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1

2 **Regional carrying capacities of freshwater consumption –**
3 **current pressure and its sources**

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10

11 **Abstract**

12 Sustainable freshwater management is an essential target for sustainability. The concept of planetary
13 boundaries evaluates whether the environmental loads from humans are within the carrying capacity of the
14 environment at a global level, while the region-specific assessment of carrying capacities of freshwater
15 consumption can complement the global scale sustainability assessment by shedding light on regional
16 sustainability. We show that 24% of the total freshwater consumption exceeds the regional carrying
17 capacities based on spatially and temporally explicit analysis (monthly data for around 11,000 watersheds).
18 Although 19% of the current total freshwater consumption is determined as “luxury consumption” beyond
19 basic needs, approximately 60% of the exceedance attributes to basic needs of freshwater for sustaining
20 human life. The international trade alleviates the overall pressure on carrying capacity by approximately
21 4.8% (18.9 billion m³) at a global level through virtual water trade; however, several producer countries
22 demonstrate additional overconsumption beyond the regional carrying capacities , while importer countries
23 that can mitigate overconsumption. Appropriate irrigation water management and the location of crop
24 production is the key to maintain our freshwater consumption levels within the regional carrying capacities
25 on a global scale. However, measures that necessitate the consideration of watershed-specific
26 environmental and economic conditions are desirable.

27 **Keywords**

28 freshwater consumption; regional carrying capacities; potential pressure on ecosystems; virtual water
29 trade; virtual overconsumption of freshwater

30 **1. Introduction**

31 Various environmental issues may be attributed to human activities. Freshwater availability is one of the
32 most relevant environmental issues and future pressure will increase owing to an unbalance between the
33 available water resources and the predicted increase in demand¹. Several methods have been developed to
34 assess the environmental impacts of freshwater consumption attributed to the unbalance between the
35 availability and demand^{2,3}. Although these methods capture the potential impacts of freshwater
36 consumption on the environment, they do not directly argue the acceptable level of freshwater consumption
37 with regard to environmental sustainability. A key step to achieve sustainable human activities is to
38 determine the acceptable level of environmental loads in terms of ecosystems and human well-being.

39 Rockström et al. have introduced the concept of planetary boundaries that relates the current status
40 of nine environmental issues to the associated threshold levels for global environmental systems^{4,5}.
41 According to this first analysis of pressure on the planetary boundaries, three planetary systems (climate
42 change, nitrogen cycle, and biodiversity loss) exceed the planetary boundaries whereas the other systems
43 including freshwater consumption are within the safe operating space. During the estimation of pressure on
44 the planetary boundaries in these studies, the thresholds of each planetary system have been set at the global
45 level. The analysis concludes that the current level of freshwater consumption (~2,600 km³/yr) is within
46 the defined thresholds (4,000 – 6,000 km³/yr). However, this conclusion and the appropriateness to assess
47 water on a global scale has been challenged⁶, as water availability is a regional issue. A suitable availability
48 of water in few regions cannot compensate for the negative effects in water-scarce regions, even if the total
49 average of both the types of regions appears to be uncritical at first sight. Second, the projected increase in
50 the demand of food in the future will pose additional pressure on freshwater availability^{7,8}.

51 Steffen et al. have addressed the regional issues by adapting the analysis of planetary boundaries
52 of freshwater consumption from a global scale to a grid scale⁹. Their analysis of planetary boundaries of
53 freshwater consumption with the grid scale resolution reveals that several basins are subjected to a high
54 risk of exceeding regional carrying capacities, while the current freshwater consumption is still within the
55 safe boundaries on a global scale. Hogeboom et al. also demonstrated large variation in the monthly blue
56 water availability (the difference in the values of the monthly environmental flow requirement and the
57 monthly blue water runoff) in watersheds at a monthly level, which results in a wide range of estimates for

58 the planetary boundaries¹⁰. This emphasizes the significance of considering regional conditions in terms of
59 sustainability of freshwater consumption.

60 Despite the progress in previous studies that is related to the regional sustainability of freshwater
61 consumption, there are still two issues that require further improvement with regard to the sustainability
62 assessment of freshwater consumption; these include the estimation of available freshwater resources and
63 the distinction between the basic and surplus demand of freshwater for fair human life. In the previous
64 planetary boundary analyses^{4, 5, 9}, the safe boundary of freshwater consumption is defined as a fraction of
65 the estimated available freshwater flow based on a specific hydrological model. Thus, the results highly
66 depend on the estimates of freshwater flow of the chosen hydrological model. However, various
67 hydrological models give different estimates of freshwater flows based on their own characteristics of
68 modeling that result in the different estimates of safe boundary of freshwater consumption¹⁰. The previous
69 analyses on the planetary boundaries adopt the LPJmL model¹¹ as the base hydrological model on water
70 flows, which typically estimates larger volumes of freshwater flows as compared to those estimated by
71 other models¹². This implies that the previous estimates of planetary boundaries of freshwater availability
72 are rather optimistic. Further, the consideration of the freshwater requirement types for human beings are
73 rather limited. Only the water requirement for ecosystems is considered as the essential water demand in
74 terms of sustainability in the previous analyses^{4, 5, 9}. This might lead to an inconsistency between the
75 sustainability of ecosystems and human life in terms of the carrying capacity assessment of freshwater.
76 Bjørn et al. discussed the allocation issue of available freshwater to human activities at a product-level by
77 calculating the actual share of the consumption of available freshwater as compared to the allocated
78 boundary of the respective activity; this study represents that the human demand of freshwater exceeds a
79 safe operating space in several watersheds¹³. Exceeded freshwater demand of humans may deprive the
80 fundamental freshwater requirement of ecosystems, whereas the entire or some share of the human demand
81 may also be necessary for sustaining human life. In this sense, the freshwater demand for human use
82 (domestic and agricultural use) must be separated into basic and surplus demand when discussing the
83 pressure on exceeding regional carrying capacities for obtaining a complete picture of the sustainability
84 assessment of freshwater use.

85 The international trade has a significant impact, which either enables freshwater scarce countries
86 to avoid domestic freshwater consumption by virtually importing freshwater through goods (particularly,

87 food commodities), or leads to an opposite effect in exporter countries if they are affected by water scarcity
88 and produce goods for export¹⁴⁻¹⁷. The demand of freshwater in a country may be satisfied by utilizing the
89 available resources in various countries through international trade of goods¹⁸⁻²⁰, which may pose the
90 exceedance of the regional carrying capacity of freshwater consumption in a region as a result of demand
91 from other regions. Therefore, an analysis of the sources and the internal and external drivers for pressures
92 on regional carrying capacity of freshwater consumption in a region is necessary for understanding and
93 managing pressures on the regional carrying capacities on a global scale.

94 We aim to assess the pressure on regional carrying capacities of freshwater consumption in the
95 watersheds with an update of the water outflow volume data, and the inclusion of the human water
96 requirement for the sustainability assessment of freshwater consumption in the regions. These refined
97 analyses of pressure on regional carrying capacities of freshwater consumption are intended to understand
98 the current status of our safe operating space and pressure with regard to the freshwater use at a regional
99 level monthly. The analysis of human water requirement will provide insights into the potential pressure
100 on ecosystems owing to our freshwater consumption and will support to find solutions for reducing pressure.
101 In addition, owing to the link of regional boundaries and global trade, the sustainability assessment of
102 regional carrying capacities must account for the tele-coupling effects that are locally caused in the
103 watersheds and remotely induced by demand and activities in different regions. The causes of high pressure
104 in watersheds are also analyzed to reveal the sources of the current pressure on the carrying capacities in
105 various regions, which is induced by external demand through global trade. This will support to plan
106 countermeasures and manage scarce freshwater resources in the future.

107 In this analysis, the available amount of freshwater resources in a watershed refers to the estimates
108 of the freshwater resource amount calculated by the WaterGAP 2.2 model²¹ which calibrates the calculated
109 outflow from a basin with the measured outflow. The carrying capacity of the freshwater consumption in a
110 watershed is quantified by deducting the environmental water requirement (EWR) that is essential for the
111 ecosystems from the total available amount of freshwater resources in a watershed. The estimated carrying
112 capacity in a watershed is compared with the freshwater consumption to assess the pressure on the
113 watershed due to the human freshwater demand. We split the total consumption into the basic needs to
114 sustain human life (human water requirement: HWR), including water for drinking, hygiene, and food
115 production, and the surplus needs that go beyond these fundamental requirements (surplus human water

116 consumption: surplus HWC); this as further explained in the next section. The analysis is conducted for
117 approximately 11,000 basins in the world, encompassing all the continents and major islands except for
118 Greenland and Antarctica. To reveal the causes of high pressure on regional carrying capacities of
119 freshwater consumption, the overconsumption of freshwater in the exporter countries is distinguished into
120 national demand and the export of goods that are related to this demand. The overconsumption related to
121 importing goods has been elucidated in the discussion on the responsibility of importer countries. The
122 analysis of trade-related effects on overconsumption identifies the effects of global linkage through
123 international trade on exceedance of the carrying capacities.

124

125

126 2. Methods

127 2.1 Definition of regional carrying capacities and freshwater demand for humanity

128 We measured the remaining water by deducting the EWR from the amount of available freshwater in
129 watersheds, and defined it as the regional carrying capacity of freshwater consumption by referring to the
130 previous studies on planetary boundary analysis^{4,5,9}. The defined regional carrying capacity of a watershed
131 for human activities is calculated at a monthly level as per the follow equation:

$$132 \quad RCC_{x,i,m} = AW_{x,i,m} - EWR_{x,i,m}, \quad (1)$$

133 where $RCC_{x,i,k}$ (m^3) denotes the regional carrying capacity for human activities in a watershed i of country
134 x for a month m , $AW_{x,i,m}$ (m^3) denotes the amount of available freshwater in a watershed i of country x for
135 a month m , and $EWR_{x,i,m}$ (m^3) denotes the EWR in a watershed i of country x for a month m . We used the
136 monthly natural flow data from the WaterGap 2.2²¹ as the amount of available freshwater in eq 1. We
137 adopted the same approach for measuring the EWR per watershed on a monthly basis²² as that adopted
138 by previous studies on planetary boundaries, wherein different proportions of the mean monthly flow are
139 defined as the EWR subject to the classification of the mean monthly flow as compared to the mean
140 annual flow (i.e. low and high flow periods). With regard to the freshwater type, we focused on the blue
141 water consumption as well as the previous studies on the planetary boundaries of freshwater use^{4,5,9}.

142 Regarding the water requirement for humans, we first determined the values of basic needs for
143 sustaining human life (HWR), and then differentiated current freshwater consumption into the basic needs
144 (HWR) and the surplus demand beyond basic requirement (surplus HWC). The HWR was calculated
145 based on the basic requirement standards for domestic water and food supply (irrigation water demand)
146 according to the following equation:

$$147 \quad HWR_{x,i,m} = DWR_{x,i,m} + IWR_{x,i,m}, \quad (2)$$

148 where $HWR_{p,i,m}$ denotes the HWR in a watershed i of country x on a month m (m^3), $DWR_{x,i,m}$ denotes the
149 domestic water requirement (DWR) in a watershed i of a crop producer country x for a month m (m^3),
150 and $IWR_{x,i,m}$ denotes the irrigation water requirement for crop production that satisfies the minimum
151 requirement of dietary energy in a watershed i of country x for a month m (m^3).

152 With regard to the DWR, the basic daily requirement of freshwater at 50 (L/capita/day), which
153 ensured that health concerns remain low²³, was fixed. The monthly DWR in a watershed ($DWR_{p,i,k}$) was

154 calculated by multiplying the basic daily requirement with the population for each month and adding the
155 values.

$$156 \quad DWR_{x,i,m} = BDR \times Pop_{x,i} \times D_m, \quad (3)$$

157 where BDR denotes the amount of basic daily requirement of freshwater per capita and day
158 (kcal/capita/day), $Pop_{x,i}$ denotes the population in watershed i of country x (capita), and D_m denotes the
159 total days of month m (days).

160 We defined the basic requirement for food supply as the irrigation water requirement (IWR). The
161 monthly IWR in a watershed ($IWR_{x,i,m}$) was estimated by scaling the current irrigation water consumption
162 in watersheds²¹ up or down corresponding to the country average ratio of the IWR to the consumed
163 irrigation water as follows:

$$164 \quad IWR_{x,i,m} = IWC_{x,i,m} \times (IWR_{x,c}/IWC_{x,c}), \quad (4)$$

165 where $IWC_{x,i,m}$ denotes the irrigation water consumption for crop production in a watershed i of country
166 x for a month m (m^3) (see equation S1 in the Supporting Information (SI)), $IWR_{x,c}$ denotes the irrigation
167 water requirement for the production of crop c in country x (m^3) (see equation S2-S4 in the SI), $IWC_{x,c}$
168 denotes the water consumption by total irrigation for the production of crop c in country x (m^3). The
169 average ratio of the IWR to the consumed irrigation water was determined based on the monthly water
170 consumption for irrigation to ensure crop production in each watershed²⁴ and the current adequacy rate
171 of dietary energy supply published by Food and Agriculture Organization of the United Nations²⁵. First,
172 the irrigation water consumption for crop production in watersheds was aggregated on country scale for
173 a year and subsequently allocated to the national supply of each importer country based on the share of
174 supply²⁷. Subsequently, the IWR was calculated by dividing the allocated amount of irrigation water
175 consumption in each country with the dietary energy supply adequacy rate (SAR) average for years during
176 2000 to 2016), as reported by FAO²⁵. We conducted this analysis for 160 crops that were defined in the
177 reference research²⁴ and aggregated them at a country scale to obtain the average nation-wide ratio of
178 basic freshwater requirement to the current water consumption for irrigation. The detailed calculation
179 procedures including equations are presented in the SI.

180

181

2.2 Distinction between basic needs and surplus demand of freshwater

Based on the reference values of the HWR obtained from eqs 2-4, we classified the current human water consumption in watersheds into basic needs and surplus demand. The actual water consumption for basic needs might be lower than the above calculated HWR, in case HWR are not met. The portion of freshwater consumption that corresponds to the HWR is determined as the sum of the domestic and irrigation water consumption that corresponds to basic human needs:

$$BHWC_{x,i,m} = BDWC_{x,i,m} + BIWC_{x,i,m} \quad (5)$$

where $BHWC_{x,i,m}$ denotes the amount of freshwater consumption that corresponds to the basic needs in watershed i of country x for a month m (m^3), $BDWC_{x,i,m}$ denotes the amount of domestic water consumption that corresponds to the basic needs in watershed i of country x for a month m (m^3), $BIWC_{x,i,m}$ denotes the irrigation water consumption that corresponds to the basic needs in watershed i of country x on a month m (m^3). The domestic and irrigation water consumption corresponding to basic needs are defined by the following equations.

$$BDWC_{x,i,m} = \begin{cases} DWR_{x,i,m} , & DWC_{x,i,m} > DWR_{x,i,m} \\ DWC_{x,i,m} , & DWC_{x,i,m} \leq DWR_{x,i,m} \end{cases}, \quad (6)$$

$$BIWC_{x,i,m} = \begin{cases} IWR_{x,i,m} , & IWC_{x,i,m} > IWR_{x,i,m} \\ IWC_{x,i,m} , & IWC_{x,i,m} \leq IWR_{x,i,m} \end{cases}, \quad (7)$$

When the actual consumption amounts of water for domestic and irrigation purposes exceed the amount required for basic needs, the determined requirements for satisfying these demand are defined as a part of the freshwater consumption that corresponds to basic needs (eqs 3 and 4). Otherwise, all the domestic and irrigation water consumption are defined as the freshwater consumption for satisfying basic needs. The surplus demand of freshwater beyond basic needs (surplus HWC) was calculated by deducting HWR from the total freshwater consumption for human activities in a watershed for a month.

$$SHWC_{x,i,m} = THWC_{x,i,m} - BHWC_{x,i,m} \quad (8)$$

where $SHWC_{x,i,m}$ denotes the amount of surplus freshwater consumption beyond basic needs in watershed i of country x for a month m (m^3), and $THWC_{x,i,m}$ denotes the total amount of freshwater consumption for the human activities in watershed i of country x for a month m (m^3). The conceptual diagram of this distinction between the basic needs and surplus demand of freshwater for humans is available in the SI (Fig. S1).

209 **2.3 Estimation of overconsumed freshwater and potential pressure on ecosystems**

210 We referred the total freshwater consumption data that was estimated in the WaterGap 2.2²¹, including
 211 consumption for irrigation, domestic use, manufacturing, electricity production and livestock production;
 212 this was aimed at achieving a consistency with data on freshwater availability and EWR. The
 213 overconsumption of freshwater was determined as the surplus of the total freshwater consumption from
 214 the remaining water for human activities according to the following equations (see also Fig.S2 in the SI):

215
$$OverFW_{x,i,m} = OverHWR_{x,i,m} + OverSHWC_{x,i,m}, \quad (9)$$

216
$$OverHWR_{x,i,m} = \begin{cases} BHWC_{x,i,m} - RCC_{x,i,m}, & BHWC_{x,i,m} > RCC_{x,i,m} \\ 0, & BHWC_{x,i,m} \leq RCC_{x,i,m} \end{cases}, \quad (10)$$

217
$$OverSHWC_{x,i,m} = \begin{cases} SHWC_{x,i,m}, & BHWC_{x,i,m} > RCC_{x,i,m} \\ SHWC_{x,i,m} - (RCC_{x,i,m} - BHWC_{x,i,m}), & BHWC_{x,i,m} \leq RCC_{x,i,m} \\ 0, & THWC_{x,i,m} \leq RCC_{x,i,m} \end{cases}, \quad (11)$$

218 where $OverFW_{x,i,m}$ denotes the overconsumption of freshwater in watershed i of country x for a month m
 219 (m^3), $OverHWR_{x,i,m}$ denotes the overconsumed amount of HWR in watershed i of country x for a month
 220 m (m^3), and $OverSHWC_{x,i,m}$ denotes the overconsumed amount of surplus HWC in watershed i of country
 221 x for a month m (m^3). In the case that BHWC exceeded the remaining water, the difference between
 222 BHWC and remaining water was defined as the overconsumption that was attributed to the HWR; herein
 223 all of the surplus HWC was determined as overconsumption. If the amount of remaining water was greater
 224 than that of BHWC, exceedance of the sum of BHWC and surplus HWC from the remaining water was
 225 defined as overconsumption that attributed to surplus HWC. When the value of the sum of HWR and
 226 surplus HWC (THWC) was smaller than that of the remaining water, no overconsumption was observed.

227 Overconsumption of freshwater for human demand deprives EWR, which may result in the
 228 occurrence of severe impacts on ecosystems. Several previous studies assessed the potential impacts of
 229 freshwater consumption on ecosystems by targeting the specific cause-effect pathways^{28–33}. No
 230 consensual methods to assess the potential impacts of freshwater consumption have been developed
 231 although a critical review summarizes relevant issues for the assessment³⁴. To account for the potential
 232 ecosystem impacts, in addition to the absolute amount of overconsumption, we adopted the ratio of
 233 freshwater overconsumption to EWR as a proxy indicator to assess the potential impacts of deprivation
 234 of EWR by exceedance of the regional carrying capacities on ecosystems:

235
$$PIE_{x,i,m} = OverFW_{x,i,m} / EWR_{x,i,m}, \quad (12)$$

236 where $PIE_{x,i,m}$ denotes the potential impacts on ecosystems associated with deprivation of EWR by
 237 overconsumption of freshwater by human activities in watershed i of country x for a month m
 238 (dimensionless).

239 **2.3 Food trade induced overconsumption and identification of responsible countries**

240 In most countries, major demand of freshwater consumption is for irrigation purposes during crop
 241 production^{21, 35}. Considering the proportion of freshwater demand, the irrigation demand dominates a
 242 major part of overconsumption (see Fig.2 in the results and discussion). Based on the results of
 243 differentiating irrigation water consumption between the national and the foreign demands (eqs S1, S2,
 244 and S3 in SI), we estimated the trade-induced overconsumption of crop-associated freshwater with regard
 245 to the consumer as well as the producer perspective.

246 For producer countries, the sum of exporting crop-associated overconsumption was compared
 247 with the national overconsumption to understand the extent to which the total national overconsumption
 248 was induced for satisfying demand in other countries. Freshwater overconsumption associated with
 249 national supply and exporting crops is calculated as a part of the irrigation water consumption that
 250 corresponds to a surplus crop production rate when compared to the minimum requirement of dietary
 251 energy:

$$252 \quad ODC_x = \begin{cases} \sum_c DomIWC_{x,c} \times (IWC_{x,c}/IWR_{x,c} - 1), & IWC_{x,c} > IWR_{x,c} \\ 0, & IWC_{x,c} \leq IWR_{x,c} \end{cases}, \quad (13)$$

$$253 \quad OEC_x = \begin{cases} \sum_c \sum_y ExpIWC_{x,c,y} \times (IWC_{x,c}/IWR_{x,c} - 1), & IWC_{x,c} > IWR_{x,c} \\ 0, & IWC_{x,c} \leq IWR_{x,c} \end{cases}, \quad (14)$$

254 where ODC_x denotes freshwater overconsumption associated with domestic supplied crops in producer
 255 country x (m^3), and OEC_x denotes freshwater overconsumption associated with exporting crops to
 256 importer country y in producer country x (m^3).

257 With regard to the importer country, the overconsumption of irrigation water that is associated
 258 with the imported crops from all countries is compared with the amount of national overconsumption;
 259 this is aimed at understanding the significance of the induced overconsumption in other countries, in
 260 relation to the domestic situation. However, the import of crops may potentially avoid overconsumption
 261 in importing countries through virtual water trade. Therefore, the virtually saved overconsumption of
 262 freshwater in importing countries is compared with the actual overconsumption of freshwater associated

263 with imported crops in the producer countries. This facilitates the assessment of the potential benefits of
 264 virtual water trade in terms of the global scale carrying capacity, while clarifying the relationship between
 265 global and regional sustainability of freshwater consumption. National overconsumption of importer
 266 countries can be determined by eqs 9, 10, and 11. Overconsumption associated with importing crops and
 267 virtually saved overconsumption of freshwater in importer countries are calculated by the following
 268 equations:

$$269 \quad OIC_y = \begin{cases} \sum_x \sum_c ExpIWC_{x,c,y} \times (IWC_{x,c}/IWR_{x,c} - 1), & IWC_{x,c} > IWR_{x,c} \\ 0, & IWC_{x,c} \leq IWR_{x,c} \end{cases} \quad (15)$$

$$270 \quad VSO_y = IWC_{y,c} \times (IM_{y,c}/DP_{y,c}) \times (OverFW_y/THWC_y), \quad (16)$$

271 where OIC_y denotes the freshwater overconsumption associated with importing crops in importer country
 272 y (m^3), VSO_y denotes the virtually saved overconsumption of freshwater in importer country y (m^3), $IM_{y,c}$
 273 denotes the imported amount of crop c in importer country y (ton), $DP_{y,c}$ denotes the amount of national
 274 production of crop c in importer country y (ton), $OverFW_y$ denotes overconsumption of freshwater in
 275 importer country y (m^3), and $THWC_y$ denotes the total amount of freshwater consumption for human
 276 activities in importer country y (m^3). The imported amount and the national production of crops are taken
 277 from the crop production statistics by FAO²⁶.

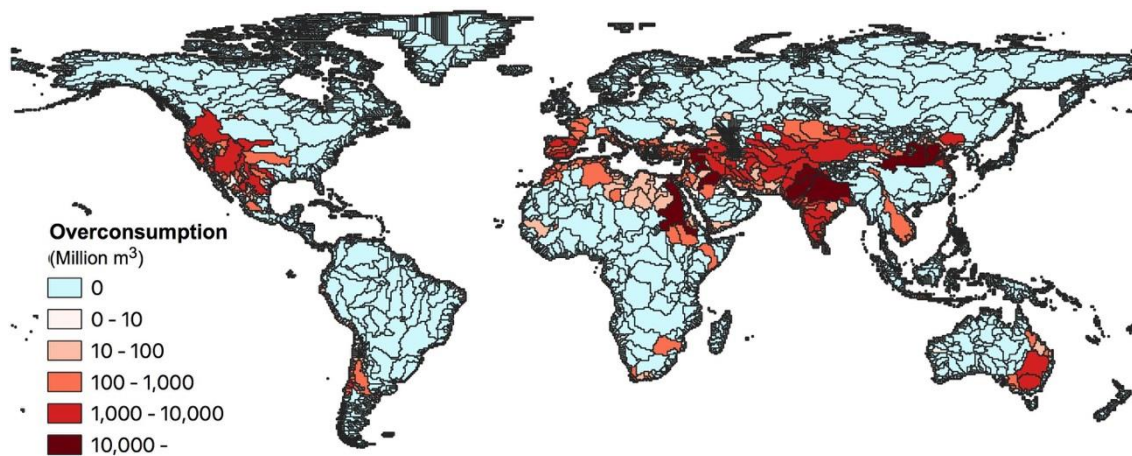
278

279 **3. Results and discussion**

280 **3.1 Overconsumption beyond regional carrying capacities**

281 Our estimation of overconsumed freshwater amounts beyond regional carrying capacities in watersheds
282 indicates a significantly more severe situation in numerous watersheds compared to a previous analysis⁹.
283 The annual total amount of overconsumed freshwater is calculated at 393 billion m³, which accounts for
284 approximately 24% of the current total global freshwater consumption (1,671 Billion m³). This exceedance
285 occurs in 1,865 watersheds (approximately 17% of the total) in the world (Fig. 1). These watersheds account
286 for approximately 79% of total annual demand of freshwater in the world, which indicates that most of our
287 current freshwater demand contributes to overstepping the boundaries for a safe operating space of
288 freshwater consumption at watershed level. The estimated overconsumption amount is different from that
289 presented in a previous analysis⁹, however, concerned areas of overconsumption generally overlapped
290 based on the results of the previous and this analyses; further, concerned areas of water stress in other
291 studies also overlapped with those in this study, based on physical water stress analysis^{24,36}.

292



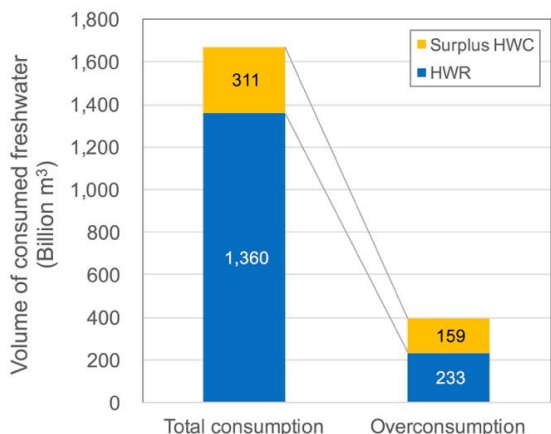
294 **Fig. 1.** Global map of freshwater overconsumption beyond regional carrying capacities. The map presents
295 the annual total amount of freshwater consumption in watersheds that exceeds regional carrying
296 capacities for a month or more. Regional carrying capacities are defined as the amount of available
297 freshwater for human demand in watersheds excluding the environmental requirements for ecosystems
298 from the natural water flow. Depth of red color represents magnitude of overconsumed freshwater
299 amount in watersheds.

300

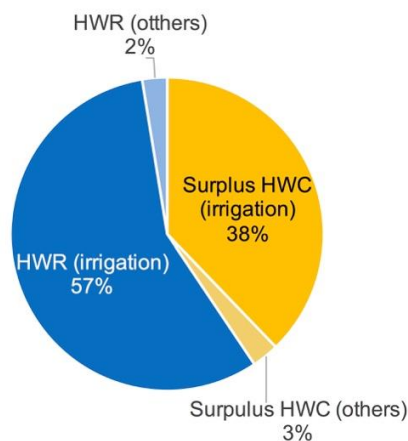
301 Overconsumption of freshwater may be attributed to our “luxury consumption” (surplus HWC),
302 which is an additional demand of freshwater for human activities beyond the basic needs to sustain human
303 life. By discriminating the basic and surplus demand of freshwater for humans, approximately 19% (311
304 billion m³) of our current total freshwater consumption is determined as surplus demand beyond essential
305 requirement of freshwater (Fig. 2a). However, surplus HWC resulting in overconsumption is estimated at
306 approximately 159 billion m³, suggesting that means that 41% of overconsumption is caused by surplus
307 freshwater consumption beyond basic needs, whereas the rest of overconsumption (59% to the total) is
308 caused by the lack of freshwater for basic needs (Fig. 2a). Irrigation demand is mostly responsible for
309 overconsumption in cases of both surplus HWC and basic demand of humanity (HWR) (Fig.2b). In some
310 watersheds, a safe operating space (which represents the volume of freshwater left for humanity) is not
311 sufficient for fulfilling the basic demand of humanity (HWR). Particularly, in the watersheds of Northern
312 Africa, Central Asia, Western Asia and Southern Europe, HWR is close to or already exceeds the safe
313 operating space (93% (Northern Africa), 109% (Central Asia), 98% (Western Asia), and 107% (Southern
314 Europe), respectively) (Fig.3). Besides, most of the watersheds (91%) where the basic needs (HWR) cause
315 overconsumption also face overconsumption by surplus demand (HWC) (Fig.S3), which suggests that the
316 luxury demand of freshwater accelerates overconsumption even in most of the watersheds facing
317 overconsumption owing to the basic needs. The deficit in freshwater for basic human demand accounts for
318 half of the overconsumption and may pose potential impacts on ecosystems in some watersheds, whereas
319 the surplus HWC beyond basic needs will accelerate and enhance the exceedance of regional carrying
320 capacities.
321

322

a

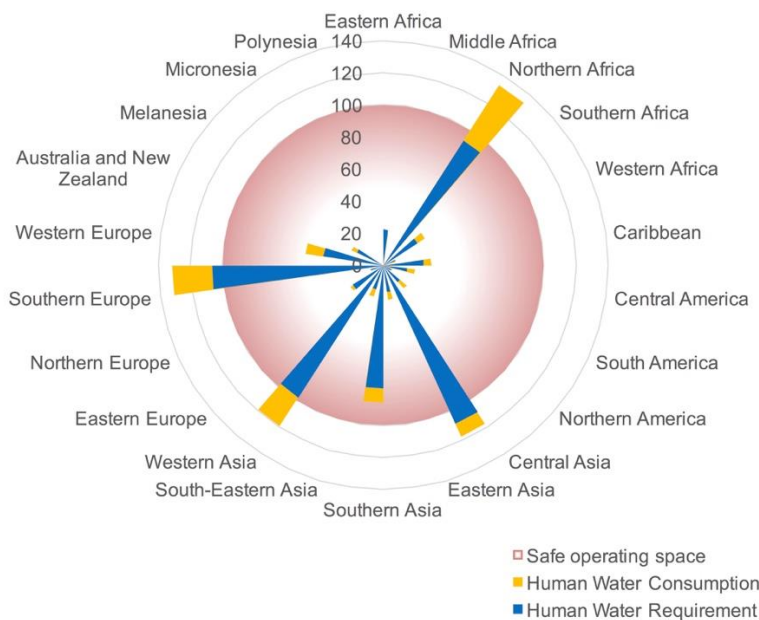


b



323

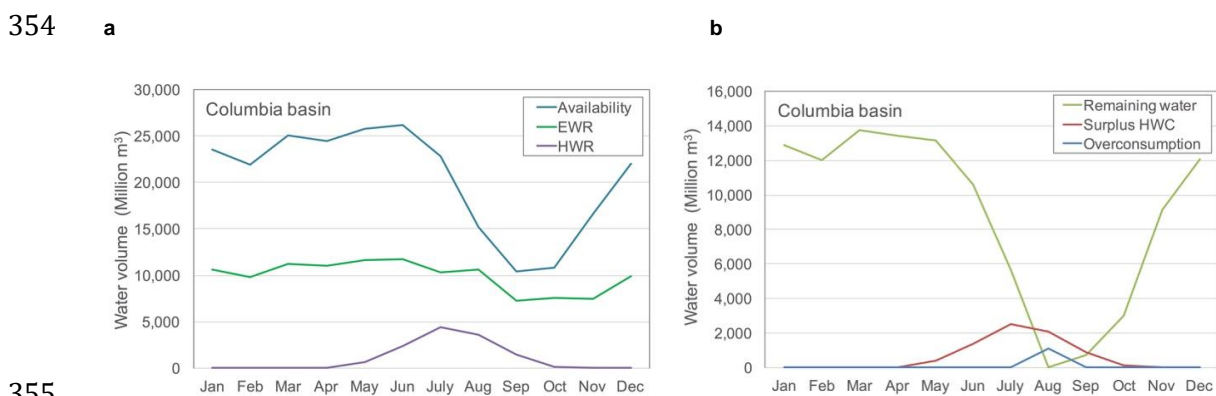
324 **Fig. 2.** Amount of freshwater overconsumption and its cause. Breakdowns of freshwater demand (human
 325 water requirement (HWR) and surplus human water consumption (Surplus HWC)) in the total
 326 consumption and overconsumption (a) and contributions of irrigation and other demand to the total
 327 overconsumption (b). Monthly consumption and overconsumption of freshwater are summed up for all
 328 watersheds over the year in the figure.



329

330 **Fig. 3.** Regional status of pressure on carrying capacities of freshwater consumption. Bars are the ratios
 331 of HWR and total HWC to the regional carrying capacities of freshwater in each region (the annual
 332 average weighted by HWR and HWC, respectively). The blue bars represent pressure of human basic
 333 needs (HWR) on carrying capacities in regions. The yellow bars represent pressure of total human
 334 demand (the total HWC), whereas the difference between the yellow bars and the blue bars indicates
 335 pressure of surplus HWC on carrying capacities in regions. Gradient red colored area represents the safe
 336 operating space of freshwater consumption regarding the regional carrying capacities.

337 In general, overconsumption occurs in watersheds where remaining water amount for human use
 338 is small or 0 (Figs. 1 and S4). However, a relatively fair amount of remaining water is available as the
 339 yearly total in several watersheds (e.g. Columbia basin (north-western part of the United States of America),
 340 Ganges basin (north-eastern part of India) and Mekong basin (Cambodia, Lao PDR, south-western part of
 341 China)) (Fig. S4), whereas overconsumption occurs in these watersheds within few months (Fig.1). This is
 342 attributable to temporal variations in availability and demand of freshwater in these watersheds. As an
 343 example of such a situation, in the Columbia basin, surplus HWC increases from May to September (Fig.
 344 4b); however, overconsumption occurs only in August when the remaining water amount drops zero
 345 because of low availability and increasing demand (Fig. 4a and b). This is the case for most of watersheds
 346 where overconsumption occurs. On a global scale, 95% of overconsumption (374 billion m³) occurs in a
 347 month when no remaining water is the available in watersheds. These facts highlight the additional risks of
 348 exceeding carrying capacities temporarily as water availability is not only regional, but also seasonal. The
 349 temporal unbalance of freshwater availability and demand can occur, even if, on average, there is remaining
 350 water for “luxury” consumption throughout a year. Water storage options (e.g. dams and reservoirs) can be
 351 used to overcome temporal shortage of water availability considering their advantages and limitations³⁷.
 352 However, for the purpose, potential effects on downstream ecosystems by water flow changes³⁸⁻³⁹ and
 353 considerations of appropriate management to minimize the effects⁴⁰⁻⁴¹ will need to be considered.



356 **Fig.4** Temporal variation in overconsumption and its cause. An example (Columbia basin) of monthly
 357 freshwater availability and demand (EWR and HWR) (a) and resulting remaining water, surplus HWC,
 358 and overconsumption (b). Remaining water represents the amount of available freshwater available for
 359 luxury demand after environmental and human water requirements are satisfied.

360

361 However, 22% of overconsumption occurs in watersheds where overshoot occurs throughout a

362 year and more than half amount of overconsumption occurs over at least six months (Fig. S5). This implies
363 that some watersheds already face continuous deficit in freshwater for surplus demand for humanity. The
364 temporal or continuous overconsumption arising from freshwater consumption by human activities may
365 have potential impacts on ecosystems that cannot avoid or immediately adopt to the changes associated
366 with the deprivation of freshwater.

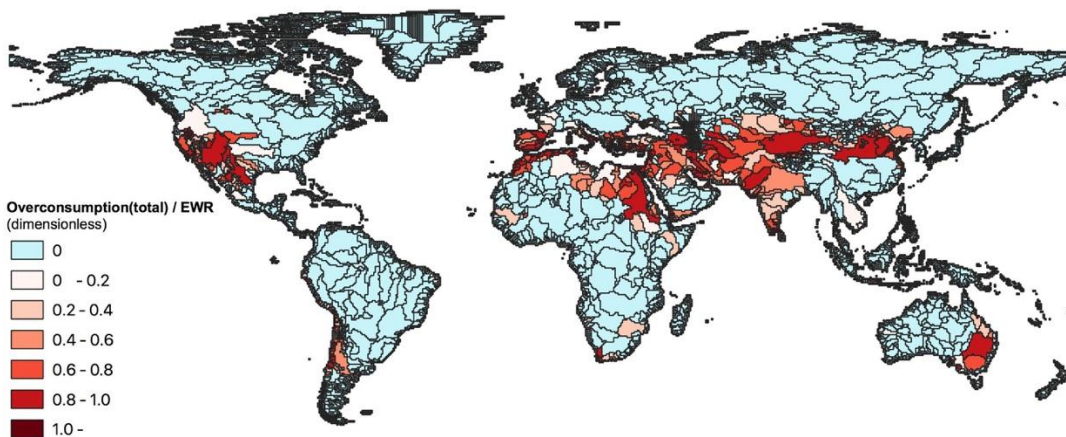
367 Most of freshwater overconsumption is caused by irrigation demand for crop production, which
368 dominates approximately 70% of the total freshwater demand^{21, 35}. In fact, 149 billion m³ of “luxury”
369 freshwater is consumed for irrigation (48% of the total surplus HWC) to support the dietary requirements
370 in some countries (particularly, the developed countries) beyond the basic requirement defined in this
371 analysis (Fig. 2b). However, this additional freshwater consumption for irrigation is not ubiquitous;
372 numerous watersheds have remaining water available for luxury consumption (Fig. S4) and the current
373 freshwater consumption including surplus demand is still within the regional carrying capacities of many
374 watersheds (Fig. 1 and 3). The most critical issue is the fact that overconsumption by surplus HWC occurs
375 in watersheds that are already fall short of freshwater resources required for basic human needs (Fig. S3).
376 The surplus demand of freshwater may not be the first cause of overconsumption, but it accelerates the
377 exceedance of regional carrying capacities that results in increasing potential impacts on ecosystems.
378 Additionally, it represents opportunities to reduce water consumption and enhance water productivity for
379 reaching the water consumption level within the regional carrying capacities.

380 The causes of shortage in freshwater resources for basic human needs can be separated into two
381 types. The first one is the temporal mismatch of freshwater supply and demand (an example shown in Fig.
382 4). Mismatch of freshwater supply and demand occurs in some watersheds only during limited periods (less
383 than 6 months in 36% of watersheds facing overconsumption) (Fig.S5). In such cases, the shift of cropping
384 timing, that is also assumed as an option for adaptation to climate change⁴², may reduce pressure on regional
385 carrying capacities in terms of freshwater consumption. However, more fundamental measures are required
386 for other watersheds where mismatch of freshwater supply and demand is more continuous (over 6 months
387 in 51% of watersheds facing overconsumption) (Fig. S5). Besides the improvement in irrigation efficiency,
388 the shift in crop types to less water intensive crops or change of production location to remaining water
389 abundant watersheds will be required for reducing potential impacts on ecosystems caused by freshwater
390 overconsumption.

391 **3.2 Severity of overconsumption for ecosystems**

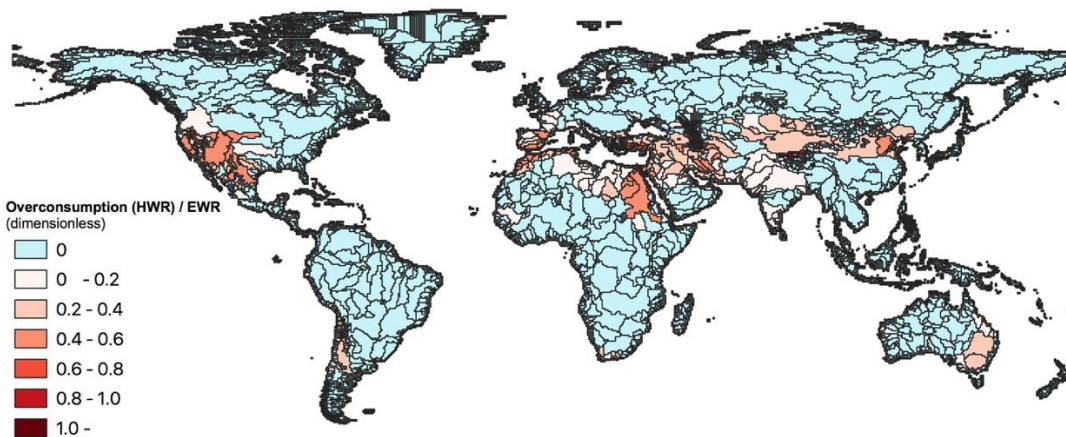
392 Ecosystems are the first receptors that directly experience the pressure of exceeding carrying capacities of
393 freshwater consumption. Exceeded amount of freshwater consumption for human activities will partially
394 or completely deprive the fundamental freshwater requirement for ecosystems (EWR). The severity of
395 overconsumption depends on the proportion of deprived freshwater to the total EWR; therefore, the ratio
396 of overconsumption to the EWR is a good proxy to assess severity of freshwater overconsumption on
397 ecosystems.

398 a



399

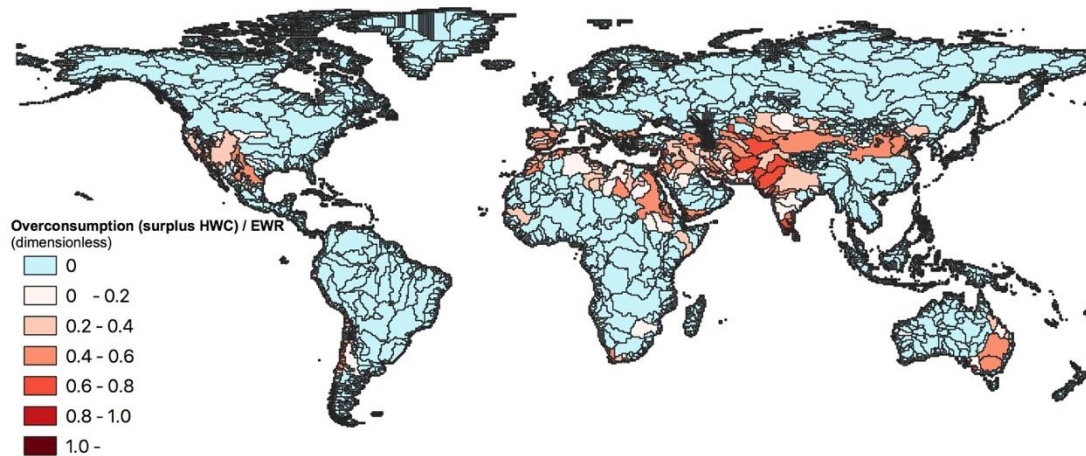
400 b



401

402

403 c



404

405 **Fig. 5.** Global map of potential pressure on ecosystems by overconsumption. Pressure represented by
406 ratio of overconsumption amount to EWR in watersheds attributing to total demand (a), HWR (b), and
407 surplus HWC (c).

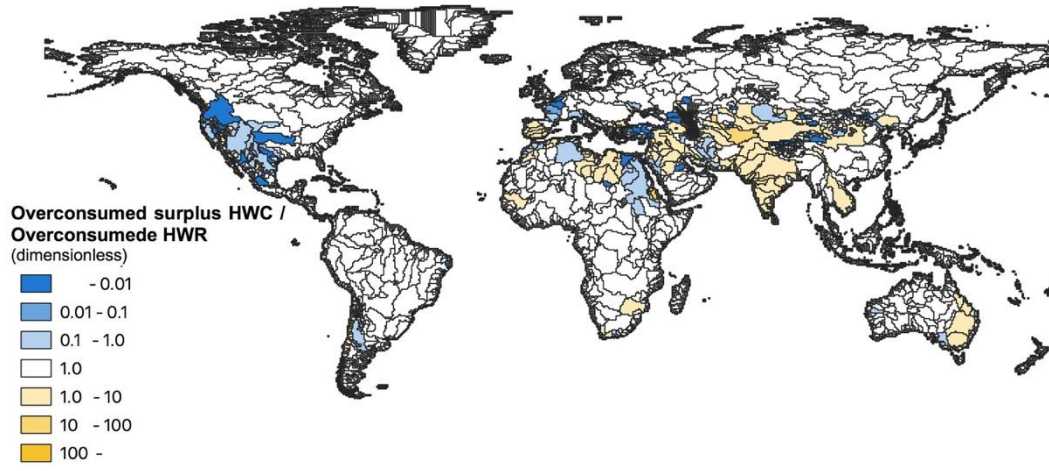
408

409 The global median shows that 63% of EWR is deprived as a result of human activities in
410 watersheds where overconsumption of freshwater occurs. A large part of overconsumption (approximately
411 81%) occurs in watersheds where more than 60% of EWR is deprived (Fig. S6). This indicates that current
412 overconsumption may tend to induce very high pressure on ecosystems, as it occurs in highly stressed
413 watersheds. Such watersheds are mainly located in North Africa, Central Asia, East Australia, and West
414 North America (Fig. 5a). In particular, North Africa and Australia are the areas with large biodiversity
415 impacts of freshwater consumption, as shown in previous research³¹⁻³³.

416 The causes of overconsumption vary largely among watersheds (Figs. 5b, 5c, and 6). Freshwater
417 for basic needs (HWR) is the main cause threatening the ecosystems health in watersheds (represented in
418 blue color; Fig.6). Therefore, the improvement of water productivity is necessary, and the support from
419 other water abundant regions through virtual water trade would probably be effective in covering the basic
420 needs in these watersheds. Furthermore, the water storage options that can mitigate temporal scarcity may
421 also be useful for some watersheds (identified in blue), where overconsumption only occurs for some
422 months in a year (Fig. S5b). Concurrently, the luxury demand of freshwater is more problematic in
423 watersheds represented in yellow (Fig. 6). Therefore, the control of surplus demand should be the first
424 priority for lowering pressure on ecosystems. Reconsideration of food consumption patterns⁴³ and reduction
425 of food waste⁴⁴ will be effective primary measures, and can complement the efforts for maintaining an

426 efficient irrigation water management.

427



428

429 **Fig.6.** Influential human demand of pressure on ecosystems as a result of the deprivation of EWR. Map
430 shows the ratios of overconsumed surplus HWC to overconsumed HWR in watersheds. The values
431 indicate that either surplus HWC (the ratio is higher than 1: yellow colored) or HWR (the ratio is lower
432 than 1: blue colored) is more influential in determining the deprivation of EWR.

433

434 **3.3 Sources of overconsumption**

435 Overconsumption of freshwater is specific to certain countries (Fig. 1). The top 10 countries account for
 436 approximately 73% of the total overconsumption in the world (Table 1). The overconsumption in these
 437 countries is mainly attributed to the agricultural demand for crop irrigation that accounts for approximately
 438 82–99% of the total overconsumption at the national scale (Table 1). However, the crop production may
 439 support not only national demand but also foreign demand through exporting to other countries. Though
 440 the proportion of exporting crop-associated overconsumption of freshwater is approximately 3% (10 billion
 441 m³) of the total freshwater overconsumption in the world, it accounts for a relatively high proportion to the
 442 total freshwater overconsumption in several countries, such as the United States of America, and Australia
 443 (Table 1).

444

445 **Table 1.** Overconsumption of freshwater in major countries and contribution of exporting crop-associated
 446 overconsumption of freshwater. The amount of freshwater overconsumption in top 10 countries are listed
 447 with the data on proportion to the world total and proportion of agricultural demand. Exporting crop-
 448 associated overconsumption data shows the significance of external demand for crop production in the
 449 context of freshwater overconsumption.

Rank	Country	Overconsumption of freshwater			Exporting crop-associated overconsumption	
		Total amount [Million m ³]	Proportion to the world total overconsumption [%]	Proportion of agricultural demand to the country total [%]	Total amount [Million m ³]	Proportion to the country total [%]
1	India	74,328	18.9	93.3	642	0.6
2	China	64,900	16.5	81.8	277	0.2
3	United States of America	31,847	8.1	90.3	4,338	10.3
4	Iran	27,154	6.9	98.0	n.a.	n.a.
5	Pakistan	22,018	5.6	95.4	147	0.7
6	Egypt	18,780	4.8	91.7	174	1.2
7	Turkey	13,692	3.5	95.8	538	0.9
8	Spain	11,370	2.9	97.1	230	1.2
9	Australia	11,264	2.9	96.4	2,152	3.1
10	Sudan	9,429	2.4	86.0	n.a.	n.a.

450

451 From an importer’s perspective, the 10 countries with the largest volume of freshwater
 452 overconsumption associated with importing crops dominate approximately 68% of the world total
 453 overconsumption attributing to imported crops (Table 2). The importance of this dependency on

454 overconsumption in other countries varies, but the shares of imported crop-associated overconsumption to
 455 the total overconsumption of the country (national and imported crop-associated overconsumption) is less
 456 than 15% (Table 2). This means that the importer countries induce additional freshwater consumption in
 457 producer countries; however, they already face overconsumption of freshwater inside the countries. Thus,
 458 they can save some amount of freshwater consumption that is required for national production of the crops .
 459 The amount of saved freshwater through international trade is known as virtual water¹⁴⁻¹⁶.

460 **Table 2.** Overconsumption of freshwater associated with imported crops. The top 10 countries and their
 461 respective proportions to the world total and comparison with national overconsumption of freshwater.
 462 Share to the total overconsumption of the country indicates significance of imported crop-associated
 463 overconsumption in comparison with overconsumption occurring inside the countries. Virtual
 464 overconsumption of freshwater is the amount of freshwater that is overconsumed if all imported crops
 465 would be nationally produced in a country.

Rank	Country	Overconsumption associated with imported crops			Virtual overconsumption of freshwater
		Volume [Million m ³]	Proportion to the world total overconsumption [%]	Share to the country's total overconsumption* [%]	Volume [Million m ³]
1	China	2,348.3	21.5	3.5	6,858.6
2	Italy	909.3	8.3	14.3	1,707.8
3	Spain	896.5	8.2	7.3	1,837.2
4	United States of America	742.3	6.8	2.3	357.5
5	Mexico	538.4	4.9	8.9	9,199.7
6	Egypt	510.8	4.7	2.6	4,948.8
7	Morocco	414.1	3.8	6.5	1,397.3
8	India	346.9	3.2	0.5	527.9
9	Algeria	335.4	3.1	14.9	76.8
10	Turkey	318.2	2.9	2.3	389.3
Global total		10,899.6	-	-	29,756.8

466 * Country's total overconsumption is defined as the sum of national overconsumption and importing crops-associated overconsumption.

467

468 By comparing the actual overconsumption of freshwater in producer countries and virtual
 469 overconsumption of freshwater in consumer countries, we can verify whether international trade alleviates
 470 the pressure on planetary boundaries of freshwater consumption or not. The virtual overconsumption of
 471 freshwater in major importer countries is generally larger than actual overconsumption in producer
 472 countries (Table 2). International trade saves 29.8 billion m³ of freshwater overconsumption as virtual water,

473 whereas 10.9 billion m³ of actual freshwater is overconsumed associated with traded crops instead.
474 Therefore, the international trade of virtual water results in the saving of approximately 18.9 billion m³
475 freshwater overconsumption at the global level. The amount of saved freshwater overconsumption is
476 relatively small compared to the total actual freshwater overconsumption (approximately 4.8% of the total
477 overconsumption), but the pressure on planetary boundaries on freshwater consumption is at least alleviated.

478 However, the international trade diverts pressure on regional carrying capacity of freshwater
479 consumption from one country to another, which makes efficient policy action more difficult. Even though
480 the pressure on planetary boundaries of freshwater can be alleviated by virtual water trade, some producer
481 countries face additional pressure on regional carrying capacities of freshwater consumption attributed to
482 exporting crops. From the perspective of available freshwater for crop production without overstepping
483 regional carrying capacities, many watersheds retain remaining water for human activities (Fig.S4).
484 However, the crop production requires suitable conditions such as climate, soils, and labor, and is affected
485 by other environmental constraints besides freshwater availability⁴⁵⁻⁴⁷. In particular, the tradeoff with land
486 use must be carefully reflected, as many water-abundant regions feature high biodiversity impacts on land
487 use⁴⁸.

488

489 **4. Implications and limitations**

490 Our results reveal that approximately 19% of our current freshwater consumption already exceeds regional
491 carrying capacities of freshwater use. In addition, this overconsumption occurs in watersheds that consume
492 approximately 79% of the total global freshwater demand. Global water demand is projected to increase
493 55% by 2050 compared to 2000¹. Therefore, the risk of overconsumption beyond carrying capacities will
494 increase in the future. In nearly 50% of the watersheds facing overconsumption of freshwater, EWR is
495 deprived by more than 63%, which implies that the ecosystems in these watersheds are under high pressure
496 of freshwater scarcity as a consequence of regional carrying capacities exceedance. In particular, a large
497 proportion of overconsumption is attributable to the irrigation water demand. Therefore, both volumetric
498 and temporal management of irrigation water (including indirect contributions by societal efforts such as
499 diversion of crop production sites, reconsideration of food consumption patterns, and reduction of food
500 waste) are of considerable importance for the sustainable use of freshwater resources.

501 Responsibility of freshwater overconsumption does not lie only with the producer countries of
502 crops. The crop importer countries are indirectly involved in overconsumption of freshwater in crop
503 producer countries through virtual water trade. International food trade generally reduces the pressure on
504 planetary boundaries as a whole, whereas the producer countries are exposed to additional pressure on
505 regional carrying capacities at the national scale. In addition to freshwater availability, there are many other
506 constraints pertaining to crop production. Therefore, from a sustainability perspective, it would not be
507 feasible for the crop importer countries to reduce their crop import and increase the national crop production.
508 However, the quantitative information based on the analysis of pressures on regional carrying capacities
509 and its sources may support the understanding of the sustainability of current freshwater consumption and
510 its linkage to food consumption by considering the region-specific conditions. This region-specific
511 assessment will complement the results of the planetary boundary assessment at the global scale including
512 other environmental systems, such as greenhouse gas emissions and biodiversity loss.

513 Herein, we focus on the sustainability of blue water consumption in terms of quantitative
514 availability of freshwater resources; however, various sources and roles of freshwater resources to sustain
515 human life should also be considered for more comprehensive sustainability assessment of freshwater
516 resources. Gleeson et al. suggested the necessity to modify the planetary boundaries definition considering
517 the specific aspects relevant to the water sub-boundaries (atmospheric water, soil moisture, surface water,

518 groundwater, and frozen water) that provide various functions through different water cycles⁴⁹.
519 Requirement of some water sub-boundaries and determination of water requirement for human
520 consumption and ecosystems for suggested water sub-boundaries are challenging owing to the complexity
521 in the mechanisms of water cycle and water utilization. However, more comprehensive definition on the
522 carrying capacities of freshwater use covering various functions of freshwater will contribute to achieving
523 sustainable freshwater use. This requires better underlying hydrological models that should be developed
524 in future research.

525 One of the novel findings in this analysis is that the large proportion of freshwater
526 overconsumption occurs owing to basic demands to sustain human life. The discrimination between basic
527 and luxury needs for human enables it to reveal this fact, which can be used for more specific policy
528 recommendations. However, the results may change depending on the criteria of HWR. We define HWR
529 as the fair amount of domestic and irrigation water use based on the criteria by the WHO and the FAO in
530 terms of ensuring low concern of health conditions (Section 2.1). We adopt the criteria for the sake of
531 consistency with water requirement for ecosystems (EWR). On the other hand, demand of freshwater for
532 industrial activities may also play a role in sustaining human life, particularly from an economic perspective.
533 For instance, electricity is used in hospitals to protect and save human lives, and freshwater is consumed
534 for electricity production by evaporation in turbines, cooling towers, and dams. However, recent results on
535 water scarcity assessment of hydropower show relative low effects on water scarcity due to beneficial
536 effects of water storage over seasons in many hydropower dams⁵⁰. The same as the EWR, the definition of
537 the freshwater amount that is required to sustain human life needs to be further examined in future research.

538 The connection between freshwater use and economic activities is also a crucial aspect for the
539 sustainability assessment of freshwater use. As is evident from the results of the analysis on the sources of
540 overconsumption, many importer countries can save national overconsumption of freshwater through
541 virtual water trade. However, D'Odorico et al. found that economic factor (gross domestic product (GDP))
542 is a more influential driver of virtual water trade than water availability factors⁵¹, which is also a conclusion
543 by Weinzettel and Pfister¹⁷. Distefano and Kelly showed that the emerging countries may not be able to
544 fully benefit from virtual water trade, and their economic growth will be restricted due to the lack of water⁵².
545 In addition, the economic activities may be affected by water scarcity not only within a country but abroad
546 as well, through international supply chains. Distefano et al. revealed the risks and effects of supply chain

547 disruption associated with freshwater scarcity based on computational analysis using a multi-regional input-
548 output model⁵³. The relation between freshwater use and economic activities is also relevant in determining
549 the basic requirements of freshwater and carrying capacities. Therefore, a more detailed analysis on these
550 aspects should be conducted in future studies.

551

552

553 **Associated content**

554 **Supporting information**

555 Additional text and figures (PDF)

556

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560

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