

Multicompartment Depletion Factors for Water Consumption on a Global Scale

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3	Multi-compartment depletion factors for water
4	consumption on a global scale
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18 KEYWORDS: Ecosystem, Freshwater availability, Water management, Impact assessment,19 Sustainability

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21 ABSTRACT Balancing human communities' and ecosystems' need for freshwater is one of the major challenges of the 21st century as population growth and improved living conditions put 22 23 increasing pressure on freshwater resources. While frameworks to assess the environmental 24 impacts of freshwater consumption have been proposed at the regional scale, an operational 25 method to evaluate the consequences of consumption on the different compartments of the water 26 system and account for their inter-dependence at the global scale is missing. Here, we develop 27 global-scale depletion factors that simultaneously quantify the effects of blue water consumption 28 on streamflow, groundwater storage, soil moisture, and evapotranspiration. Freshwater availability 29 and blue water consumption are estimated using the outputs from a global-scale surface water-30 groundwater model over the period 1960-2000. The resulting depletion factors are provided for 31 8,664 river basins, representing 93% of the landmass with significant water consumption, i.e., excluding Greenland, Antarctica, deserts, and permanently frozen areas. Our depletion factors 32 33 show that water consumption leads to the largest water loss in rivers, followed by aquifers, and 34 soil while increasing evapotranspiration. Depletion factors vary regionally with ranges of up to 4 35 orders of magnitude depending on the annual consumption level, the type of water use, aridity, 36 and water transfer between compartments. The developed depletion factors might be integrated 37 into sustainability assessment tools to assess the ecological impacts of blue water consumption.

38 SYNOPSIS

Balancing pressures on freshwater resources requires understanding how water consumption
changes water availability to humans and ecosystems. We develop regionalized depletion factors
quantifying historical freshwater depletion per unit consumption volume for four key
compartments of the water cycle.

43 1. INTRODUCTION

44 Currently, half of the global population lives in water-scarce areas, and this number is likely to increase by 2050. (1) On the one hand, humans depend on freshwater for industrial, domestic, and 45 46 agricultural uses. On the other hand, human well-being also relies on healthy terrestrial and 47 freshwater ecosystems and ecosystem services. (²) In many areas, human activities already extract 48 freshwater at levels that put affected ecosystems at risk, and global water demand for all uses is predicted to increase by up to 30% by 2050. $(^{3-5})$ Flow alteration, e.g., by dam construction and 49 water consumption, is one persistent threat to aquatic biodiversity. (⁶) Water consumption has also 50 51 been linked to the loss of terrestrial species, e.g., terrestrial mammals, birds, amphibians, and plants. (^{7,8}) A sustainable management of water resources is required, calling for a balance between 52 53 anthropogenic water consumption and water availability to sustain human development while 54 safeguarding ecosystems. $(^{9})$

New integrated approaches and tools are needed to address the challenges posed by multiple, and often conflicting, water needs for humans and ecosystems. (¹⁰) Several tools and methods have already been proposed to tackle these issues, including water footprinting, (^{9,11}) planetary boundaries, (¹²) integrated water resource management, (¹³) life cycle assessment (LCA), (^{14–16}) and environmentally extended multi-regional input-output analysis. (¹⁷) The integrated nature of hydrological systems requires that the assessment of environmental impacts of water consumption differentiate between water compartments to reflect distributions and renewability levels among

water sources. (¹⁸) Different compartments interact with varying strengths and over a wide range 62 63 of geographical and temporal scales with other components of the Earth system, such as the 64 atmosphere, biosphere, and lithosphere. Evaluating the ecological impacts of water management 65 decisions, particularly, requires accounting for the hydrologic processes that determine the relationships between surface and subsurface waters, as surface water, soil water, and groundwater 66 influence one another. (19) Existing life cycle impact assessment (LCIA) models for freshwater 67 consumption characterize the associated damages to ecosystems and human health. $(^{8,14,20-24})$ 68 69 However, the interlinkages across water compartments are rarely considered, except for a few 70 studies modelling the recycling and transfer of evapotranspiration and LCIA models quantifying potential impacts on ecosystems. (^{8,21,25,26}). Several of these models are not harmonized and their 71 geographical scope are limited to 30% of global wetland and the Netherlands. (8,27) Moreover, 72 73 global LCIA models used to quantify the impacts of water consumption on freshwater ecosystems do not account for the exchanges between surface water and groundwater. $(^{22-24})$ This entails that 74 1 m³ of water consumed upstream in a river basin is assumed to correspond to a reduction of 1 m³ 75 76 downstream. In reality, river basins respond differently to water withdrawals. This needs to be 77 modelled in an integrated way to account for the interactions between the different compartments and on a global scale. (¹⁸) A regionalized multimedia model would thus allow for differentiation 78 79 of the impacts of consuming water on different ecosystems (e.g., wetlands, lakes, rivers). To date, a framework for such a model has been proposed by Núñez et al. (18), but it has not been 80 81 operationalized.

Our study is a first attempt to operationalize the framework modelling water transport in LCIA and quantify the consequences of blue water consumption on freshwater availability across multiple compartments and geographical regions with global coverage. To this end, we (i) describe

85 relevant hydrological compartments and variables for human activities and ecosystem functioning, 86 and (ii) quantify the changes in these hydrological variables due to blue water consumption and 87 the exchanges between water compartments with regionalized depletion factors. We define 88 depletion factors for four compartments, i.e., atmosphere, groundwater, surface water, and soil, 89 which were identified as essential to maintain the life support, climate regulation, and water storage functions of water in the global earth system. $(^{28-30})$ To satisfy the need for spatial 90 91 differentiation, global coverage, and multi-compartment resolution, we rely on a physically-based 92 surface water-groundwater hydrological model running at a high resolution (i.e., 5-arcminutes, 93 approximately 10 km x10 km at the equator) globally.

94 2. MATERIALS AND METHODS

95 2.1. Modelling Scope

Water availability in the surface water, groundwater, soil, and atmosphere compartments can be 96 97 represented by several different hydrological variables. In this study, we selected key hydrological 98 variables for ecosystem functioning and human livelihoods based on their environmental 99 relevance, i.e., streamflow (Q), groundwater storage (GWS), evapotranspiration rate (ET), and soil 100 moisture (SM) (Table 1, Figure 1) by reviewing literature and published life cycle impact 101 assessment methods. We investigate how surface and groundwater water consumption (i.e., blue 102 water) influence the hydrological variables by calculating hydrological indicators (D_i for *i* equal 103 to Q, GWS, ET, SM) defined as the cumulated change over time in the variables induced by blue 104 water consumption (Table 1). Streamflow change is potentially detrimental to wetland, and freshwater biodiversity because it directly affects freshwater habitat size and suitability. (7,22-105 106 ^{24,27,31,32}) Soil moisture and evapotranspiration are key to the thriving of vegetation and the coupling between terrestrial water compartments and precipitation. (^{29,30}) Evapotranspiration 107

108 changes alter air moisture and regional precipitation regimes, thus possibly damage ecosystems by 109 reducing green water for natural vegetation and crops as well as blue water for freshwater ecosystems and human supply. (25,26,30,33,34) Soil drying affects vegetation activity and can 110 potentially lead to species extinctions. $(^{8,30,35})$ Groundwater storage and streamflow are equally 111 112 relevant to human water supply, as approx. 52.0% and 47.7% of total global water withdrawals 113 come from groundwater and surface water (the remaining 0.3% is desalinated). (⁵) Groundwater 114 storage change can lead to saline intrusions, groundwater depletion, and land subsidence that reduce the availability of groundwater to humans $(^{36-39})$. It can also damage freshwater and 115 116 terrestrial biodiversity. Groundwater storage and discharge support river base flow, (³) groundwater-dependent ecosystems, (8,35) and groundwater-fed wetlands, (7) while saline 117 intrusions can affect coastal streams and wetlands.⁽⁴⁰⁾ Therefore, changes in the hydrological 118 119 variables streamflow, soil moisture, evapotranspiration, and groundwater storage, in particular 120 freshwater loss, can put at risk the integrity of ecosystems and human communities.



- Figure 1: Cause-effect chain linking water consumption to hydrological indicators and subsequently to ecosystems and freshwater natural resources.
- **Table 1.** Selected hydrological indicators for estimating depletion factors.

Compartment	Hydrological variable	Unit of the variable	Description of hydrological indicator
Surface water	Streamflow Q(t)	m ³ ·yr ⁻¹	Change of streamflow, i.e., river discharge, at the outlet of the river basin $D_Q(t)$ expressed in (m ³ .yr ⁻¹). For each year (t) between 1960 and 1990, 10 years moving averages were calculated.
Groundwater	Groundwater storage GWS(t)	m ³	Change of groundwater storage volume D_{GWS} , in both confined and unconfined aquifers, between 1960 and 2000 (expressed in m ³). Volume change is estimated based on simulated groundwater head drawdown and aquifer storativity and specific yields (i.e., the volume of groundwater released from a unit area of aquifer for a unit drawdown of groundwater head). The groundwater head drawdown is the difference between the annual average

			groundwater head in the decades 1990-2000 and 1960-1970.
Soil	Soil moisture SM(t)	m ³	Change of soil moisture volume D_{SM} over the top 1.5 m of soil depth between 1960 and 2000 (expressed in m ³). The change is the difference between the annual average soil moisture in the decades 1990-2000 and 1960-1970.
Atmosphere	Evapotranspiration rate ET(t)	m ³ ·yr ⁻¹	Change of evapotranspiration rate from vegetation, bare soil, and open water D_{ET} (expressed in m ³ .yr ⁻¹). For each year (t) between 1960 and 1990, 10 years moving averages were calculated.

125

126 In hydrogeology, the term groundwater depletion refers to the persistent loss of groundwater 127 volume and decline of groundwater levels resulting from the long-term withdrawals from the 128 aquifer at a rate exceeding the annual groundwater recharge. (³⁶) Groundwater depletion also 129 increases the aquifer capture, i.e. the reduction of aquifer discharge or the increase of recharge, thus possibly resulting in streamflow depletion and loss of evapotranspiration. (^{3,36,41}) Different 130 131 from scarcity, which represents the competition between humans and ecosystems for available 132 freshwater resources on a yearly (or monthly) basis, depletion is the multi-annual (e.g., 40 years) loss of freshwater in a given region induced by water consumption. (⁴²) In this study, we extend 133 134 the concept of water depletion to the soil, surface water, and atmosphere compartments introducing 135 the hydrological indicators Di for each hydrological variable *i* (noted D₀, D_{GWS}, D_{SM}, D_{ET} and 136 defined in Table 1, Section 2.3.1, Table S2 in Support Information provides extended calculation 137 details) quantifying the change of the hydrological variables induced by total blue water 138 consumption. The hydrological indicators are calculated for a 40-years historical period (1960-139 2000) so that they reflect long-term ongoing water transfer processes. D_i describes average trends 140 that are useful to model potential environmental impacts in LCIA. The year 1960 was deemed an 141 acceptable reference state because water consumption rates have been increasing since the 1950s 142 when irrigated agriculture started to expand globally. Note that the absolute value of the

143 groundwater storage GWS(t) is unknown and only the groundwater storage change D_{GWS} is 144 quantified (Table 1). (⁵) It represents the total groundwater availability change, including the exchanges with rivers, soil, and the atmosphere. $(^{36})$ 145

- 2.2. Global-scale Surface water-Groundwater Model 146
- 147

148 We used the physically-based Global-scale Surface water - Groundwater Model PCR-149 GLOBWB-MF simulating groundwater and surface water hydrology at high resolution and 150 including water demand and water use from three different sectors, i.e., the domestic sector, the 151 industry, and agriculture (i.e., irrigation and livestock). (³) Hereafter, the model is called GSGM, its features and performance are comprehensively documented in literature. (3,43-46) The GSGM 152 153 performs a dynamic simulation of water consumption and groundwater-surface water interactions. 154 The dynamic modelling of these interactions is a unique feature of the model and a prerequisite 155 for analyzing the effects of groundwater withdrawal on streamflow (Figure S7). The groundwater 156 model MF (Modflow) simulates groundwater heads and groundwater flows in the aquifer in 3D. 157 While the lateral groundwater flows can contribute significantly to the water budget of river basins, 158 the groundwater head governs the interactions between groundwater and soil, and groundwater and rivers. (43,47) The hydrological model (PCR-GLOBWB, Figure S7b) and the groundwater 159 160 model (MF) are fully coupled to compute the interactions between surface, groundwater, and soil. 161 It also includes a vegetation compartment where the land cover is considered static, therefore, it 162 models crop water use (from precipitations and soil). The coupled model runs at 5 arc-minutes 163 resolution and at daily timestep. It includes a water demand and water use module that dynamically 164 allocates sectoral water demands from irrigated agriculture, industries, households, or livestock to 165 withdrawal of desalinated water, groundwater, or surface water based on the availability of these resources (Figure S7c). (⁴⁵) Moreover, surface water withdrawals are limited by an environmental 166

167 flow requirement, as legislation usually prescribes a minimum streamflow.(⁴⁵) Return flows of 168 unconsumed withdrawn water, flowing back to groundwater or surface water resources are 169 included in the estimate of water availability and are sector-specific. The strength of the dynamic 170 allocation scheme is that it does not depend on data on groundwater withdrawal fractions for a 171 specific year or region. Thus, the GSGM is more flexible when simulating the global hydrological 172 system over a long period in the context of climate change (⁴⁵). Section S1.1 of the Support 173 Information provides details of the GSGM.

174 Published results from the GSGM provided grid-cell estimates of routed monthly surface water 175 streamflow $(q_k(t))$, monthly groundwater head $(h_k(t))$, annual soil moisture (sum of top and bottom 176 soil moisture storage $sm1_k(t) + sm2_k(t)$, and annual evapotranspiration (et_k(t)), as well as other 177 central model inputs such as annual net water consumption rate $(wc_k(t))$, grid cell area (a_k) , and 178 aquifer storativity (Sy i.e., the volume of groundwater released from a unit area of aquifer for a 179 unit drawdown of groundwater head) (see Figure S7, calculation details in Support Information 180 Section 1.2, 1.3, and **Table S1**). ⁽³⁾ Water consumption rate is defined as the difference between 181 withdrawals and return flows. The grid cell return flows are assumed to happen in the same grid 182 cell as withdrawals. Yet, return flows to surface water can influence downstream surface water 183 availability due to river routing, and return flows to groundwater may influence streamflow 184 downstream through surface water-groundwater interactions that are explicitly included in the 185 model.

We focus on blue water consumption consequences only; thus, we removed the influence of green water consumption and climate variations on the water balance. The model was run twice: once including man-made perturbations in the form of surface water and groundwater withdrawals, dams, and reservoirs (i.e., a human-impacted run) and once without water consumption or dams 190 (i.e., a natural run). The human impacted run reflects the influence of climate, land use and blue 191 water consumption on the hydrological cycle, while the natural run only includes the effect of 192 climate and land use. To derive the depletion factors, we subtract the Di calculated with the natural 193 set from the Di calculated with the human set to remove the influence of background hydrological 194 processes on the Di. In doing so, we isolate the effect of blue water consumption (incl. 195 desalination) and dams on the water system (6,862 dams) and remove the effect of climate change and land use from the DFi. (^{48–50}) Therefore, the effect of climate change and land use is removed 196 197 from the DF_i.

198 2.3. Depletion Factors Modelling

2.3.1.

199 200

Depletion Factors

201 In hydrogeology, the capture fraction and the depletion potential indicators estimate the streamflow depletion due to additional groundwater pumping over time. (^{41,51,52}) Similarly, we 202 203 define the depletion factors in this study as the historical rate at which water availability in each 204 compartment, represented by the selected hydrological indicators, is affected by blue water 205 consumption (Table 1). Because the consequences of blue water consumption occur after a delay 206 which varies for each compartment and each river basin, we define DFs that represent the dynamic 207 evolution of the water balance over the period 1960 to 2000. In a river basin, the change in storage 208 over time is equal to the cumulated flows in and out of the boundaries of the river basin. The 209 depletion factors (DF_i) for each hydrological indicator i (noted DF₀, DF_{GWS}, DF_{SM}, DF_{ET}) are 210 derived from the equation of the water balance of a river basin over the period 1960 to 2000, as 211 explained in Support Information Section S1.4 and S1.5. Each DF_i corresponds to a selected term of the water balance representing the change in the compartment relative to the blue waterconsumption as in Eq.1 and Eq.2.

For evapotranspiration and streamflow, depletion factors follow Eq. 1, which is similar to the equation for transient multimedia fate factors proposed by Núñez et al.(¹⁸):

216
$$DF_i = \frac{\int_{1960}^{2000} D_i(t)dt}{WC} (\text{Eq. 1})$$

Where WC (expressed in m³) is the cumulated net water consumption from the river basin's 217 218 surface and groundwater from 1960 to 2000 (see Equation S1-4 and S29). The D_O and D_{ET} (expressed in m³·yr⁻¹) are integrated over time to obtain an estimate of the cumulated volume 219 220 change leaving the river basin to the ocean ($[D_O(t)dt)$ and the atmosphere ($[D_{ET}(t)dt)$ from 1960 to 2000. We corrected for climate influence by subtracting ($\int D_O(t)dt$) and ($\int D_{ET}(t)dt$) calculated with 221 222 the natural set. After this correction, the numerator of Eq.1 is interpreted as the cumulated change 223 of streamflow (D_Q) and evapotranspiration (D_{ET}) caused by blue water consumption and is 224 expressed in (m³). Therefore, the hydrological indicators (Di) represent the changes induced by 225 human blue water consumption only, excluding other influential factors such as climate change 226 and green water use (i.e., rainfall part of the evapotranspiration). For groundwater storage and soil 227 moisture the depletion factor is the ratio between the hydrological indicator D_i (D_{GWS} and D_{SM} 228 respectively) and cumulated blue consumption volume WC following Eq. 2. Eq. 2 includes the 229 cumulated change of the storages GWS and SM over time following the literature about groundwater depletion. (^{5,36,43,48}) Cumulated values are used to avoid depletion double-counting 230 231 from one year to the next.

232
$$DF_i = \frac{D_i}{WC} (\text{Eq. 2})$$

Where D_i is the difference of hydrological indicator *i* groundwater storage and soil moisture between 1960 and 2000 expressed in (m³). We also corrected the influence of climate and hydrological background on D_{GWS} , D_{SM} calculated with the human-impacted set by subtracting the cumulated changes calculated with the natural set.

237 The WC and the D_i at the river basin scale was derived from the GSGM data for the human and 238 the natural sets following the procedure described in the Supplementary Information Sections S1.3 239 to 1.5. First, the river basin-scale annual average of each hydrological indicator was computed 240 summing the grid cells' values for $wc_k(t)$, $gws_k(t)$, $sm_k(t)$, $et_k(t)$ and selecting the value of the grid 241 cell at the river mouth for $q_k(t)$ (Section S1.3). We calculated the 10-year running averages of 242 streamflow, evapotranspiration, and soil moisture to reduce the influence of inter-annual 243 variability on the depletion factors. Running averages were also applied to groundwater head and 244 groundwater storage to harmonize the interpretation of depletion factors across hydrological 245 indicators. Running averages were deemed acceptable because the objective of the depletion 246 factors is to summarize large-scale anomalies and trends. Therefore, the D_i represents the 247 cumulated change between the decades 1960-1970 and 1990-2000.

248 Because the compartments are hydrologically interconnected, changes in the hydrological 249 variables Di can be directly induced by water consumption in the same compartment or indirectly 250 by the change in the boundary flows at the interface with other water compartments. For example, 251 streamflow depletion can result from direct pumping in the river, or by the groundwater drawdown 252 induced by groundwater pumping. Therefore, the DFs include the exchanges between 253 compartments, and they can represent either a loss or a gain of water volume in the river basin so 254 that the loss in one compartment in one region can be compensated by a gain in other compartments 255 and regions. Eventually, negative DF_i values thus indicate a loss and positive DF_i values indicate a gain of water in the considered compartments between the decades 1960-1970 and 1990-2000. For example, a DF_Q value of -0.1 (streamflow) means that each m³ of water consumed has induced a reduction in the streamflow discharge volume of 0.1 m³ historically in the river basin. The DFs are dimensionless (m³ cumulative change/m³ cumulative consumption) and are derived from the water balance change over a specific period and river basin, which allows comparing the sensitivity of the different compartments to blue water consumption.

262 2.3.2. Spatial Aggregation at the Basin Scale

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We modelled and reported the depletion factors at the river basin scale (calculation details in 264 265 Section S1.2. of Support Information), here defined as the hydrologically-connected portion of 266 land with an outlet to the sea or an internal sink. We considered the river basin scale large enough 267 to support the assumption that the change of streamflow, groundwater storage, soil moisture, and 268 evapotranspiration within a river basin relates only to the consumption in the same river basin, i.e., 269 consumption and return flows of surface water occur in the same basin. This is backed by the fact 270 that human impacts on freshwater ecosystems are often studied at the river basin scale, as river 271 basin boundaries represent impassable barriers for most aquatic species. (53)

The river basin boundaries were delineated based on the hydrologically-conditioned digital elevation model used in GSGM to ensure consistency with streamflow data. This resulted in a total of 20,317 river basins with a median area of 683 km², and a range of 11 to 5,912,646 km². In basins with low consumption, i.e., below the threshold of the 25% percentile of total consumption volume over the period 1960-2000 (i.e. <0.01 Mm³/yr), we assumed that water consumption estimates in the GSGM were too uncertain to yield meaningful results. (⁵⁴) Therefore, we decided to exclude those 11,654 river basins, corresponding to 13% of the global landmass (excl. Antarctica and Greenland) and 7% of the landmass where consumption occurs, that is roughly the combined sizeof deserts in Australia, Africa, and Asia (Figure 1 land surface in grey).

The GSGM outputs were aggregated at the river basin scale to calculate the DFs following the calculation procedure described in Support Information Section 1.2, 1.3.

283 3. RESULTS AND DISCUSSION

284

Global Consumption Increase and Associated Depletion

285

3.1.

286 Global annual consumption of freshwater was estimated to have increased by approx. 20% between 1960 and 2000 (from 2200 km³.yr⁻¹ to 2625 km³.yr⁻¹) in the GSGM. Consumption has 287 288 increased for over 90% of the analyzed landmass (Figure 2). Consequently, streamflow (Q), 289 groundwater storage (GWS), and soil moisture (SM) have decreased, locally, as median depletion 290 factors (DF) were found to be negative (Figure 2, Table 2) over more than 61% of the analyzed 291 landmass. Water consumption increased evapotranspiration (ET) for 83% of the total landmass (negative DF), at a median rate of 0.23 m³ per 1 m³ water consumption. Moreover, the groundwater 292 - surface water withdrawal ratio was on average 0.05 (area-weighted median, 25th percentile: 0.01; 293 75th percentile: 0.37), which means that surface water consumption is more intense than 294 295 groundwater consumption over the considered period (river basins' ratios are shown in **Table 3**). 296 The global situation, represented by the median DF values in Table 2, can be illustrated by the 297 cases of the Ganges and Indus River basins (Figure S2, S3). In the Indus River basin, negative DFs were obtained for streamflow, groundwater storage, and soil moisture (Table 3), thus 298 299 confirming earlier observations and scarcity assessments that intense freshwater consumption has reduced surface and groundwater availability. (42,55) In the Ganges River basin, only streamflow 300 301 has decreased (negative DF), while groundwater storage, soil moisture and evapotranspiration 302 increased (positive DF). Thus, the overall water depletion due to consumption is more intense in 303 the Indus River basin than in the Ganges River basin. Positive DFs for evapotranspiration and soil 304 moisture found in both river basins indicate that irrigation provides soil moisture to support crop 305 growth. Positive groundwater storage DF in the Ganges River basin suggests that return flows 306 from irrigation is recharging the aquifer while return flows are not compensating groundwater 307 withdrawals in the Indus River basin (negative DF). These results are consistent with McDonald 308 et al.'s study of the Indo-Gangetic aquifer system, where the Indus River basin and the Upper 309 Ganges River (western part of the Ganges River basin) were reported to be subject to intense 310 groundwater depletion, causing streamflow infiltration into the aquifer and streamflow reduction at the Indus River mouth. (55) The authors also found that, the situation in the lower Ganges River 311 312 basin has not been as critical (eastern part of the Ganges River basin), with average null 313 groundwater table drawdown, and no river infiltration to the aquifer. The depletion factors portray 314 the average freshwater availability change at the basin-scale (from 1960 to 2000), but the local 315 differences between irrigated cropland versus non-irrigated land (farms and natural vegetation) are 316 masked. For instance, SM decrease and ET increase dominate in the Indus River basin but locally, 317 evapotranspiration may decrease for natural vegetation and non-irrigated farms. Irrigation is the 318 most important water use in terms of consumption volume representing from 70% to 90% of global 319 modelled withdrawals and on average 54% of country withdrawals according to FAO's statistics in 2018. (^{5,56,57}) Irrigation substitutes insufficient soil moisture to support crops' transpiration at 320 321 optimal rates, coherently with the irrigation demand calculation scheme of the GSGM. Thus, 322 positive evapotranspiration DFs were found in areas of marked irrigation practices (Figure 2). 323 Streamflow depletion has been the most widespread effect of consumption since 1960 with 7,795 324 out of 8,502 river basins being impacted, i.e., 95% of the analyzed landmass, due to the continuous

325 increase in water consumption rates from 1960 to 2000 (Figure 2, S1) and the relatively low 326 groundwater-surface water ratio. Streamflow reduction comes from the short-term effects of direct 327 withdrawals from rivers and the delayed, indirect effects of groundwater pumping. High surface 328 water consumption possibly comes from the better accessibility of surface water and average lower pumping cost, as groundwater pumping cost increases with groundwater table drawdown. (⁵⁸) In 329 330 the GSGM, surface water withdrawals occur before groundwater, as long as the streamflow is higher than the environmental flow requirements. (⁴⁵) Moreover, in approx. 40% of the river basins 331 332 where groundwater is used, increased aquifer capture contributes to streamflow decrease. $(^{47})$ In 333 this case, water from the river would continue flowing to the aquifer even though all water 334 consumption would stop. Therefore, streamflow depletion can occur in the long term (40 years) 335 despite higher renewability rates compared to groundwater.

The largest median depletion factors were found for the surface water compartment (streamflow DF). Comparing the impact of consuming 1 m³ of water on aquifers and streamflow water availability, the area weighted water loss in streamflow (-0.85 m³) is 25 times higher than in the aquifer (-0.034 m³) and 43 times higher than soil moisture (-0.019 m³).

Global groundwater depletion was estimated to 94 km³/yr based on the results (3,800 km³ from 340 1960 to 2000; in line with de Graaf et al. (³)), which is consistent to previous estimates 113 km³·yr⁻ 341 ¹ from 2000 to 2009 (⁴⁸) and from approx. 70 to 333 km³·yr⁻¹ from 1960-2010. (^{59,60}) High 342 343 groundwater storage depletion may stem from the longer response time of aquifers, i.e., time to 344 reach equilibrium, which depends on recharge rate and hydrogeological properties of the sub-345 surface (e.g., transmissivity). Aquifer response time estimates range from 10 to 1000 years in regions where groundwater consumption takes place. (61) Based on groundwater response time 346 347 maps, 2,890 (33%) of the river basins with groundwater response time below 50 years have DF₀

and DF_{GWS} representing the dynamics of water transfers over the period 1960-2000. (⁶¹) These 348 349 basins are generally small and located for example in Italy, Denmark, Southern Norway, Iceland, 350 Western Germany (Rhine basin), and Central America. Thus, groundwater storage can be 351 considered depleted over the period in the remaining 5,774 (67%) river basins, which represents 352 most of the analyzed landmass. In these regions, streamflow depletion induced by groundwater 353 pumping is delayed since surface-groundwater interactions occur at larger time scale than the 354 considered 40 years period. De Graaf et al. found that between 17% and 21% of the river basins 355 already face streamflow depletion in 2019 while 42% to 79% would in 2050, confirming the important delay necessary to observe the effect of groundwater consumption on streamflow and 356 the potential magnitude of the phenomenon. (3) Due to the long response time of aquifers, our 357 358 groundwater storage DF values likely tend to overestimate, while streamflow DFs underestimate 359 the depletion that would occur at the steady state.





Figure 2. Global maps of water consumption change and resulting depletion factors for streamflow, groundwater compartment storage, soil moisture, and evapotranspiration for 8,664 river basins from 1960 to 2000. The effect of water consumption on the different depletion factors is split between positive (left) and negative (right) values for simplicity of representation.

365 **Table 2**. Depletion factor interquartile range results, negative and positive values are shown in red

and blue respectively.

Depletion factors	Unit	25th percentile	50th percentile	75th percentile	DF<0 (% tot landmass)	
Discharge	m ³ /m ³	-0.99	-0.85	-0.43	95%	
Groundwater storage	m ³ /m ³	-0.96	-0.034	0.12	61%	
Soil moisture	m ³ /m ³	0.25	-0.020	0.010	63%	
Evapotranspiration	m ³ /m ³	0.0037	0.23	0.91	17%	

Percentiles are calculated on the depletion factors maps at 5arcmin spatial resolution. The total
 landmass excludes Greenland and Antarctica.

369 3.2. Drivers of Regional Depletion Patterns

Depletion factors for groundwater storage factors span 4 and all other hydrological indicators depletion factors span 3 orders of magnitude across river basins, showing the importance of spatial differentiation (**Figure 2**, **Table 3**). We provide below general explanations based on the results and literature about the mechanisms causing this distribution rather than case by case analysis of the depletion mechanisms. The spatial patterns of DF reflect the intensity of regional depletion in the water compartments, the type of water use (e.g., irrigation), inter-compartment exchanges (e.g., controlled by groundwater heads), and aridity.

High streamflow depletion due to consumption is found in arid regions (-1 to -0.5), such as the Mediterranean, East Australia, Central America, and Southern South America, but also in Europe and the Amazon region. Only a few river basins show streamflow increase (5% of the analyzed landmass) in arid warm regions (e.g., Australia, Arabic peninsula), where streamflow is larger with consumption than without consumption. This is possibly because approx. 80% groundwater withdrawals for industry and domestic use were returned to streamflow, compensating surface water withdrawals (a similar conclusion was drawn by de Graaf et al. (⁴⁵)). 384 Globally, evapotranspiration has overall increased due to water consumption between 1960 and 385 2000 (see DF values in Figure 2). At country scale, the analysis of remote sensing data showed 386 that irrigated agriculture has increased evapotranspiration in Brazil, China, Benin, India, Pakistan, 387 Germany and Thailand, which is consistent with the positive evapotranspiration DF distribution observed in Figure 2. (62) In addition to the irrigation effect, evapotranspiration increase is also 388 389 found in regions where the main consumption drivers are domestic water use, like in tropical Africa 390 (Congo $DF_{ET} = 1.02$). Overall, strong evapotranspiration increase is found in arid regions such as 391 Australia, e.g., in the river basin Murray-Darling where $DF_{ET} = 1.57$ is six times higher than the 392 global median value. One possible explanation is the very high potential evaporation rates in these 393 regions, which causes return flows from groundwater withdrawals or desalination tend to 394 evaporate rather than return to rivers, aquifers, or soil. In contrast to above trends, 395 evapotranspiration depletion was found in 17% of the landmass. For example in Northern Europe 396 (-0.1 to 0), Northern North America (-0.1 to 0), and Malaysia and Indonesia (-0.1 to -1). Even 397 though water consumption can increase the evapotranspiration in a grid-cell, other trends can 398 reduce it at the basin-scale. In the case of Northern North America and Northern Europe, soil 399 drying (negative DF_{SM}) can explain the reduction of evapotranspiration.

Variability in DF_{ET}, DF_{GWS} and DF_{SM} relates also to the feedbacks between groundwater, soil moisture, and evapotranspiration changes, which are driven by groundwater table depth. (61,63) In regions with shallow water table, groundwater indirectly supports evapotranspiration via capillary rise. (see the map of regions where capillary rise occurs in **Figure S8**). (61) In irrigated crop fields, evapotranspiration increases, and groundwater and soil moisture vary simultaneously because soil moisture is driven by infiltration and capillary rise (e.g., Indus, Niger DF for groundwater and soil moisture have the same sign, **Table 3**). Evapotranspiration and soil moisture are not sensitive to groundwater depletion if the groundwater table is already low and capillary rise from the
groundwater to the soil is negligible (e.g., Paraná, Sacramento DF for groundwater and soil
moisture have opposite signs, Table 3). (⁶³)

410 We found groundwater storage depletion for regions where groundwater over-exploitation has 411 been reported previously, e.g., in the Alluvial River basin of Arizona (-0.5 to -0.1), Mississippi embayment (Mississippi: -0.034), Indo-Gangetic aquifer (Indus: -0.028) (e.g., ^{5,64,65}). Groundwater 412 413 depletion is most severe in regions where water consumption is high and surface water scarce, e.g., 414 the Indus river basin. Moreover, severe depletion (<-1) corresponds to regions where long aquifer response times (>10.000 yr) and small recharge rates (e.g., estimated by Cuthbert et al. (⁶¹)) can 415 416 be observed, such as in Australia, Western USA, or in the Arabic peninsula. Positive groundwater 417 depletion factors are found in Northern Europe (>0.01), Eastern China (Yangtze: 0.0085), North-418 Eastern Brazil (São Francisco: 0.093), North-Eastern USA (Hudson: 0.07) corresponding to water 419 gains in the aquifer due to consumption. In irrigated regions, groundwater gain relates to the 420 infiltration of water used for irrigation, which can compensate for groundwater withdrawals (e.g., 421 São Francisco, Yangtze), while in other regions where irrigation is not significant, the gain of 422 groundwater may relate to groundwater lateral flows or surface water seepage rather than local 423 consumption.

Depletion factors >1 or < -1, (e.g., Danube and Murray-Darling rivers) correspond to a water gain or loss superior to WC. These changes can be compensated by losses or gains in other compartments of the same river (e.g., surface water storage), or neighbor rivers (through lateral groundwater flow changes). (⁴⁷) For instance, evapotranspiration gain in the Murray-Darling river (DF_{ET} =1.57), is compensated by losses in the other compartments (DF_Q + DF_{SM} + DF_{GWS} = -0.92) and gains from other compartments or neighbor basins (1.57-0.92 = -0.65). Similarly, the Danube 430 river loses water to other river basins or in other compartments not mapped by the DFs (sum DFs= 431 -0.97). Therefore, water consumption in neighbor river basin can influence local depletion. 432 Extreme values for DF_{GWS} and DF_{SM}, e.g., in the Zambezi river, the Amazon, and the Congo river, 433 suggest lower accuracy of the GSGM outputs and underestimation of water consumption in these 434 regions.(⁴⁶) We analyze the effect of GSGM uncertainty on the DFs in details in Section 3.5.

Table 3. Depletion factors and cumulated consumption for major river basins around the world,
 positive and negative depletion factors are reported in blue and red respectively.

	Cumulated	Depletion factors						
River basin name	consumption	Streamflow	Groundwater storage	Soil moisture	Evapo- transpiration			
	4 km ³ 1960-2000	m ³ /m ³	m ³ /m ³	m³/m³	m ³ /m ³			
Amazon	64 (+106%; 0.35)	-1.30	-1.50	-1.45	0.91			
Congo	120 (+76%; 0.03)	-0.11	-66.55	16.52	1.02			
Danube	92 (+39%; 0.06)	-1.24	-0.019	-0.0006	0.29			
Euphrate	1,940 (+11%; 0.25)	-0.63	-0.047	-0.0024	0.93			
Ganges	8,778 (+17%; 0.66)	-0.35	0.016	0.00050	0.57			
Hudson	564 (+52%; 0.02)	-0.97	0.070	-0.04	-0.022			
Indus	5,282 (+11%; 5.25)	-0.59	-0.028	-0.0022	0.80			
Mekong	3,929 (+2%; 0.01)	-0.18	-0.00064	0.00012	0.12			
Mississipi	2,520 (+33%; 0.41)	-0.86	-0.03	-0.04	0.53			
Murray-Darling	314 (+3%; 0.22)	-0.68	-0.21	-0.03	1.57			
Niger	265 (+8%; 0.02)	-0.04	-0.04 -0.16		0.71			
Nile	1,850 (+5%; 0.03)	-0.76	-0.13	0.0012	0.75			
Paraná	314 (+90%; 0.10)	-0.73	0.26	-0.23	0.36			
Rhine	288 (+55%; 0.33)	-1.03	-0.16	0.0053	0.03			
Sacramento	420 (-25%; 0.50)	-0.77	0.026	-0.00010	0.96			
São Francisco	98 (+33%; 0.28)	-0.55	0.093	0.13	0.62			
Volga	866 (+22%; 0.08)	-1.00	0.046	-0.020	0.12			

Yangtze	12.038 (+0.1%; 0.69)	-0.08	0.0085	-0.0014	0.12
Yukon	0.9 (+86%; 0.01)	-0.80	0.55	0.32	0.0026
Zambezi	5.04 10 ⁻⁴ (+158%; 0.22)	0.11	221.05	-85.47	-0.0037

Consumption change and average groundwater – surface water consumption ratio are reported
in parenthesis after the cumulated consumption. The consumption change is relative to the mean
value over the period 1960 to 2000.

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3.3. Hotspot Regions for Water Depletion

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442 Major hotspots of combined surface and groundwater depletion are revealed when overlapping the maps of negative DF for groundwater storage and streamflow. These regions include the 443 444 Amazon, North of Argentina, Central America, Sahel, Eastern Africa, North America, the 445 Mediterranean, Central and Eastern Europe, parts of North-Eastern Russia, the Middle East, 446 Central Asia, Pakistan, Mekong, North China, and Eastern Australia. Most of the hotspots river 447 basins have been reported to be water stressed for 1 to 4 months annually, except the Amazon, 448 which is not water stressed but is still negatively impacted by consumption. (⁶⁶) Therefore, water 449 efficiency improvements and consumption reduction schemes should be implemented in priority 450 in these river basins while keeping in mind social equity, for example increasing irrigation 451 efficiency and reallocating water to higher water productivity sectors. $(^{9,67})$

Moreover, putting the depletion factors in perspective with the historical change of the water system highlights the specific influence of blue water consumption on its evolution. Our results (**Figure 2**) and the identified hotspot regions indicate that water consumption contributes to observed streamflow reduction in mid and tropical latitudes, to soil drying in North Africa, Eastern Asia, Europe, and North America, which may lead to irreversible damages to terrestrial and aquatic ecosystems. (^{68,69})

Surface water and groundwater consumption effects 3.4. 458

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460 The depletion factors include the intertwined effects of surface water and groundwater 461 consumption, but each source of water consumption has a different contribution to freshwater 462 availability change. For instance, surface water withdrawals have a direct effect on streamflow. In 463 contrast, groundwater withdrawals have a direct impact on groundwater storage and an indirect 464 impact on streamflow stemming from the groundwater-surface water connection. The return flows 465 (i.e., the water that is used but not consumed) also influence the final surface and groundwater 466 availability in different ways and depending on the water use. For example, when groundwater is 467 used for industry or domestic uses, return flows go to surface water (Figure S7), while when 468 surface water is used for irrigation, it infiltrates in the soil (Figure S7). This changes the timing of 469 the freshwater resource since surface water compartment residence time is much shorter than 470 groundwater residence time. As a result, the withdrawal compartment and the return flow 471 compartment both influence the duration and the volume of the water availability change, thus the 472 DFs. Given the non-linearity of the system as exemplified above, disentangling the effect of each 473 water source remains a non-trivial issue out of the scope of this study.

- 3.5. 474
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Limitations and research needs

476 In this study we propose a first step toward the operationalization of the multi-media fate factor 477 framework proposed by Núñez et al. exploring the possibilities offered by state-of-the-art global hydrological models outputs. (¹⁸) While our depletion factors fulfill several requirements discussed 478 479 in the framework, such as spatial differentiation, global geographical coverage, mechanistic 480 modelling of the exchanges between the compartments, and regional water consumption effects, 481 other aspects need further research.

482 The adopted water budget approach at the river basin scale does not allow to quantify depletion 483 occurring in a different river basin. Aquifer boundaries do not correspond to river basin 484 boundaries, especially in the 2,890 river basins where groundwater response time is short (<50 years) and lateral groundwater transfer significant. (⁴⁷) In these cases blue water consumption in 485 486 one river basin can contribute to freshwater availability change in another neighbor basin due to 487 lateral groundwater transfer. It was however not possible to include capture zones, i.e., the portion 488 of groundwater affected by water consumption, in this study because the precise location of wells and their pumping flows are unknown at the global scale. (⁵¹) In addition, the aggregation of the 489 490 hydrological indicators at the river basin scale may be too coarse to highlight local water depletion 491 in large river basins, like the Congo or the Amazon, or smaller aquifer systems, and differences between irrigated and non-irrigated land. (⁷⁰) These limitations should be addressed in future 492 493 studies focusing on sub- or inter-river basins capture zones.

494 Another relevant improvement could be to calculate distinct depletion factors for the effect of 495 surface water withdrawal from groundwater withdrawal, as they have different effects on the water 496 cycle. Our approach was to quantify historical depletion, which results from the intertwined and 497 non-linear effect of surface and groundwater consumption. Therefore, where both surface and 498 groundwater are consumed, attributing a share of depletion to surface or groundwater consumption 499 was unpractical. As a result, the depletion factors cannot be used to assess whether consuming 500 surface water or groundwater within a river basin causes more depletion. An analytical framework 501 such as the one used by Bierkens et al. may be an approach to explore. $(^{71})$

502 Moreover, DF_{ET} quantifies the evaporation changes induced by blue water consumption but not 503 the related precipitation changes because the GSGM is not coupled with an atmospheric model. 504 The DF_{ET} could be combined with evapotranspiration recycling indicators to estimate the change 505 of precipitation over land induced by blue water consumption. (^{25,26}) Because of this feedback 506 loop, future studies using GSGMs could consider dynamic precipitation rates rather than observed 507 precipitation data.

508 Other sources of uncertainty influence the results such as the GSGM and other modelling aspects 509 Our results are tied to the GSGM outputs uncertainty, which in turns reflect the uncertainty in climate forcing and underlying datasets for parametrization. (3,43-46,54,72,73) The uncertainty is 510 511 lowest in regions where sufficient robust data is available e.g., USA, Canada, Australia, and 512 Europe. The GSGM performance for streamflow is reported to be lower in the Rocky Mountains 513 where snow dynamics dominate (as this processes are not well captured in the model), Eastern 514 Europe and African rivers (in particular the Niger) where groundwater parametrization needs improvements. (⁴⁶) It performs insufficiently for total water storage (hence including discharge, 515 516 soil moisture, and groundwater storage simulations) in the Amazon River, intertropical rivers in 517 Africa (e.g., Nile, Niger) due to issues with the meteorological forcing data accuracy (e.g., 518 precipitation) and groundwater response time parametrization issues and in high latitude basins (e.g., Yukon River, Iceland) due to deficiencies in modelling ice processes. (⁴⁶) In addition, GSGM 519 520 performance assessment shows that Malaysia, Japan, Patagonia, the Congo and the Zambezi regions perform poorly as well. (⁴⁶) As a consequence of the GSGM lower performance in these 521 522 regions, the DFs are more uncertain and should be interpreted accordingly.

Moreover, the dynamic water demand allocation scheme may introduce uncertainty in the DF because the groundwater fractions are underestimated or overestimated compared to observed data and the extraction of surface or groundwater have different effects. (⁴⁵) Domestic and industrial water consumption are underestimated, especially in regions where withdrawals for thermoelectric power plant cooling is significant, such as eastern Europe, France, the UK, Russia, eastern USA.

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(⁴⁶) Water consumption by small agricultural water users are also underestimated (⁴⁶). This results
in a systematic overestimation of the depletion factors, which partly explains DFs values >1 or <-
1. Thus, the depletion hotspots regions should be investigated further to confirm the results with
local models or field observations. Nevertheless, overall trends and anomalies are well captured
by the GSGM, thus the DFs are suitable for comparative studies across river basins.

533 The depletion factors were calculated for selected hydrological indicators essential for 534 freshwater dependent ecosystems and human communities, but not for all the hydrological 535 variables. Water availability in other compartments of the water cycle may be affected by 536 consumption, such as the surface water storage, precipitation, or lateral groundwater flows inter-537 river basins. These changes are also modeled in the GSGM but we do not provide DFs for these 538 other compartments because they are less relevant to ecosystems and freshwater resources 539 conservation. Nevertheless, the water balance is closed for each grid-cells in the GSGM and by extension in the river basins. $({}^{46}, {}^{3})$ Thus we assume that the depletion factors represent adequately 540 541 the water balance.

We considered soil moisture and evapotranspiration as hydrological variables (DF numerator) rather than consumptive green water flows (DF denominator) because our focus was on the effect of blue water consumption on the water cycle. Therefore, DF_{ET} captures the blue part of evapotranspiration but it does not capture the blue-green water consumption (soil moisture) induced by land use change. (^{34,74}) The response of the hydrological cycle to land use change could be quantified using the depletion factor approach, but comparing GSGM outputs for a natural land cover and entropized land cover. (⁵⁰)

549 Historical depletion from 1960 to 2000 is not representing steady state effects of water 550 consumption hence it should be primarily used for retrospective assessments. They might be relevant to understand the dynamics of post-2020 freshwater flows and storages where past consumption practices continue, but periodic depletion factors update is needed to represent adequately the future evolution of the water system, e.g., every decade. In particular, updates would capture changes in surface-groundwater interactions and precipitation/evapotranspiration under climate change.

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557 3.6. Potential applications for impacts assessment and water 558 management

The developed depletion factors show how sensitive key hydrological compartments are to water consumption changes at river basin level globally. Such new assessment capability can be used in several contexts to support environmental impact assessment and water use management strategies. Depletion factors use should be restricted to areas where the GSGM performance is good, excluding the regions mentioned in Section 3.5.

564 First, depletion factors can be used to operationalize water sustainability assessment. Several 565 authors proposed to shift from a single freshwater resource planetary boundary to multiple sub-566 boundaries to preserve key water functions in the global earth system i.e., hydro-climate regulation, terrestrial and aquatic biosphere support, and storage. (29,75) These sub-boundaries 567 568 cover the main water compartments - atmospheric water, soil moisture, surface water, 569 groundwater, and frozen water, and are represented by interim indicators (called control variables), 570 namely evapotranspiration, carbon uptake, streamflow, baseflow, and icesheet volume, 571 respectively. Except frozen water, our compartments and associated DFs correspond to the sub-572 boundaries scope, providing a tool to tie together water consumption, multi-compartment 573 depletion, and potential damages to aquatic and terrestrial ecosystems. Thus, depletion factors may 574 also be useful to convert the safe operating space within each sub-boundary, for example, the

575 minimum streamflow to preserve aquatic ecosystems in a river basin, into sustainable water 576 consumption allowance. Future research could investigate how to connect the depletion factors to 577 each freshwater sub-boundaries or even, if the selected hydrological indicators in this study could 578 be relevant control variables.

579 Moreover, the resulting DFs can be implemented in life cycle assessment (LCA), for example 580 to assess the potential impacts of water consumption on ecosystem quality. LCA is typically used 581 to quantify potential environmental impacts associated with products and services from a life cycle 582 perspective. They can be integrated in life cycle impact assessment methodologies to translate blue 583 water consumption to water resources depletion, human health, and ecosystems damage. For 584 example, the water consumption impact assessment on aquatic ecosystem currently used in the LCIA methodology Recipe2016, builds on the assumption that consumption of 1 m³ of water leads 585 586 to 1 m³ of streamflow reduction in any river basin across the world. $(^{22,76})$ Using the DF₀ developed in our study instead, consumption of 1 m³ of water would lead to a reduction of streamflow ranging 587 588 from 0.99 to 0.43 depending on the basin (Table 1), therefore would lead to more accurate 589 characterization factors for water use. The 1:1 assumption might be more appropriate where DFs 590 are deemed uncertain.

The use of models including the DFs in LCA is appropriate for systems where the average water supply mix is a reasonable assumption, e.g., unspecified water origin in the Life Cycle Inventory, for large-scale systems. (^{77,78}) Therefore, they can be used for modelling average impacts in LCA because the DFs equals the total depletion divided by the water consumption in the river basin. (^{14,77,78}) The reference state of the DFs is the year 1960 for data availability reason. Nonetheless, water consumption rates were estimated to be small in 1960 compared to the 2000 level the difference stemming mostly from irrigation increase. (⁵) Thus, the reference state could be assumed
"pristine" for blue water consumption in regions where irrigation is the main water use.

599 Moreover, the depletion factors could be a useful proxy for potential impacts on freshwater 600 resources in LCA. A previous study framing freshwater resources in LCA suggested using an 601 indicator named potential freshwater depletion, defined as the water consumption beyond the renewability rate for a certain period and expressed in m³. (³⁷) An estimate of long-term availability 602 603 change of streamflow and groundwater storage is the product of DF₀ respectively DF_{GWS} with the 604 water consumption. Therefore, we illustrate how to use the DFs in the LCA context to compare 605 the potential impacts of two consumer products in a fictional case study. A company decides to 606 purchase a new part, and there are two options: part A produced in Europe and part B produced in 607 the USA, both of which require the same water consumption volume for their production of 50 m³ 608 (see Table S3). To decide which part they will buy, they compare the potential impacts on freshwater availability (expressed in m³ freshwater availability change) of each part from cradle 609 610 to gate (i.e., material production and manufacturing). The company assumes that the consumption 611 volumes entirely come from the Hudson and the Rhine River basins and that it corresponds to the 612 average supply mix of surface and groundwater. The results indicate that part B has lower potential impacts on freshwater resources (Aircraft A: -59.5 m³ and B: -45 m³) because of the higher 613 614 potential streamflow depletion in the Rhine River and groundwater storage increase in the Hudson 615 River basin (Table S3). Therefore, the company gives preference toward part B.

616 Given their limitations, our DFs should be applied carefully according to the applicability domain 617 discussed in this paper. While future studies can tackle these limitations, our CFs represent a great 618 improvement compared to state of the art assumptions in water use fate factors in LCIA. Thereof, 619 they can provide important insights to water and sustainability managers by indicating which620 compartments are more vulnerable to water consumption.

621 Supporting information.

- 622 Supporting Information 1: Description of the GSGM outputs, supplementary methods to depletion
- 623 factors calculation, including supplementary figures and tables (.docx).
- 624 Supporting Information 2: Raster files of the basin delineation, cumulated consumption and
- 625 consumption 1960-2000, and depletion factors (.tiff).
- 626 This information is available free of charge via the Internet at http://pubs.acs.org.

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630 Author Contributions

631 The manuscript was written through contributions of all authors. All authors have given approval 632 to the final version of the manuscript. CrediT author statement: EP conceptualized the study. EP, 633 MD, VB developed the method; IDG pre-processed and provided the outputs of the GSGM 634 (resources); VB provided the basin delineation map; EP developed the code and performed the 635 analysis (software, formal analysis), MD produced the visualizations (maps), EP produced the data 636 curation. EP, MD, VB, IDG contributed to the original draft, MZH, MR, AL, IDG, VB, MD 637 reviewed and edited the draft, AL, MZH, and MR supervised the research, EP did the project 638 management.

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644 ABBREVIATIONS

645 DF: depletion factor, Q: streamflow, GWS: groundwater storage, SM, soil moisture, ET:

646 evapotranspiration, D_Q, D_{SM}, D_{GWS}, D_{SM}: hydrological indicators for each hydrological variable,

647 DF_Q , DF_{SM} , DF_{GWS} , DF_{SM} : depletion factor for each hydrological variable, WC: water

648 consumption, LCA: life cycle assessment, LCIA: life cycle impact assessment, EF: effect factor,

649 FF: fate factor, CF: characterization factor

650 DECLARATION OF COMPETING INTEREST

651 The authors declare that they have no known competing financial interests or personal 652 relationships that could have appeared to influence the work reported in this paper.

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