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# Regional carrying capacities of freshwater consumption – current pressure and its sources

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### 2 Regional carrying capacities of freshwater consumption –

#### 3 current pressure and its sources

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#### 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 m<sup>3</sup>) 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 demand<sup>1</sup>. Several methods have been developed to 34 assess the environmental impacts of freshwater consumption attributed to the unbalance between the 35 availability and demand<sup>2,3</sup>. 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<sup>4,5</sup>. 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 ( $\sim 2.600 \text{ km}^3/\text{yr}$ ) is within 46 the defined thresholds  $(4,000 - 6,000 \text{ km}^3/\text{yr})$ . However, this conclusion and the appropriateness to assess 47 water on a global scale has been challenged<sup>6</sup>, 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<sup>7,8</sup>.

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 scale<sup>9</sup>. 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 the planetary boundaries<sup>10</sup>. This emphasizes the significance of considering regional conditions in terms of
 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<sup>4, 5, 9</sup>, 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 modeling that result in the different estimates of safe boundary of freshwater consumption<sup>10</sup>. The previous 68 69 analyses on the planetary boundaries adopt the LPJmL model<sup>11</sup> 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 models<sup>12</sup>. 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 terms of sustainability in the previous analyses<sup>4, 5, 9</sup>. This might lead to an inconsistency between the 74 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 watersheds<sup>13</sup>. 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,

food commodities), or leads to an opposite effect in exporter countries if they are affected by water scarcity and produce goods for export<sup>14–17</sup>. The demand of freshwater in a country may be satisfied by utilizing the available resources in various countries through international trade of goods<sup>18–20</sup>, which may pose the exceedance of the regional carrying capacity of freshwater consumption in a region as a result of demand from other regions. Therefore, an analysis of the sources and the internal and external drivers for pressures on regional carrying capacity of freshwater consumption in a region is necessary for understanding and 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 model<sup>21</sup> 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

#### 126 **2. Methods**

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

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

132 
$$RCC_{xim} = AW_{xim} - EWR_{xim}, (1)$$

133 where  $RCC_{xi,k}$  (m<sup>3</sup>) 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<sup>3</sup>) denotes the amount of available freshwater in a watershed i of country x for 135 a month m, and  $EWR_{xim}$  (m<sup>3</sup>) 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  $2.2^{21}$  as the amount of available freshwater in eq 1. We 137 adopted the same approach for measuring the EWR per watershed on a monthly basis<sup>22</sup> 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<sup>4,5,9</sup>.

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

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

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

152 With regard to the DWR, the basic daily requirement of freshwater at 50 (L/capita/day), which 153 ensured that health concerns remain  $low^{23}$ , was fixed. The monthly DWR in a watershed (*DWR*<sub>*p,i,k*</sub>) was 154 calculated by multiplying the basic daily requirement with the population for each month and adding the155 values.

$$DWR_{x,i,m} = BDR \times Pop_{x,i} \times D_m, \tag{3}$$

where *BDR* denotes the amount of basic daily requirement of freshwater per capita and day (kcal/capita/day),  $Pop_{x,i}$  denotes the population in watershed *i* of country *x* (capita), and  $D_m$  denotes the 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 watersheds<sup>21</sup> up or down corresponding to the country average ratio of the IWR to the consumed 163 irrigation water as follows:

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

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<sup>3</sup>) (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<sup>3</sup>) (see equation S2-S4 in the SI),  $IWC_{xc}$ 168 denotes the water consumption by total irrigation for the production of crop c in country x (m<sup>3</sup>). 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 watershed<sup>24</sup> and the current adequacy rate 171 of dietary energy supply published by Food and Agriculture Organization of the United Nations<sup>25</sup>. 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  $supply^{27}$ . 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 FAO<sup>25</sup>. We conducted this analysis for 160 crops that were defined in the reference research<sup>24</sup> and aggregated them at a country scale to obtain the average nation-wide ratio of 177 178 basic freshwater requirement to the current water consumption for irrigation. The detailed calculation 179 procedures including equations are presented in the SI.

180

#### 182 **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:

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

189 where  $BHWC_{x,i,m}$  denotes the amount of freshwater consumption that corresponds to the basic needs in

190 watershed *i* of country *x* for a month *m* ( $m^3$ ), *BDWC*<sub>*x,i,m*</sub> denotes the amount of domestic water

191 consumption that corresponds to the basic needs in watershed *i* of country *x* for a month m (m<sup>3</sup>),

192  $BIWC_{x,i,m}$  denotes the irrigation water consumption that corresponds to the basic needs in watershed *i* of 193 country *x* on a month *m* (m<sup>3</sup>). The domestic and irrigation water consumption corresponding to basic

194 needs are defined by the following equations.

195 
$$BDWC_{x,i,m} = \begin{cases} DWR_{x,i,m} , & DWC_{x,i,m} > DWR_{x,i,m} \\ DWC_{x,i,m} , & DWC_{x,i,m} \le DWR_{x,i,m} \end{cases},$$
(6)

196 
$$BIWC_{x,i,m} = \begin{cases} IWR_{x,i,m} , & IWC_{x,i,m} > IWR_{x,i,m} \\ IWC_{x,i,m} , & IWC_{x,i,m} \le IWR_{x,i,m} \end{cases},$$
(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.

$$SHWC_{x,i,m} = THWC_{x,i,m} - BHWC_{x,i,m}$$
(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<sup>3</sup>), and *THWC*<sub>*x,i,m*</sub> denotes the total amount of freshwater consumption for the human activities in watershed *i* of country *x* for a month *m* (m<sup>3</sup>). 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

We referred the total freshwater consumption data that was estimated in the WaterGap 2.2<sup>21</sup>, including consumption for irrigation, domestic use, manufacturing, electricity production and livestock production; this was aimed at achieving a consistency with data on freshwater availability and EWR. The overconsumption of freshwater was determined as the surplus of the total freshwater consumption from the remaining water for human activities according to the following equations (see also Fig.S2 in the SI):

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

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

217 
$$OverSHWC_{x,i,m} = \begin{cases} SHWC_{x,i,m} & , & BHWC_{x,i,m} > RCC_{x,i,m} \\ SHWC_{x,i,m} - (RCC_{x,i,m} - BHWC_{x,i,m}), & BHWC_{x,i,m} \le RCC_{x,i,m} \\ 0 & , & THWC_{x,i,m} \le RCC_{x,i,m} \end{cases}$$
(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<sub>x,i,m</sub> denotes the overconsumed amount of HWR in watershed *i* of country *x* for a month 220 m (m<sup>3</sup>), and *OverSHWC<sub>xi,m</sub>* denotes the overconsumed amount of surplus HWC in watershed *i* of country 221 x for a month m (m<sup>3</sup>). 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 <sup>28–33</sup>. No 230 consensual methods to assess the potential impacts of freshwater consumption have been developed although a critical review summarizes relevant issues for the assessment<sup>34</sup>. To account for the potential 231 232 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 
$$PIE_{x,i,m} = OverFW_{x,i,m} / EWR_{x,i,m}, \qquad (12)$$

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

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

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

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

252 
$$ODC_{x} = \begin{cases} \sum_{c} DomIWC_{x,c} \times (IWC_{x,c}/IWR_{x,c} - 1), & IWC_{x,c} > IWR_{x,c}, \\ 0, & IWC_{x,c} \le IWR_{x,c}, \end{cases}$$
(13)

253 
$$OEC_{x} = \begin{cases} \sum_{c} \sum_{y} ExpIWC_{x,c,y} \times (IWC_{x,c}/IWR_{x,c} - 1), & IWC_{x,c} > IWR_{x,c} \\ 0, & IWC_{x,c} \le IWR_{x,c} \end{cases}$$
(14)

where  $ODC_x$  denotes freshwater overconsumption associated with domestic supplied crops in producer country *x* (m<sup>3</sup>), and  $OEC_x$  denotes freshwater overconsumption associated with exporting crops to importer country *y* in producer country *x* (m<sup>3</sup>).

With regard to the importer country, the overconsumption of irrigation water that is associated with the imported crops from all countries is compared with the amount of national overconsumption; this is aimed at understanding the significance of the induced overconsumption in other countries, in relation to the domestic situation. However, the import of crops may potentially avoid overconsumption in importing countries through virtual water trade. Therefore, the virtually saved overconsumption of freshwater in importing countries is compared with the actual overconsumption of freshwater associated with imported crops in the producer countries. This facilitates the assessment of the potential benefits of virtual water trade in terms of the global scale carrying capacity, while clarifying the relationship between global and regional sustainability of freshwater consumption. National overconsumption of importer countries can be determined by eqs 9, 10, and 11. Overconsumption associated with importing crops and virtually saved overconsumption of freshwater in importer countries are calculated by the following equations:

269 
$$OIC_{y} = \begin{cases} \sum_{x} \sum_{c} ExpIWC_{x,c,y} \times (IWC_{x,c}/IWR_{x,c} - 1), & IWC_{x,c} > IWR_{x,c} \\ 0, & IWC_{x,c} \le IWR_{x,c}, \end{cases}$$
(15)

270 
$$VSO_{y} = IWC_{y,c} \times (IM_{y,c}/DP_{y,c}) \times (OverFW_{y}/THWC_{y}), \quad (16)$$

where  $OIC_y$  denotes the freshwater overconsumption associated with importing crops in importer country y (m<sup>3</sup>),  $VSO_y$  denotes the virtually saved overconsumption of freshwater in importer country y (m<sup>3</sup>),  $IM_{y,c}$ denotes the imported amount of crop c in importer country y (ton),  $DP_{y,c}$  denotes the amount of national production of crop c in importer country y (ton),  $OverFW_y$  denotes overconsumption of freshwater in importer country y (m<sup>3</sup>), and  $THWC_y$  denotes the total amount of freshwater consumption for human activities in importer country y (m<sup>3</sup>). The imported amount and the national production of crops are taken from the crop production statistics by FAO<sup>26</sup>.

#### 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 analysis<sup>9</sup>. 283 The annual total amount of overconsumed freshwater is calculated at 393 billion m<sup>3</sup>, which accounts for 284 approximately 24% of the current total global freshwater consumption (1,671 Billion m<sup>3</sup>). 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 analysis<sup>9</sup>, 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<sup>24,36</sup>.

292



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

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 m<sup>3</sup>) 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 m<sup>3</sup>, 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.





520 consumption and overconsumption (a) and contributions of imgation 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

Fig. 3. Regional status of pressure on carrying capacities of freshwater consumption. Bars are the ratios of HWR and total HWC to the regional carrying capacities of freshwater in each region (the annual average weighted by HWR and HWC, respectively). The blue bars represent pressure of human basic needs (HWR) on carrying capacities in regions. The yellow bars represent pressure of total human demand (the total HWC), whereas the difference between the yellow bars and the blue bars indicates pressure of surplus HWC on carrying capacities in regions. Gradient red colored area represents the safe 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 m<sup>3</sup>) 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 limitations<sup>37</sup>. 352 However, for the purpose, potential effects on downstream ecosystems by water flow changes<sup>38–39</sup> and considerations of appropriate management to minimize the effects<sup>40-41</sup> will need to be considered. 353

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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<sup>21, 35</sup>. In fact, 149 billion m<sup>3</sup> 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 change<sup>42</sup>, 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**

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

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

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The global median shows that 63% of EWR is deprived as a result of human activities in watersheds where overconsumption of freshwater occurs. A large part of overconsumption (approximately 81%) occurs in watersheds where more than 60% of EWR is deprived (Fig. S6). This indicates that current overconsumption may tend to induce very high pressure on ecosystems, as it occurs in highly stressed watersheds. Such watersheds are mainly located in North Africa, Central Asia, East Australia, and West North America (Fig. 5a). In particular, North Africa and Australia are the areas with large biodiversity impacts of freshwater consumption, as shown in previous research<sup>31–33</sup>.

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 patterns<sup>43</sup> and reduction 425 of food waste<sup>44</sup> will be effective primary measures, and can complement the efforts for maintaining an

#### 427



- 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
- 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 m<sup>3</sup>) 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.

the context of neshwater overconsumption.

		Ov	erconsumption of freshv	Exporting crop-associated overconsumption		
Rank	Country	Total amount [Million m <sup>3</sup> ]	Proportion to the world total overconsumption [%]	Proportion of agricultural demand to the country total [%]	Total amount [Million m <sup>3</sup> ]	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

From an importer's perspective, the 10 countries with the largest volume of freshwater overconsumption associated with importing crops dominate approximately 68% of the world total 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 water<sup>14-16</sup>.

**Table 2**. Overconsumption of freshwater associated with imported crops. The top 10 countries and their

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

would be nationally produced in a country.

	Country -	Over	Virtual overconsumption of freshwater			
Rank		Volume [Million m <sup>3</sup> ]	Proportion to the world total overconsumption [%]	Share to the country's total overconsumption* [%]	Volume [Million m <sup>3</sup> ]	
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

By comparing the actual overconsumption of freshwater in producer countries and virtual overconsumption of freshwater in consumer countries, we can verify whether international trade alleviates the pressure on planetary boundaries of freshwater consumption or not. The virtual overconsumption of freshwater in major importer countries is generally larger than actual overconsumption in producer countries (Table 2). International trade saves 29.8 billion m<sup>3</sup> of freshwater overconsumption as virtual water, 473 whereas 10.9 billion m<sup>3</sup> 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 m<sup>3</sup> 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 availability<sup>45–47</sup>. In particular, the tradeoff with land 486 use must be carefully reflected, as many water-abundant regions feature high biodiversity impacts on land 487 use<sup>48</sup>.

#### 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  $2000^1$ . 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.

Herein, we focus on the sustainability of blue water consumption in terms of quantitative availability of freshwater resources; however, various sources and roles of freshwater resources to sustain human life should also be considered for more comprehensive sustainability assessment of freshwater resources. Glesson et al. suggested the necessity to modify the planetary boundaries definition considering 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 cycles<sup>49</sup>. 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 dams<sup>50</sup>. 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 factors<sup>51</sup>, which is also a conclusion 543 by Weinzettel and Pfister<sup>17</sup>. 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 water<sup>52</sup>. 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	disr	uption associated with freshwater scarcity based on computational analysis using a multi-regional input-				
548	outp	output model <sup>53</sup> . The relation between freshwater use and economic activities is also relevant in determining				
549	the	e basic requirements of freshwater and carrying capacities. Therefore, a more detailed analysis on these				
550	aspe	ects should be conducted in future studies.				
551						
552						
553	Ass	ociated content				
554	Sup	porting information				
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