the Middle East.

Nonetheless, as shown in Figure 2, results of the three models are not dissimilar, with HCP_{Q90} and $HCP_{Q50\text{-}90}$ almost overlapping for high HCP values, and the three curves converging as flow increases.

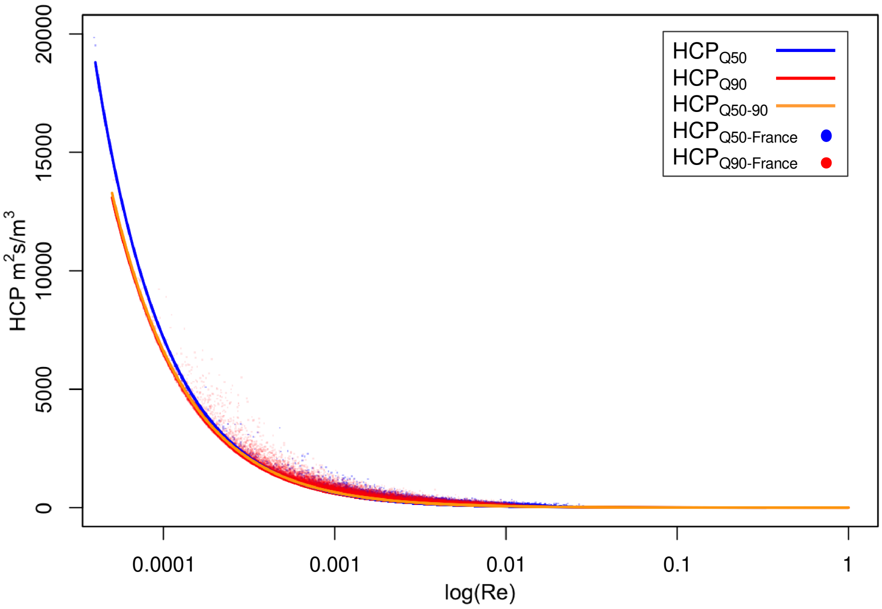


Figure 2. Power models describing HCP variation with Reynolds number. Curves fitted on HCP values at *Q50* and *Q90* in French rivers

2.4 HCP global model's input variables and application at reach scale

As demonstrated by the simplified HCP Equations 2, 3, 4, HCP can be calculated globally from river discharge and width. At present, global flow data estimated at watershed scale are available (WaterGAP, Alcamo et al., 2003; Döll et al., 2003), a global dataset have been recently derived from WaterGAP for discharge at river segment scale (Linke et al., 2019), but yet no *Q50* and *Q90* data are available. A regression model to estimate mean, annual streamflow was recently proposed based on empirical data from globally distributed gauging stations (Equation 5, adapted from Barbarossa et al., 2017).

$$Q_{\mathrm{it}} = 10^{9.066} \cdot A_{\mathrm{i}}^{1.018} \cdot H_{\mathrm{i}}^{-0.509} \cdot S_{\mathrm{i}}^{0.464} \cdot P_{\mathrm{it}}^{2.070} \cdot 10^{-0.038 \cdot T_{\mathrm{it}}} \quad (5)$$

To improve temporal resolution of existing datasets, in this study, this model was used to calculate discharge at reach i and month t from the input parameters, listed in Table 2 along with the data sources used.

Table 2. Input data for discharge calculation at river reach (adapted from Barbarossa et al., 2017)

Variable	**Unit**	**Data source**	**Reference**	**Resolution**	
				Spatial	**Temporal**
Drainage area (A)	m^2	A simple global river bankfull width and depth database	Andreadis et al., 2013	15 arc-sec	-
Altitude (H)	m	HydroSHEDS	Lehner and Grill, 2013	15 arc-sec	-
Slope (S)	(°)	HydroSHEDS (calculated)			
Precipitation (P)	m/s	WorldClim	Fick and Hijmans, 2017	30 arc-sec	Month
Temperature (T)	°C	WorldClim			

Drainage area was taken from the hydraulic geometry dataset of Andreadis et al. (2013) where catchment surface values are associated to each river segment present in the HydroSHEDS 15 arc-sec hydrographic network with river segments in desert areas masked out. Minimum, maximum and average altitudes were attributed to each segment based on the HydroSHEDS digital elevation model (DEM) at 15 arc-sec. Reach length was also calculated to be able to derive average slope in degrees according to Equation 5. A factor of 0.5 which is half of the resolution of the DEM, was added to Equation 6 to avoid zero values of slope that would result in zero discharge. It was therefore implicitly assumed that with a slope equal to zero, river reach discharge is fed by upstream water inertial flow.

$$Slope_{\mathrm{i}} = \arcsin\left(\frac{H_{\mathrm{i}\,max} - H_{\mathrm{i}\,min} + 0.5}{Length_{\mathrm{i}}}\right) \cdot \left(\frac{180}{\pi}\right) \tag{6}$$

Precipitation and temperature were derived from the WorldClim database at 30 arc-sec resolution. Considering that the dataset provides climatic data with a monthly resolution, streamflow values (Q) were calculated for each month t, substituting monthly values of P and T in Equation 5. All spatial geoprocessing was carried out using SAGA and QGIS (Conrad et al., 2015; Quantum GIS Development Team, 2017).

Currently no global databases are available including width (W) at the reach scale for monthly discharge values. However, hydraulic geometry relationships between discharge, width, depth and velocity have been described extensively and, with some approximation depending on the chosen method, can be computed by models that remain valid worldwide (Leopold and Maddock, 1953; Park, 1977; Rhodes, 1978). In particular, Morel et al. (2020) collected most of the hydraulic geometry data available at the scale of stream reaches. They found high intercontinental similarity in hydraulic geometry models between France and New Zealand, suggesting that their results can be applied globally. Here, to provide global hydraulic geometry relationships that represent variations in width W in space (among reaches) and time (with discharge Q), we used a combination of the "downstream" (in space) and "at-a-station" (in time) formulations of hydraulic geometry of Leopold and Maddock (1953), following the approach of Lamouroux and Souchon (2002) and Morel et al. (2020) (Equation 7):

$$W_{\mathrm{it}} = \left[\mathrm{a_d} \cdot \bar{Q}_{\mathrm{i}}^{\,\mathrm{b_d}}\right] \cdot \left[\frac{Q_{\mathrm{it}}}{\bar{Q}_{\mathrm{i}}}\right]^{\mathrm{b}} \tag{7}$$

where a_d and b_d are the "downstream" hydraulic geometry parameters for width, and b is the "at-a-station" exponent that describes variations with discharge. We fitted these three parameters to the data from 1304 reaches of France and New Zealand available in Morel et al. (2020), giving $a_d = 7.482$, $b_d = 0.477$, and $b = 0.148$.

To demonstrate the applicability of the global HCP model at the reach scale, habitat change potential was quantified on 449 508 river segments covering Europe and the Middle Eastern regions. Since all variables were calculated on rivers derived from SRTM-based datasets (NASA's Shuttle Radar Topography Mission), such as HydroSHEDS, the dataset is limited to rivers below 60°N latitude (taken from Andreadis et al., 2013). The original model developed for French rivers has limited relevance for high flow periods and, in consequence, the derived global model as well. Global HCP was calculated using Equation 4 on a monthly basis because for a large-scale application it is not possible to determine high, median and low flows in regions with different climate and hydrological conditions. For this reason, it is not possible to exclude some months a priori from the characterization. This choice is further discussed in section 4.

2.5 HCP aggregation at watershed scale

Regionalization of characterization factors is necessary because in LCA it is difficult to obtain the detail of local water withdrawal and release, especially for background activities and pre-compiled processes in existing databases, where only average national values are usually available. With regard to the HCP model, the optimal spatial resolution should be a trade-off between habitat model uncertainties at the local scale and HCP spatial variability (Damiani et al., 2019). HCP modeling at watershed level could be the best option in this sense. Reach HCPs were thus aggregated according to watershed boundaries defined in the HydroBASINS dataset (Lehner and Grill, 2013) at level 03 and 04 (HB03, HB04), assigning to each river segment the Pfafstetter codes corresponding to the respective watersheds. The formula used for the aggregated characterization factor at watershed (CF_{wt}) was taken from Damiani et al. (2019) where the ratio between individual length of river segments and the total length of all catchment rivers is the weighting factor for HCPs calculated at reach that are subsequently summed up in an aggregated score. However, since high stream order rivers are not included in the European database (Strahler order 1 and part of Strahler order 2), we chose to also aggregate based on average river water volume V (m^3) per month t residing in each river segment, as in Equation 8:

$$CF_{\mathrm{wt}} = FF_{\mathrm{wt}} \cdot EF_{\mathrm{wt}} = \frac{\mathrm{d}Q_{\mathrm{wt}}}{\mathrm{d}CWU_{\mathrm{wt}}} \cdot \sum_{\mathrm{i}=1}^{\mathrm{n}} HCP_{\mathrm{it}} \cdot \frac{V_{\mathrm{it}}}{\sum_{\mathrm{i}=1}^{\mathrm{n}} V_{\mathrm{it}}} \tag{8}$$

where water volume is the product of width W, depth D and length. It was therefore necessary to calculate monthly river depth D, by means of Equation 9, following the same reasoning of Equation 7:

$$D_{\mathrm{it}} = \left[\mathrm{c_d} \cdot \bar{Q}_{\mathrm{i}}^{\mathrm{f_d}}\right] \cdot \left[\frac{Q_{\mathrm{it}}}{\bar{Q}_{\mathrm{i}}}\right]^{\mathrm{f}} \tag{9}$$

where c_d and f_d are the "downstream" hydraulic geometry parameters for depth, and f is the "at-a-station" exponent ($c_d = 0.340$, $f_d = 0.259$, $f = 0.292$ from the data in Morel et al., 2020). The difference between length and volume weighting is that the first method implies equal weight for all reaches in the drainage basin and missing high order streams would likely bias the result of the characterization. In the latter the quantity of water that a river provides to the drainage basin is the weighting factor. This implies the assumption that the water consumed within a watershed has higher probability of being withdrawn from rivers with higher volume of available water.

After aggregation, the outputs of the generalized model were compared to those resulting from the French model to test results consistency. Four watersheds entirely included into French borders were taken into account. *Q90* and August characterization factors were compared for the local and the generalized model respectively. According to the data used for HCP modeling in this study, August is generally the driest month of the year, with exceptions such as in glacier-fed streams. It is therefore more likely to have low flows (*Q90*) occurring in this period of the year.

2.6 Application to European agricultural water use

The global, regionalized HCP model was applied to a case study to discuss its usability and interest for LCA. Agriculture alone is responsible for 70% of global water withdrawals (UNESCO and UN-Water, 2020), 40% in Europe (European Environment Agency, 2018). The impact of 1 m^3 water consumption for agricultural use according to available agricultural water supply mixes was assessed (WSmix, Leão et al., 2018). Calculations were made for selected European countries with agricultural water consumption greater than 1 000 million m^3/year, including Turkey and Azerbaijan (SI, Table S4). Since the HCP model applies to surface water habitats, impact is calculated for the share of surface water in the WSmix. This encompasses generic surface water consumption data, spring water, inter-basin transferred water and reservoirs. Although, artificial impoundments per se are not directly covered by the HCP model which is more sensitive to habitat variation in streams, reservoirs were included because the differentiation between the two types of water sources was available for a few countries only, while in most cases the information is hidden in generic surface water use. Moreover, reservoir water is often used to maintain river flow in dry periods or when water demand is higher, and in this case can thus be considered as stream water, except that abstraction is delayed in time. National annual average HCPs were calculated from watershed HCPs of each country and compared with the AWARE CFs for agriculture at the same spatial and temporal resolution. AWARE quantifies available water remaining after the demand of humans and aquatic ecosystems has been met (Boulay et al., 2018). Since Spain had the best detail on watershed and sub-watershed WSmixes among selected countries in Leão et al. (2018), comparisons between

HCP and AWARE were also made at watershed scale for Spanish river basins to discuss spatial scale choices for HCP characterization (SI, Table S5).

3. RESULTS AND DISCUSSION

3.1 HCP modeling at reach and watershed scale

The mean annual streamflow model applied to European rivers and adjusted with monthly climatic data, allows estimating the seasonal variability in river discharge along the year, deriving from rainfall and temperature. Figure 3 represents the detail of monthly *Q* and HCP distribution in the selected rivers excluding extreme values (R robustbase package for skewed distributions, Hubert and Vandervieren, 2008). Outliers are not represented because of the size of the data sample and the high variability of European and Middle Eastern climatic conditions and river regimes. The latter would result in extremely low discharge values for small rivers in dry periods (e.g. small streams in the Mediterranean region and the Middle East) and six orders of magnitude greater flows in big rivers during wet months (e.g. in major rivers of continental Europe). For each month, streamflow distribution is right skewed with maximum median and average values of 1.03 m^3/s and 61.58 m^3/s respectively (both in December), reflecting the predominance of small streams in the modeling dataset.

A reduction in river discharge in dry months is associated to a lower average Reynolds number in river reaches and therefore to higher habitat change potential for those habitats more likely to be damaged by water deprivation (shallow and well oxygenated running waters). Figure 3 confirms the lower availability of water in summer months and the associated higher habitat sensitivity to water consumption. In wet season, indicatively from November to April, 95% of European rivers included in the study fall between discharge values of 0 and 299.6 m^3/s. From

May to October Q is between 0 and 37.4 m^3/s. The derived HCP is comprised between 0 and 4 070.9 m^2 s/m^3 in wet months and between 0 and 13 352.9 m^2 s/m^3 in dry season (see SI, Tables S2 and S3).

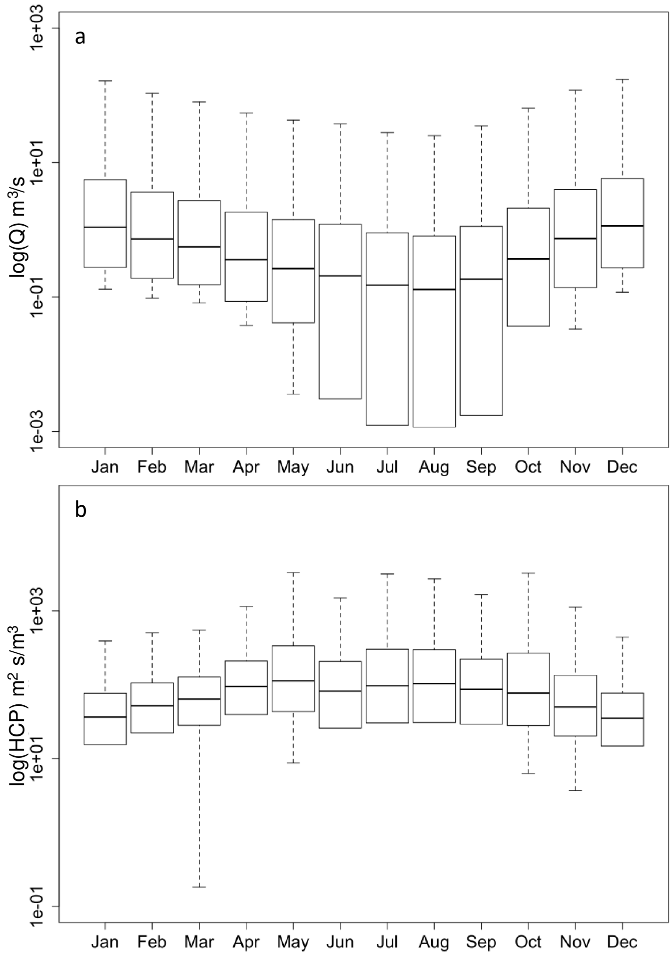


Figure 3. Monthly discharge Q in European rivers (a) and HCP characterization factors distribution (b)

Figure 4 illustrates HCP in European and Middle Eastern reaches in January and July. Characterization factors of the other months are shown in SI, Figure S1. The results highlight an increase of habitat change potential in dry season, especially in the Mediterranean region and diffusely in arid areas of the Middle East and the Caspian Sea (Kazakhstan, Turkmenistan, Iran).

Dark grey-shaded river segments are those where the HCP model cannot be applied for different reasons. Overall, HCP greater than 25 000 m^2 s/m^3 were considered outside the validity range of the habitat model, according to the scores obtained in the local HCP model (Damiani et al., 2019) from which the generalized model was derived. The maximum amount of such values was observed in August for 44 860 river segments corresponding to 10% of the total. These streams are located essentially in the Middle East and in desert regions, corroborating the non-applicability of the model since it has been developed from river ecosystems pertaining to different climatic regions and hydrological conditions.

A characterization factor is also not quantifiable in rivers where discharge is equal to 0. According to the formula used to quantify Q, described in section 2, this may happen for two reasons. The first one is for reaches that are not sustained by runoff fed from rainfall and that cease to flow periodically (Figure 4b). In the modeled dataset this applies to 12.8% of river segments maximum in September, mostly in arid and desert areas. In this case, the global HCP model is not applicable since rivers dry out and no habitat is present. Moreover, it should be considered that the uncertainty deriving from applying the characterization model on non-perennial rivers, such as those represented in Figure 4a and masked out in Figure 4b in the Arabian Peninsula, is high. In Figure 3, the peaks in HCP values in May and October is due to the fact that precipitation and thus a modest value of discharge can be attributed to these rivers at the two boundaries between wet and dry season, resulting in high HCP extremes (SI, Table S3 and Figure S1). However, ecosystems of intermittent and ephemeral rivers are still the subject of extensive research (Leigh et al., 2016) and, although potential physical habitat availability can be represented by the HCP indicator, these streams are characterized by specific ecological mechanisms that cannot be exhaustively described by the HCP model.

Discharge, and therefore HCP, could not be attributed also in river segments where the altitude is equal to or lower than 0. These conditions are distinctive in estuarine and brackish areas that are out of the scope of the HCP model. Even if fish species are not taken into account, impact of water use on wetland ecosystems is covered by the models proposed by Verones et al. (2013a, 2013b) which can be therefore complementary to our model.

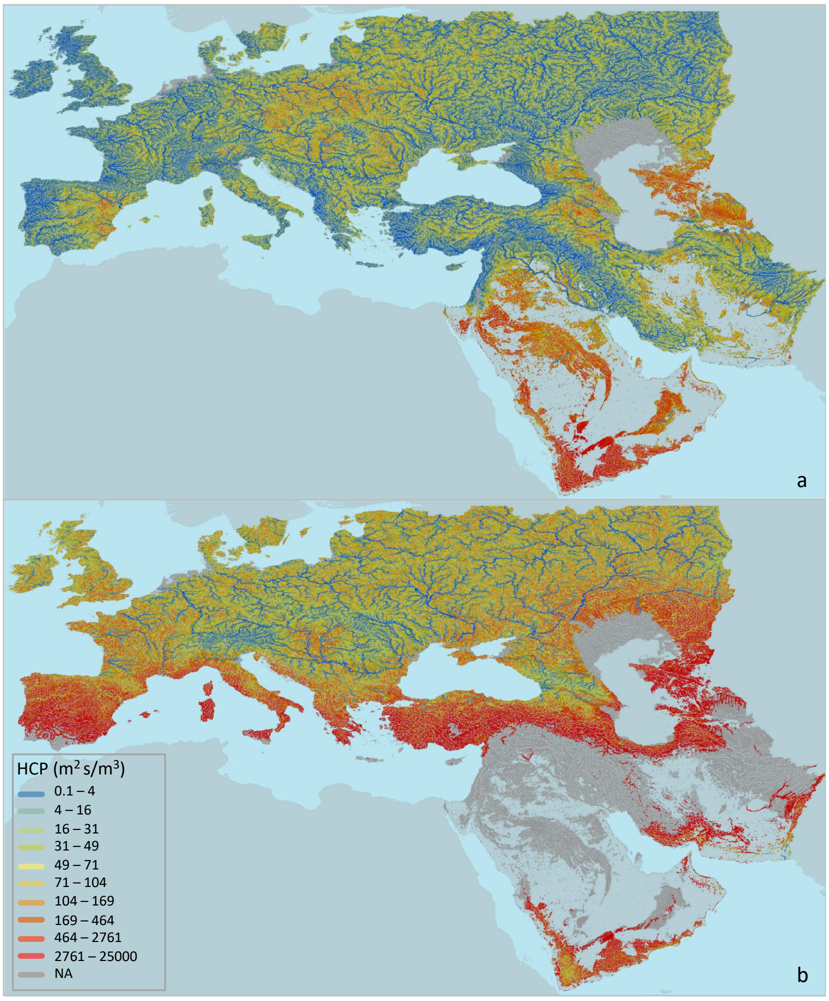


Figure 4. Habitat change potentials in a) January and b) July

3.2 Watershed characterization factors

Aggregated characterization factors at watershed level reflect the outcomes of reach-scale HCP with higher values during summer months in Mediterranean and arid regions for both aggregation formulas tested on river lengths and volumes (the latter applied in Figure 4). Higher level aggregation at HB03 averages the impact of smaller, contiguous sub-watersheds resulting overall in lower HCP scores. Outcomes of both aggregation methods highlight a decrease of HCP values when volume weighting is performed, as shown in Table 3.

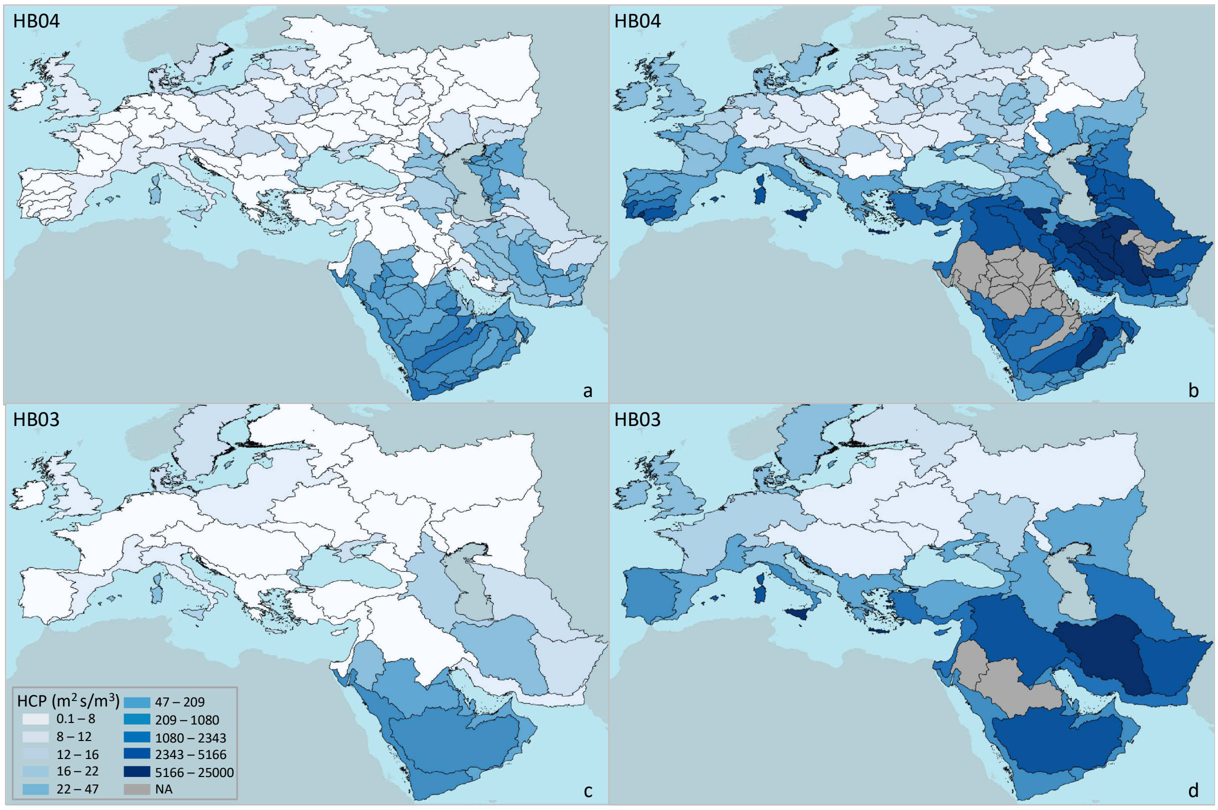


Figure 5. Aggregation of reach-scale HCPs based on water volumes in a) January, HB04; b) July, HB04; c) January, HB03; d) July, HB03

3.3 Consistency analysis

In French watersheds at HB04, the comparison between aggregated HCPs on length in the local model and in the present study showed six times smaller HCP deriving from the generalized model. This is due to the fact that small, high order streams are missing in the European database (Strahler orders 1 and 2 with higher HCP) but not in the detailed French RHT network. Moreover, the relative magnitudes of the characterization value between watersheds are different in both models. Aggregation on volume is therefore preferable as the relationships between watersheds remain consistent and the ratio between local and generalized CFs is decreased to two times when high order streams are taken into account. Recalculating aggregated CFs from the local French model excluding river segments with Strahler order 1 and 2, resulted in further reducing the discrepancy with global HCP scores for France, showing very close characterization factors (Table 3). In absolute terms, these differences are far below the root-mean-squared error associated to the generalized model in equation 4. Uncertainty resulting from deriving a generalized model from a spatially limited one, can be attenuated if at-reach characterization factors are aggregated at watershed scale. Notwithstanding, on a continental scale the deviation of generalized CFs from local CFs is negligible, as demonstrated in Figure 6 for aggregated HCPs.

Table 3. Comparison between aggregated HCP scores (m^2 s/m^3) for French watersheds from the local model (Q90) and the generalized, global characterization model applied to European river basins (July)

Pfaf	**HCP_l**		**HCP_v**				**HCP_l**	**HCP_v**	**HCP_v**	**HCP_v**	**FR**	**EU**
	FR	**EU**	**FR**	**FR St>1**	**FR St>2**	**EU**	**FR/EU**	**FR/EU**	**FR/EU (FR St>1)**	**FR/EU (FR St>2)**	**HCP_l/ HCP_v**	**HCP_l/ HCP_v**
2321	710.2	144.4	65.8	34.0	25.1	33.8	4.9	1.9	1.0	0.7	10.8	4.3
2322	898.8	126.1	72.6	38.6	28.5	26.9	7.1	2.7	1.4	1.1	12.4	4.7
2323	784.4	153.7	109.5	67.0	47.6	73.9	5.1	1.5	0.9	0.6	7.2	2.1
2324	526.6	99.7	44.4	22.4	17.0	18.8	5.3	2.4	1.2	0.9	11.9	5.3
						$\bar{x}$	5.6	2.1	1.1	0.8	10.5	4.1

Pfaf: Pfafstetter code from HydroBASINS; *St*: Strahler order; *FR*: local French model; *EU*: global model at the European scale; *HCP_l*: HCP length *l* weighting; *HCP_v*: HCP volume *v* weighting

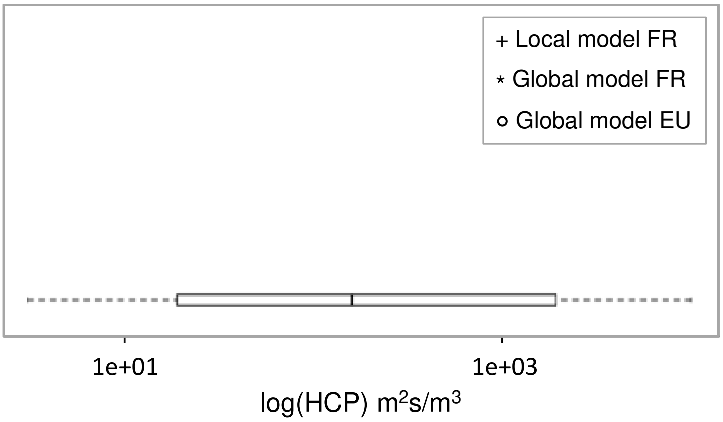


Figure 6. Characterization factors for European watersheds with the detail of French watersheds HCP calculated using the generalized (July) and the local model (Q90), including high order streams

3.4 HCP and AWARE for agricultural water use

When comparing AWARE and HCP it should be kept in mind that indicator units are not the same. While AWARE CFs are dimensionless, the HCP model quantifies the potential alteration in habitat surface (m^2) for marginal discharge change (m^3/s). At country scale, the most evident difference between both characterization approaches depicted in Figure 7a is the country where consuming 1 m^3 of water for agriculture has the greatest impact. AWARE indicates Azerbaijan as the most impacted country, while the highest HCP is attributed to Greece. This is due to intrinsic differences of both models. AWARE represents available water remaining net of water demand by humans and ecosystems (Boulay et al., 2018). As a result, high surface water demand in Azerbaijan (SI, Table S4) is likely to increase the AWARE score compared to countries where human water demand is less intense. On the contrary, HCP indicates habitat sensitivity to water consumption regardless of the use and it is rather dependent on topographical and climatic conditions. CF for Greece appears therefore higher and heavily influenced by HCP of insular areas (e.g. Figure 4 and Figure 5). When the water mix is not taken into account and the impact is allocated on all water sources indifferently, outcomes for Greece are closer in both models (SI, Figure S2). In Ukraine, a relatively large water demand is the main reason for the difference between AWARE and the HCP score, according to which stream habitats appear to be less sensitive to consumptive water use.

When corresponding inventory data are available, impact assessment can be brought to watershed level as illustrated in Figure 7b. The same concept discussed above applies to Spanish river basins where the Ebro is the most stressed according to AWARE and the Tinto-Odiel-Piedras catchment shows the highest habitat sensitivity. The HCP value for the Ebro stimulates reflection on the spatial scales used for HCP aggregation. Values for the Ebro, as well as for other sensitive Spanish river basins such as the Jucar or the Segura included in Figure 4, were averaged with reach characterization factors of Southern France at HB04 scale (Figure 5). In critical regions, a narrower spatial resolution could be beneficial to catch the detail of particularly vulnerable watersheds that would otherwise be lost using large scale characterization factors.

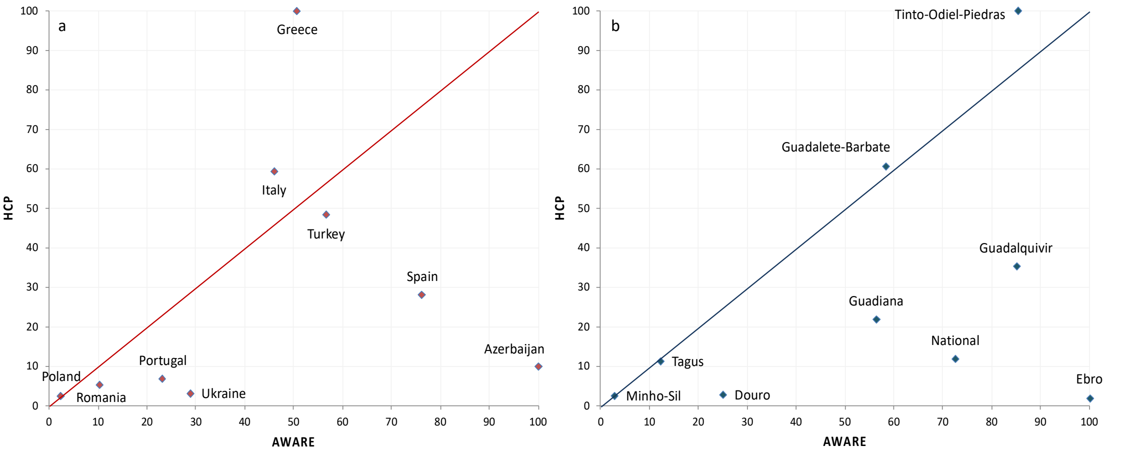


Figure 7. Impact of 1 m^3 consumption of surface water for agriculture according to AWARE and HCP characterization models at a) country level and b) watershed scale in Spain

4. CONCLUSIONS AND RESEARCH OUTLOOK

Impact assessment of water consumption through habitat change potential modeling on individual river segments represents an advancement in terms of environmental relevance and spatial resolution of water consumption LCIA models. This study demonstrates the transferability of a high-resolution local HCP model at the continental scale and the validity of the chosen approach. The new model can be used to develop global characterization factors. Results at reach scale highlighted the importance of including small streams in the assessment, since they are the most sensitive to water volume change, and the habitats they harbor are therefore more likely to be affected by consumptive water use.

Even if LCA inventories frequently do not support this level of detail, high-resolution characterization could highlight the uncertainty derived from ignoring spatial variability when characterizing at lower spatial resolution. On the other hand, if spatially resolved inventory data are used lower uncertainty could be achieved.

In order to facilitate the operationalization of the generalized HCP model, aggregation at watershed has been carried out. However, in regions where HCP at reach is higher, a more refined spatial resolution is preferable. On the contrary, for large watersheds in less vulnerable regions, for instance in Central European river basins, a high level of detail would probably be excessive and counter-productive in terms of inventory data availability. To allow applicability of the HCP model in the short-term, country HCPs can be easily calculated and, even if important details at the watershed scale may be missing, results can be compared with those deriving from existing models such as AWARE. In addition, some interesting differences were highlighted between both models demonstrating the interest of HCP characterization as a complementary indicator focused specifically on assessing impacts on freshwater habitats.

The importance of linking inventory data and impact assessment refers as well to the characterization of water consumption from a temporal point of view. For instance, in the example discussed above, annual average CFs were associated to annual WSmix. Monthly CFs are available, but the same detail is not provided by current water consumption data in inventories. Moreover, reservoir water has been included in generic surface water consumption. However, reservoirs can be used to ensure sufficient supply of water volumes needed for human activities and ecosystems in dry season, mitigating water shortage in downstream rivers, which is not taken into account in current models (neither in AWARE nor in the HCP model). Nonetheless, river regulation and inter-basin transfer may involve non-marginal changes in river environmental and ecological conditions that would not be covered by the HCP model as it is.

Concerning the temporally resolved assessment of HCP, it should also be considered that the HCP model does not apply to all flow magnitudes. Consequences of a high flow period on freshwater habitats are different than during low flows. Calculating monthly HCP has been necessary because it is not possible to define locally when low and high flows occur. However, monthly discharges used to compute HCP can be still considered averages and therefore high flow peaks are flattened. An alternative to modeling monthly CF would be to derive median and minimum discharge for each river segment as a proxy for *Q50* and *Q90*, and use the resulting HCP for the wet and the dry season respectively, as done in Damiani et al. (2019). This solution could also be compared with HCPs from average and minimum discharge modeled in other existing databases (e.g. Linke et al., 2019). Notwithstanding, the HCP value for high discharge is extremely low and yet likely to be overestimated because deriving from fitting a model on median and low flow HCPs. In addition, given the temporal resolution of HCP being monthly, this is not likely to occur frequently, assuming high flow peaks do not tend to last longer than a couple of weeks. Furthermore, inventory data are currently not likely to reflect temporal resolutions beyond trimestral or seasonal resolution and will in most cases be annual averages. Uncertainty deriving from including potential high flow periods in the characterization is therefore likely to be negligible in practice.

It is also important to mention that water consumption LCA could fully take advantage of temporal and spatial quantification of water consumption inventory data and impact characterization, only if inventory and effects are linked by a mechanistic fate factor describing water balance variations in different environmental compartments following withdrawal (e.g. aquifer, river, soil; Núñez et al., 2018).

As a long-term perspective, a mechanistic pathway linking water consumption to a fate factor and an effect factor based on HCP allows reach-scale, mechanistic, endpoint impact modeling when combined with information on the biological context at the reach scale. This could include the presence or absence of species or functional guilds adapted to a certain hydraulic habitat (considering also their economic, social, and cultural values). A reduction in river discharge in dry months results in lower average Reynolds number in river reaches and in higher HCP for those habitats, and therefore those species, more vulnerable to water volume alteration. Ecohydrological habitat models at the root of the HCP model are derived from empirical, species abundance data. Relating habitat availability to predicted sensitive species abundance and density, which is currently subject of extensive research (Lamouroux and Olivier, 2015; Mérigoux et al., 2015), could allow developing LCIA indicators of potential abundance when hydraulics is the limiting factor. In addition, regarding hydraulic modeling of river habitat, width and depth equations used in the present study are discharge dependent but can be improved including geomorphological variables, as for instance catchment slopes, geology or landcover (Morel et al., 2020).

With the purpose of developing global endpoint models based on freshwater habitat change potential, it is even more crucial to define the range of validity of the model. In the present study, HCP values greater than 25 000 m^2 s/m^3 were excluded. These were mostly associated with streams in arid and desert regions that are most likely characterized by ecological conditions different from those on which the HCP model is based. These rivers are predominantly intermittent and identified calculating discharge at monthly resolution. A better, global characterization of intermittent streams from a hydrologic and ecological perspective would certainly improve the applicability of the model in the most arid areas. To limit HCP outliers, the possibility to apply the model on a minimum discharge threshold could also be investigated, based on hydrology, water users, demographics, or water management policies adopted in certain regions.

It should also be considered that the generalized model has been developed based on local HCP calculated using habitat preference equations for species that are not ubiquitous. However, it is assumed that hydrological and hydraulic conditions within validity of the HCP model would globally determine the establishment of comparable habitats and the presence (or absence) of species with convergent behavior and habitat preferences (Lamouroux et al., 2002), allowing to define species archetypes to apply the HCP model at the global level for midpoint and endpoint LCIA.

ASSOCIATED CONTENT

A Supporting Information document is available including:

- statistics on modeled streamflow values and HCPs;
- HCP monthly maps;
- data used for the AWARE and HCP model comparison.

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