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

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Abstract

Sustainable freshwater management is an essential target for sustainability. The concept of planetary boundaries evaluates whether the environmental loads from humans are within the carrying capacity of the environment at a global level, while the region-specific assessment of carrying capacities of freshwater consumption can complement the global scale sustainability assessment by shedding light on regional sustainability. We show that 24% of the total freshwater consumption exceeds the regional carrying capacities based on spatially and temporally explicit analysis (monthly data for around 11,000 watersheds). Although 19% of the current total freshwater consumption is determined as "luxury consumption" beyond basic needs, approximately 60% of the exceedance attributes to basic needs of freshwater for sustaining human life. The international trade alleviates the overall pressure on carrying capacity by approximately 4.8% (18.9 billion m^3) at a global level through virtual water trade; however, several producer countries demonstrate additional overconsumption beyond the regional carrying capacities , while importer countries that can mitigate overconsumption. Appropriate irrigation water management and the location of crop production is the key to maintain our freshwater consumption levels within the regional carrying capacities on a global scale. However, measures that necessitate the consideration of watershed-specific environmental and economic conditions are desirable.

Keywords

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

1. Introduction

Various environmental issues may be attributed to human activities. Freshwater availability is one of the most relevant environmental issues and future pressure will increase owing to an unbalance between the available water resources and the predicted increase in demand[1]. Several methods have been developed to assess the environmental impacts of freshwater consumption attributed to the unbalance between the availability and demand[2,3]. Although these methods capture the potential impacts of freshwater consumption on the environment, they do not directly argue the acceptable level of freshwater consumption with regard to environmental sustainability. A key step to achieve sustainable human activities is to determine the acceptable level of environmental loads in terms of ecosystems and human well-being.

Rockström et al. have introduced the concept of planetary boundaries that relates the current status of nine environmental issues to the associated threshold levels for global environmental systems[4,5]. According to this first analysis of pressure on the planetary boundaries, three planetary systems (climate change, nitrogen cycle, and biodiversity loss) exceed the planetary boundaries whereas the other systems including freshwater consumption are within the safe operating space. During the estimation of pressure on the planetary boundaries in these studies, the thresholds of each planetary system have been set at the global level. The analysis concludes that the current level of freshwater consumption (~2,600 km^3/yr) is within the defined thresholds (4,000 – 6,000 km^3/yr). However, this conclusion and the appropriateness to assess water on a global scale has been challenged[6], as water availability is a regional issue. A suitable availability of water in few regions cannot compensate for the negative effects in water-scarce regions, even if the total average of both the types of regions appears to be uncritical at first sight. Second, the projected increase in the demand of food in the future will pose additional pressure on freshwater availability[7,8].

Steffen et al. have addressed the regional issues by adapting the analysis of planetary boundaries of freshwater consumption from a global scale to a grid scale[9]. Their analysis of planetary boundaries of freshwater consumption with the grid scale resolution reveals that several basins are subjected to a high risk of exceeding regional carrying capacities, while the current freshwater consumption is still within the safe boundaries on a global scale. Hogeboom et al. also demonstrated large variation in the monthly blue water availability (the difference in the values of the monthly environmental flow requirement and the monthly blue water runoff) in watersheds at a monthly level, which results in a wide range of estimates for the planetary boundaries[10]. This emphasizes the significance of considering regional conditions in terms of sustainability of freshwater consumption.

Despite the progress in previous studies that is related to the regional sustainability of freshwater consumption, there are still two issues that require further improvement with regard to the sustainability assessment of freshwater consumption; these include the estimation of available freshwater resources and the distinction between the basic and surplus demand of freshwater for fair human life. In the previous planetary boundary analyses[4, 5, 9], the safe boundary of freshwater consumption is defined as a fraction of the estimated available freshwater flow based on a specific hydrological model. Thus, the results highly depend on the estimates of freshwater flow of the chosen hydrological model. However, various 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[10]. The previous analyses on the planetary boundaries adopt the LPJmL model[11] as the base hydrological model on water flows, which typically estimates larger volumes of freshwater flows as compared to those estimated by other models[12]. This implies that the previous estimates of planetary boundaries of freshwater availability are rather optimistic. Further, the consideration of the freshwater requirement types for human beings are rather limited. Only the water requirement for ecosystems is considered as the essential water demand in terms of sustainability in the previous analyses[4, 5, 9]. This might lead to an inconsistency between the sustainability of ecosystems and human life in terms of the carrying capacity assessment of freshwater. Bjørn et al. discussed the allocation issue of available freshwater to human activities at a product-level by calculating the actual share of the consumption of available freshwater as compared to the allocated boundary of the respective activity; this study represents that the human demand of freshwater exceeds a safe operating space in several watersheds[13]. Exceeded freshwater demand of humans may deprive the fundamental freshwater requirement of ecosystems, whereas the entire or some share of the human demand may also be necessary for sustaining human life. In this sense, the freshwater demand for human use (domestic and agricultural use) must be separated into basic and surplus demand when discussing the pressure on exceeding regional carrying capacities for obtaining a complete picture of the sustainability assessment of freshwater use.

The international trade has a significant impact, which either enables freshwater scarce countries 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[14–17]. The demand of freshwater in a country may be satisfied by utilizing the available resources in various countries through international trade of goods[18–20], 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.

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

In this analysis, the available amount of freshwater resources in a watershed refers to the estimates of the freshwater resource amount calculated by the WaterGAP 2.2 model[21] which calibrates the calculated outflow from a basin with the measured outflow. The carrying capacity of the freshwater consumption in a watershed is quantified by deducting the environmental water requirement (EWR) that is essential for the ecosystems from the total available amount of freshwater resources in a watershed. The estimated carrying capacity in a watershed is compared with the freshwater consumption to assess the pressure on the watershed due to the human freshwater demand. We split the total consumption into the basic needs to sustain human life (human water requirement: HWR), including water for drinking, hygiene, and food production, and the surplus needs that go beyond these fundamental requirements (surplus human water consumption: surplus HWC); this as further explained in the next section. The analysis is conducted for approximately 11,000 basins in the world, encompassing all the continents and major islands except for Greenland and Antarctica. To reveal the causes of high pressure on regional carrying capacities of freshwater consumption, the overconsumption of freshwater in the exporter countries is distinguished into national demand and the export of goods that are related to this demand. The overconsumption related to importing goods has been elucidated in the discussion on the responsibility of importer countries. The analysis of trade-related effects on overconsumption identifies the effects of global linkage through international trade on exceedance of the carrying capacities.

2. Methods

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[4,5,9]. The defined regional carrying capacity of a watershed for human activities is calculated at a monthly level as per the follow equation:

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

where $RCC_{x,i,k}$ (m^3) denotes the regional carrying capacity for human activities in a watershed *i* of country *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 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 monthly natural flow data from the WaterGap 2.2[21] as the amount of available freshwater in eq 1. We adopted the same approach for measuring the EWR per watershed on a monthly basis[22] as that adopted by previous studies on planetary boundaries, wherein different proportions of the mean monthly flow are defined as the EWR subject to the classification of the mean monthly flow as compared to the mean annual flow (i.e. low and high flow periods). With regard to the freshwater type, we focused on the blue water consumption as well as the previous studies on the planetary boundaries of freshwater use[4,5,9].

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^3), $DWR_{x,i,m}$ denotes the domestic water requirement (DWR) in a watershed *i* of a crop producer country *x* for a month *m* (m^3), 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^3).

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

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

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).

We defined the basic requirement for food supply as the irrigation water requirement (IWR). The monthly IWR in a watershed ($IWR_{x,i,m}$) was estimated by scaling the current irrigation water consumption in watersheds[21] up or down corresponding to the country average ratio of the IWR to the consumed irrigation water as follows:

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

where $IWC_{x,i,m}$ denotes the irrigation water consumption for crop production in a watershed *i* of country *x* for a month *m* (m^3) (see equation S1 in the Supporting Information (SI)), $IWR_{x,c}$ denotes the irrigation water requirement for the production of crop *c* in country *x* (m^3) (see equation S2-S4 in the SI), $IWC_{x,c}$ denotes the water consumption by total irrigation for the production of crop *c* in country *x* (m^3). The average ratio of the IWR to the consumed irrigation water was determined based on the monthly water consumption for irrigation to ensure crop production in each watershed[24] and the current adequacy rate of dietary energy supply published by Food and Agriculture Organization of the United Nations[25]. First, the irrigation water consumption for crop production in watersheds was aggregated on country scale for a year and subsequently allocated to the national supply of each importer country based on the share of supply[27]. Subsequently, the IWR was calculated by dividing the allocated amount of irrigation water consumption in each country with the dietary energy supply adequacy rate (SAR) average for years during 2000 to 2016), as reported by FAO[25]. We conducted this analysis for 160 crops that were defined in the reference research[24] and aggregated them at a country scale to obtain the average nation-wide ratio of basic freshwater requirement to the current water consumption for irrigation. The detailed calculation procedures including equations are presented in the SI.

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).

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[21], 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):

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

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

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

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

Overconsumption of freshwater for human demand deprives EWR, which may result in the occurrence of severe impacts on ecosystems. Several previous studies assessed the potential impacts of freshwater consumption on ecosystems by targeting the specific cause-effect pathways [28–33]. No consensual methods to assess the potential impacts of freshwater consumption have been developed although a critical review summarizes relevant issues for the assessment[34]. To account for the potential ecosystem impacts, in addition to the absolute amount of overconsumption, we adopted the ratio of freshwater overconsumption to EWR as a proxy indicator to assess the potential impacts of deprivation of EWR by exceedance of the regional carrying capacities on ecosystems:

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

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).

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[21, 35]. 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:

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

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

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

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:

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

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

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

3. Results and discussion

3.1 Overconsumption beyond regional carrying capacities

Our estimation of overconsumed freshwater amounts beyond regional carrying capacities in watersheds indicates a significantly more severe situation in numerous watersheds compared to a previous analysis[9]. The annual total amount of overconsumed freshwater is calculated at 393 billion m^3, which accounts for approximately 24% of the current total global freshwater consumption (1,671 Billion m^3). This exceedance occurs in 1,865 watersheds (approximately 17% of the total) in the world (Fig. 1). These watersheds account for approximately 79% of total annual demand of freshwater in the world, which indicates that most of our current freshwater demand contributes to overstepping the boundaries for a safe operating space of freshwater consumption at watershed level. The estimated overconsumption amount is different from that presented in a previous analysis[9], however, concerned areas of overconsumption generally overlapped based on the results of the previous and this analyses; further, concerned areas of water stress in other studies also overlapped with those in this study, based on physical water stress analysis[24,36].

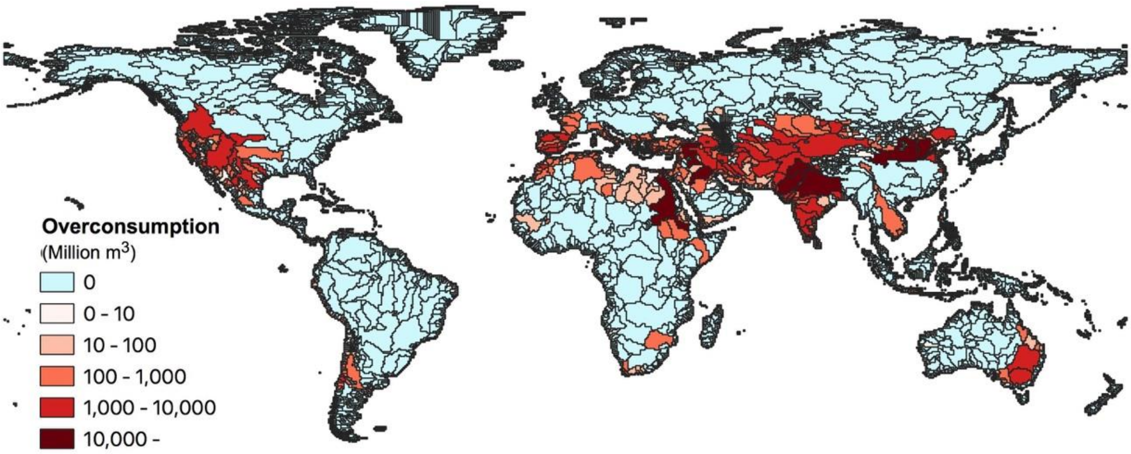


Fig. 1. Global map of freshwater overconsumption beyond regional carrying capacities. The map presents the annual total amount of freshwater consumption in watersheds that exceeds regional carrying capacities for a month or more. Regional carrying capacities are defined as the amount of available freshwater 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.

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

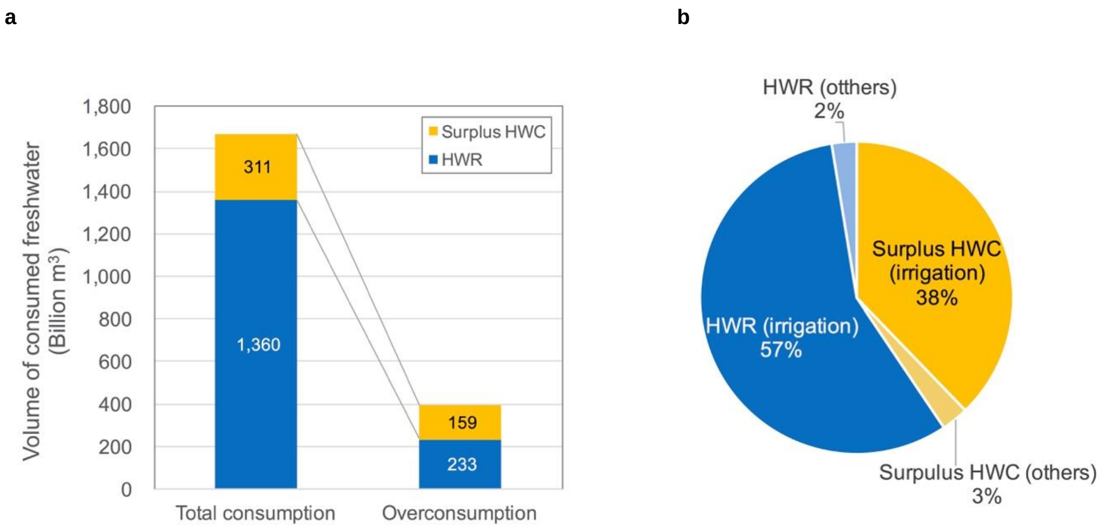


Fig. 2. Amount of freshwater overconsumption and its cause. Breakdowns of freshwater demand (human water requirement (HWR) and surplus human water consumption (Surplus HWC)) in the total consumption and overconsumption (a) and contributions of irrigation and other demand to the total overconsumption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

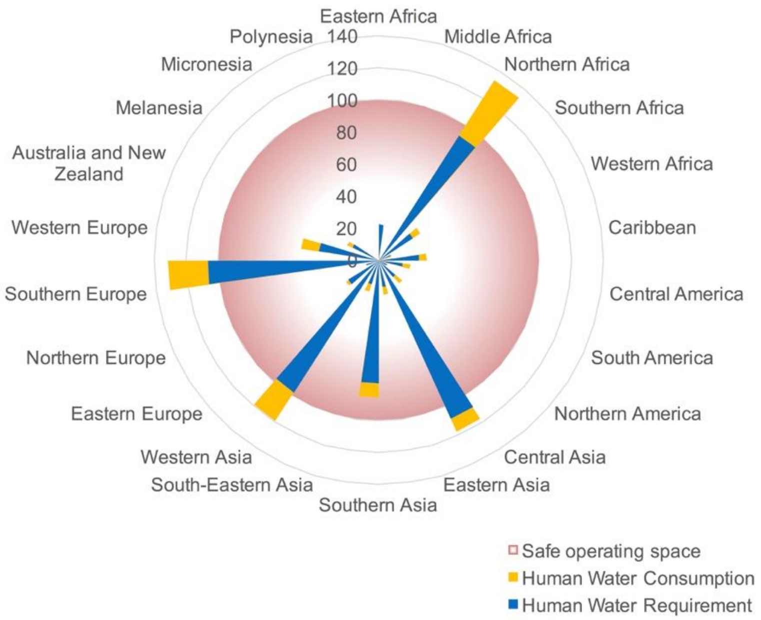


Fig. 3. Regional status of pressure on carrying capacities of freshwater consumption. Bars are the ratios of HWR and total HWC to the regional carrying capacities of freshwater in each region (the annual average weighted by HWR and HWC, respectively). The blue bars represent pressure of human basic needs (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.

In general, overconsumption occurs in watersheds where remaining water amount for human use is small or 0 (Figs. 1 and S4). However, a relatively fair amount of remaining water is available as the yearly total in several watersheds (e.g. Columbia basin (north-western part of the United States of America), Ganges basin (north-eastern part of India) and Mekong basin (Cambodia, Lao PDR, south-western part of China)) (Fig. S4), whereas overconsumption occurs in these watersheds within few months (Fig.1). This is attributable to temporal variations in availability and demand of freshwater in these watersheds. As an example of such a situation, in the Columbia basin, surplus HWC increases from May to September (Fig. 4b); however, overconsumption occurs only in August when the remaining water amount drops zero because of low availability and increasing demand (Fig. 4a and b). This is the case for most of watersheds where overconsumption occurs. On a global scale, 95% of overconsumption (374 billion m^3) occurs in a month when no remaining water is the available in watersheds. These facts highlight the additional risks of exceeding carrying capacities temporarily as water availability is not only regional, but also seasonal. The temporal unbalance of freshwater availability and demand can occur, even if, on average, there is remaining water for “luxury” consumption throughout a year. Water storage options (e.g. dams and reservoirs) can be used to overcome temporal shortage of water availability considering their advantages and limitations[37]. However, for the purpose, potential effects on downstream ecosystems by water flow changes[38–39] and considerations of appropriate management to minimize the effects[40–41] will need to be considered.

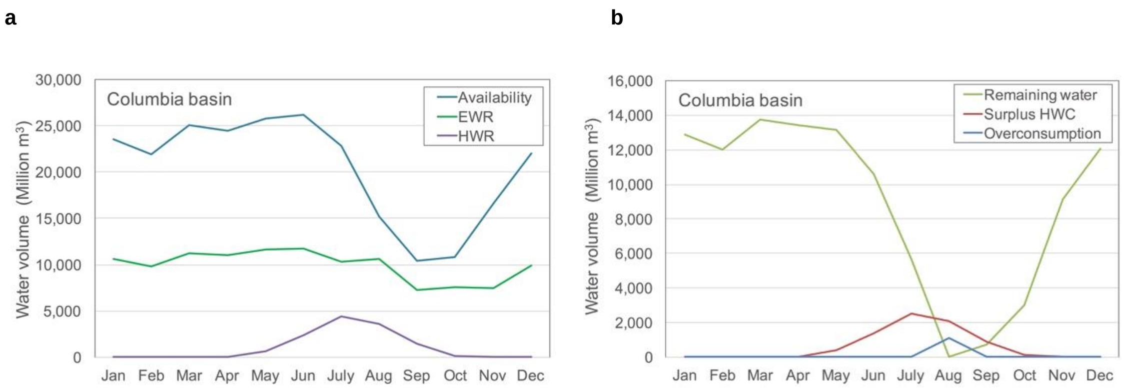


Fig.4 Temporal variation in overconsumption and its cause. An example (Columbia basin) of monthly freshwater availability and demand (EWR and HWR) (a) and resulting remaining water, surplus HWC, and overconsumption (b). Remaining water represents the amount of available freshwater available for luxury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

However, 22% of overconsumption occurs in watersheds where overshoot occurs throughout a year and more than half amount of overconsumption occurs over at least six months (Fig. S5). This implies that some watersheds already face continuous deficit in freshwater for surplus demand for humanity. The temporal or continuous overconsumption arising from freshwater consumption by human activities may have potential impacts on ecosystems that cannot avoid or immediately adopt to the changes associated with the deprivation of freshwater.

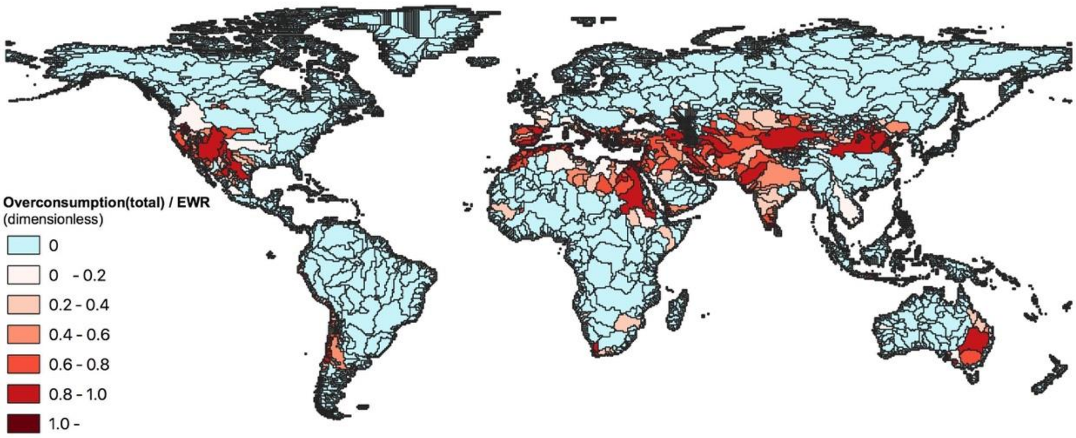
Most of freshwater overconsumption is caused by irrigation demand for crop production, which dominates approximately 70% of the total freshwater demand[21, 35]. In fact, 149 billion m^3 of "luxury" freshwater is consumed for irrigation (48% of the total surplus HWC) to support the dietary requirements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

The causes of shortage in freshwater resources for basic human needs can be separated into two types. The first one is the temporal mismatch of freshwater supply and demand (an example shown in Fig. 4). Mismatch of freshwater supply and demand occurs in some watersheds only during limited periods (less than 6 months in 36% of watersheds facing overconsumption) (Fig.S5). In such cases, the shift of cropping timing, that is also assumed as an option for adaptation to climate change[42], may reduce pressure on regional carrying capacities in terms of freshwater consumption. However, more fundamental measures are required for other watersheds where mismatch of freshwater supply and demand is more continuous (over 6 months in 51% of watersheds facing overconsumption) (Fig. S5). Besides the improvement in irrigation efficiency, the shift in crop types to less water intensive crops or change of production location to remaining water abundant watersheds will be required for reducing potential impacts on ecosystems caused by freshwater overconsumption.

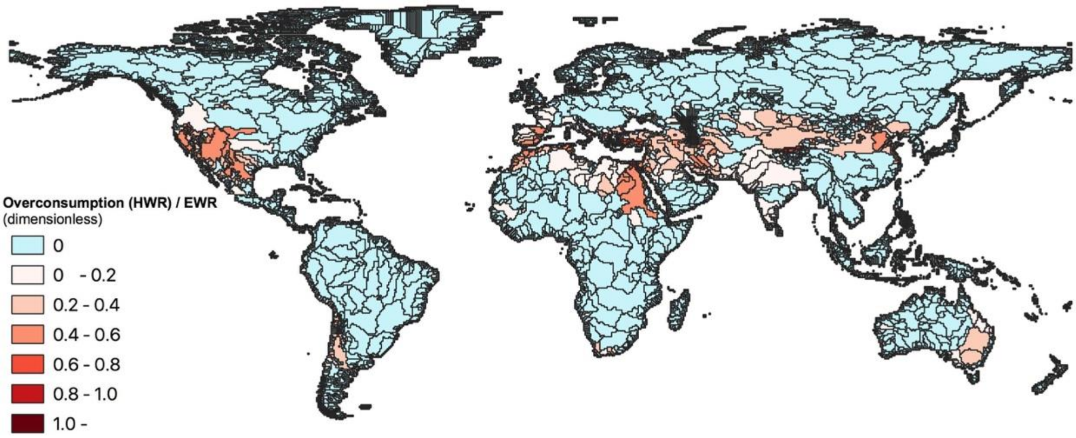
3.2 Severity of overconsumption for ecosystems

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.

a



b



c

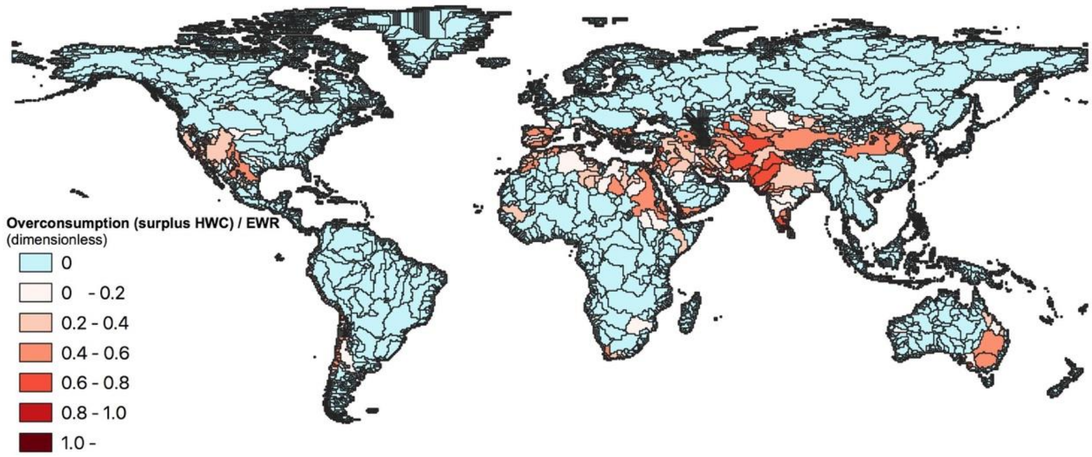


Fig. 5. Global map of potential pressure on ecosystems by overconsumption. Pressure represented by ratio of overconsumption amount to EWR in watersheds attributing to total demand (a), HWR (b), and surplus HWC (c).

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[31–33].

The causes of overconsumption vary largely among watersheds (Figs. 5b, 5c, and 6). Freshwater for basic needs (HWR) is the main cause threatening the ecosystems health in watersheds (represented in blue color; Fig.6). Therefore, the improvement of water productivity is necessary, and the support from other water abundant regions through virtual water trade would probably be effective in covering the basic needs in these watersheds. Furthermore, the water storage options that can mitigate temporal scarcity may also be useful for some watersheds (identified in blue), where overconsumption only occurs for some months in a year (Fig. S5b). Concurrently, the luxury demand of freshwater is more problematic in watersheds represented in yellow (Fig. 6). Therefore, the control of surplus demand should be the first priority for lowering pressure on ecosystems. Reconsideration of food consumption patterns[43] and reduction of food waste[44] will be effective primary measures, and can complement the efforts for maintaining an efficient irrigation water management.

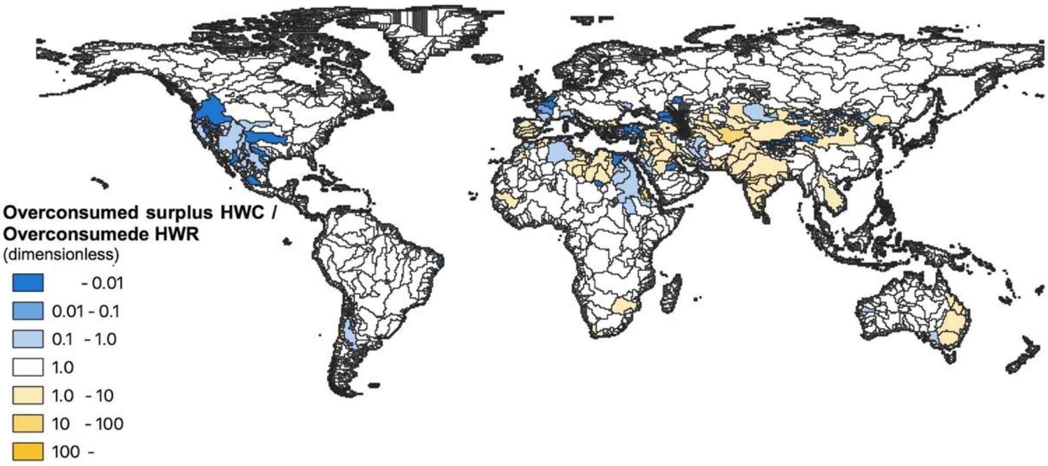


Fig.6. Influential human demand of pressure on ecosystems as a result of the deprivation of EWR. Map shows the ratios of overconsumed surplus HWC to overconsumed HWR in watersheds. The values indicate that either surplus HWC (the ratio is higher than 1: yellow colored) or HWR (the ratio is lower than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

3.3 Sources of overconsumption

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

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

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 overconsumption in other countries varies, but the shares of imported crop-associated overconsumption to the total overconsumption of the country (national and imported crop-associated overconsumption) is less than 15% (Table 2). This means that the importer countries induce additional freshwater consumption in producer countries; however, they already face overconsumption of freshwater inside the countries. Thus, they can save some amount of freshwater consumption that is required for national production of the crops . The amount of saved freshwater through international trade is known as virtual water[14–16].

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. Share to the total overconsumption of the country indicates significance of imported crop-associated overconsumption in comparison with overconsumption occurring inside the countries. Virtual overconsumption of freshwater is the amount of freshwater that is overconsumed if all imported crops 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

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

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^3 of freshwater overconsumption as virtual water, whereas 10.9 billion m^3 of actual freshwater is overconsumed associated with traded crops instead. Therefore, the international trade of virtual water results in the saving of approximately 18.9 billion m^3 freshwater overconsumption at the global level. The amount of saved freshwater overconsumption is relatively small compared to the total actual freshwater overconsumption (approximately 4.8% of the total overconsumption), but the pressure on planetary boundaries on freshwater consumption is at least alleviated.

However, the international trade diverts pressure on regional carrying capacity of freshwater consumption from one country to another, which makes efficient policy action more difficult. Even though the pressure on planetary boundaries of freshwater can be alleviated by virtual water trade, some producer countries face additional pressure on regional carrying capacities of freshwater consumption attributed to exporting crops. From the perspective of available freshwater for crop production without overstepping regional carrying capacities, many watersheds retain remaining water for human activities (Fig.S4). However, the crop production requires suitable conditions such as climate, soils, and labor, and is affected by other environmental constraints besides freshwater availability[45–47]. In particular, the tradeoff with land use must be carefully reflected, as many water-abundant regions feature high biodiversity impacts on land use[48].

4. Implications and limitations

Our results reveal that approximately 19% of our current freshwater consumption already exceeds regional carrying capacities of freshwater use. In addition, this overconsumption occurs in watersheds that consume approximately 79% of the total global freshwater demand. Global water demand is projected to increase 55% by 2050 compared to 2000[1]. Therefore, the risk of overconsumption beyond carrying capacities will increase in the future. In nearly 50% of the watersheds facing overconsumption of freshwater, EWR is deprived by more than 63%, which implies that the ecosystems in these watersheds are under high pressure of freshwater scarcity as a consequence of regional carrying capacities exceedance. In particular, a large proportion of overconsumption is attributable to the irrigation water demand. Therefore, both volumetric and temporal management of irrigation water (including indirect contributions by societal efforts such as diversion of crop production sites, reconsideration of food consumption patterns, and reduction of food waste) are of considerable importance for the sustainable use of freshwater resources.

Responsibility of freshwater overconsumption does not lie only with the producer countries of crops. The crop importer countries are indirectly involved in overconsumption of freshwater in crop producer countries through virtual water trade. International food trade generally reduces the pressure on planetary boundaries as a whole, whereas the producer countries are exposed to additional pressure on regional carrying capacities at the national scale. In addition to freshwater availability, there are many other constraints pertaining to crop production. Therefore, from a sustainability perspective, it would not be feasible for the crop importer countries to reduce their crop import and increase the national crop production. However, the quantitative information based on the analysis of pressures on regional carrying capacities and its sources may support the understanding of the sustainability of current freshwater consumption and its linkage to food consumption by considering the region-specific conditions. This region-specific assessment will complement the results of the planetary boundary assessment at the global scale including 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, groundwater, and frozen water) that provide various functions through different water cycles[49]. Requirement of some water sub-boundaries and determination of water requirement for human consumption and ecosystems for suggested water sub-boundaries are challenging owing to the complexity in the mechanisms of water cycle and water utilization. However, more comprehensive definition on the carrying capacities of freshwater use covering various functions of freshwater will contribute to achieving sustainable freshwater use. This requires better underlying hydrological models that should be developed in future research.

One of the novel findings in this analysis is that the large proportion of freshwater overconsumption occurs owing to basic demands to sustain human life. The discrimination between basic and luxury needs for human enables it to reveal this fact, which can be used for more specific policy recommendations. However, the results may change depending on the criteria of HWR. We define HWR as the fair amount of domestic and irrigation water use based on the criteria by the WHO and the FAO in terms of ensuring low concern of health conditions (Section 2.1). We adopt the criteria for the sake of consistency with water requirement for ecosystems (EWR). On the other hand, demand of freshwater for industrial activities may also play a role in sustaining human life, particularly from an economic perspective. For instance, electricity is used in hospitals to protect and save human lives, and freshwater is consumed for electricity production by evaporation in turbines, cooling towers, and dams. However, recent results on water scarcity assessment of hydropower show relative low effects on water scarcity due to beneficial effects of water storage over seasons in many hydropower dams[50]. The same as the EWR, the definition of the freshwater amount that is required to sustain human life needs to be further examined in future research.

The connection between freshwater use and economic activities is also a crucial aspect for the sustainability assessment of freshwater use. As is evident from the results of the analysis on the sources of overconsumption, many importer countries can save national overconsumption of freshwater through virtual water trade. However, D'Odorico et al. found that economic factor (gross domestic product (GDP)) is a more influential driver of virtual water trade than water availability factors[51], which is also a conclusion by Weinzettel and Pfister[17]. Distefano and Kelly showed that the emerging countries may not be able to fully benefit from virtual water trade, and their economic growth will be restricted due to the lack of water[52]. In addition, the economic activities may be affected by water scarcity not only within a country but abroad as well, through international supply chains. Distefano et al. revealed the risks and effects of supply chain disruption associated with freshwater scarcity based on computational analysis using a multi-regional input-output model[53]. The relation between freshwater use and economic activities is also relevant in determining the basic requirements of freshwater and carrying capacities. Therefore, a more detailed analysis on these aspects should be conducted in future studies.

Associated content

Supporting information

Additional text and figures (PDF)

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