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ABSTRACT

The challenge of sustainably feeding billions of people, particularly in highly populated emerging economies, such as Bangladesh, requires addressing the environmental consequences of crop production, such as sustainable water use in agriculture. Here, we assessed the sustainability of crop water use and analyzed the balance of water use and nutrient density by integrating the crop water use and nutritional provision data with a hydrological model, WaterGAP 2.2d. Findings revealed that Bangladesh overconsumed approximately 20 billion m^3 of freshwater (19 % of total water consumption) owing to crop production during 2000–2016, with rice being a key crop. Shifting crop consumption from rice to alternative crops, such as potatoes, sweet potatoes, and maize, can improve both nutritional adequacy and sustainable water use. The analytical framework supports sustainable crop production by identifying key crops and watersheds that can contribute to sustainability, considering both sustainable water use and nutritional adequacy.

1. Introduction

Putting the sustainability of food systems for environmental and human health on the international agenda, the Sustainable Development Goals (SDGs) recognize the contribution of freshwater resources and nutrition to sustainable development and their role in improving the well-being of people worldwide (United Nations, 2015). In this context, a sustainable food system is important for delivering not only nutrition but also food security in such a way that the economic, social, and environmental bases for creating food security and nutrition for coming generations are not compromised. In the environmental dimension of sustainable food systems, sustainability is determined by ensuring that the impact of producing foods on the natural environment is minimized (FAO, 2010).

In terms of the environmental aspects relevant to food systems, the intensive water demand for crop production is one of the most important issues (Pfister et al., 2011). A significant proportion of total water consumption, estimated at approximately 85 %, is attributed to crop production (Shiklomanov, 2003). Global crop production is responsible for creating huge pressure on the limited available freshwater for humankind, and it is estimated that nearly 40 % of the world's population and a significant number of ecosystems are experiencing freshwater scarcity (Pastor et al., 2022; Pfister et al., 2011). The updated United Nations Water Development Report predicts that almost six billion people will suffer from freshwater scarcity by 2050, although this prediction also hints at an underestimation of the actual figure (Boretti and Rosa, 2019; United Nations, 2018). At present, the global water demand for all uses is ~4600 km^3 which will increase by 20–30 % by 2050, lead the global water demand of 5500–6000 km^3 per year (Burek et al., 2016). The defined planetary boundaries or thresholds for safe operating space for humans also include global freshwater use, and according to (Rockström et al., 2009), the safe limit is less than 4000 km^3 per year of freshwater for consumptive purposes. As a global community, we face the dilemma of finding ways to feed the growing billions and ensure that food is produced in a sustainable and socially acceptable manner (Sokolow et al., 2019).

The sustainability of finite water resources considering ecosystem health is usually discussed as to whether the consumption of water by humanity deprives the environmental water requirement (EWR) or not (Mekonnen and Hoekstra, 2016; Motoshita et al., 2020) and, as well as in the original concept of the planetary boundary framework, which aims to define a safe operating space for present societies to develop and

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thrive according to the resilience and functioning of the earth system (Steffen et al., 2015). The regional carrying capacity of water use in global watersheds is defined as the remaining water for humans, which is obtained by deducting the EWR from the natural flows of surface water and groundwater, excluding fossil groundwater. Thus, a defined boundary represents the limit of human water consumption that ensures healthy conditions in aquatic ecosystems. On the other hand, freshwater consumption beyond the regional carrying capacity is defined as freshwater overconsumption. The EWR is the minimum amount of water required to support ecosystem functioning (Pastor et al., 2014). Water consumption by humans results in the deprivation of water for other users, which can have major environmental consequences, mainly on ecosystems. For example, aquatic plants and animals may be affected by a lack of sufficient water for their sustenance (Hanafiah et al., 2011; Pierrat et al., 2023; Verones et al., 2013, 2017). Furthermore, the overconsumption of freshwater could have affected the downstream residents who are dependent on it. Subsequent water overconsumption can ultimately lead to reduced crop yields, which, in turn, can propagate malnutrition among populations, especially in underdeveloped and developing countries (Boulay et al., 2011; Motoshita et al., 2018; Pfister et al., 2009). The pressure of water deprivation in the EWR by humans depends on the balance of the remaining water above the EWR and water consumption in an area that is specific to local conditions. In the context of sustainability, beyond the assessment of the potential impacts on the environment, overconsumption beyond the carrying capacity of sustainable water resource use should be assessed by considering the specific local conditions of water resources (Mekonnen and Hoekstra, 2016; Motoshita et al., 2020).

The sustainability of food production and consumption is especially important for emerging economies facing a growing population. Bangladesh is the 8th most populous country in the world, followed by China, India, the United States, Indonesia, Pakistan, Brazil, and Nigeria. Bangladesh has the highest population density among these top-populated nations, with approximately 1119 people per square kilometer (BBS, 2022), making it one of the most densely populated countries in the world, and positioning it as the 8th most densely populated country globally (World Bank, 2023). High population density is a challenge for feeding the country, because the size of the land area determines the amount of available freshwater that can be collected from precipitation. Therefore, densely populated countries may face a dilemma between feeding the population and the limited availability of freshwater resources. The sustainable feeding of a growing and highly dense population could play a role in other emerging economies. Bangladesh as an emerging economy of the world, having one of the fertile lands in the world, thanks to its hundreds of rivers that crisscross the country and bring alluvial deposit, makes it an agriculture dependent economy (SRDI, 2020). Based on the recent estimates (Fiscal Year 2019–20) provided by Bangladesh Bank, agricultural crops, fisheries, livestock, and forest products together account for ~12 % of the total GDP of the country, while employing roughly 40 % of the total population. Bangladesh produces significant amounts of food to feed its growing billions (Roy et al., 2019). The continual backing of policies aimed at enhancing food grain production to fulfill domestic needs has played a crucial role in bolstering self-sufficiency, particularly in rice and maize, in Bangladesh; however, the country still relies on the import of agricultural commodities such as vegetable oil and cotton (FAOSTAT, 2021). Despite significant economic progress, 35 % of Bangladesh's population faces food insecurity, primarily due to a lack of diversity in food, with 70 % of the food intake comprising cereals, leading to inadequate protein and micronutrient intake (USAID, 2018). The agricultural sector contributes to total water withdrawal and use to a greater extent, which is evident from international statistics. According to AQUASTAT database, the total water withdrawal in Bangladesh during 2018–2022 period was ~36 billion cubic meters, of which agricultural water withdrawal shared about 88 % (~32 billion cubic meters), a figure notably higher than the global ratio, where agriculture typically constitutes approximately 70 % of total water withdrawal (FAO, 2022). Assessing the sustainability of water use for food production in Bangladesh is key to exploring the challenges and solutions to promote a sustainable approach to nutrition and the environment in emerging economies.

Here, we aimed to assess the sustainability of water consumption required to feed the growing population of Bangladesh as an emerging economy from the perspective of temporal changes and crop types with high geographical resolution. Existing studies related to the global-level assessment of water availability and use have found that grid-level approaches often underestimate water availability and overestimate water stress or scarcity for regional-level assessments (Beek et al., 2012; Wada et al., 2014). Conversely, employing a sub-basin and county-level approach to estimate water availability in a region furnishes significantly more precise information, given the finer geographical resolution, compared to a grid-based approach. However, in either case, information on the local-level water supply should be integrated into the modeling framework to generate a better and more accurate estimate of water availability in the region, which is often influenced by the local climate (Wada et al., 2016). In this study, we demonstrate more accurate estimates of water overconsumption for crop production beyond the local carrying capacity of freshwater in Bangladesh by considering the local climate conditions. First, we updated the crop water requirements in Bangladesh using local climatic data at a watershed scale. We also calculated the freshwater consumption in a watershed of the country using the latest hydrological model, WaterGAP 2.2d. By incorporating the regional carrying capacity concept that defines the amount of freshwater available for human demand in the watershed after excluding the environmental water requirement needed to sustain the ecosystem from natural flow, we also estimated the freshwater overconsumption induced by crop cultivation. Furthermore, we investigated the relationship between the nutrient density of food crops and freshwater overconsumption to establish a balance between sustainable water use and nutritional considerations. The analytical framework presented in this study aims to bolster sustainable crop production in Bangladesh by identifying the key crops and watersheds that play crucial roles in achieving a sustainable balance between water use and nutritional adequacy.

2. Material and methods

2.1. Updating the crop water requirement

The Food and Agriculture Organization (FAO) of the United Nations developed the CROPWAT (Allen et al., 1998) model for estimating the crop water requirement (CWR) of any plant. Typically, the CWR is dependent mainly on the climatic conditions of a region and can be estimated using the methodology developed by the FAO. We used Eq. 1 to calculate the CWR for the past 50 years (1960–2019). A comprehensive summary of all utilized data, accompanied by a concise overview and respective sources, is presented in Supplementary Table 1.

$$CWR_{c,t} = 10 \times \sum \left(K_c \times ET_{o,t}\right) \tag{1}$$

where $CWR_{c,t}$ (m^3/ha) represents the crop water requirement of the crops grown in Bangladesh in year 't'; K_c (unitless) is the crop specific coefficient estimated by FAO, and ET_o (mm/year) denotes the reference evapotranspiration of Bangladesh in year 't'. The crop-specific coefficient (K_c) is crucial for calculating the water needs of individual crops and relies on factors such as crop type, growth stage, and environmental conditions, thus significantly influencing the accurate estimation of crop water requirements. A factor of 10 converts the CWR from millimeters to cubic meters per hectare, as shown in the above equation. We sourced the K_c for all crops cultivated in Bangladesh from Chapagain and Hoekstra, 2004. In the CWR literature, a constant ET_o is often used, which tends to underestimate or overestimate the CWR and eventually the crop water use (CWU), which represents the water demand considering the production efficiency of crops, as formulated by Eq. 2. Production efficiency, a key concept in our study, refers to the yield of the water used for crop production. This helps to measure how effectively water is utilized to produce crops. Understanding this term clarifies the link between the water consumption and crop yield.

$$CWU_{c,t} = \frac{CWR_{c,t} \times Production_{c,t}}{Yield_{c,t}} \tag{2}$$

where $CWU_{c,t}$ represents the crop water use (m^3) of crop '*c*' in year '*t*'; $Production_{c,t}$ (tons) denotes the production of the crop '*c*' in year '*t*'; and $Yield_{c,t}$ (t/ha) shows the yield of the crop '*c*' in year '*t*'. To accurately measure the CWU, it is necessary to use year-specific ET_o using local climatic data. Several methodologies already exist, such as the FAO Penman-Monteith model (Allen et al., 1998), Abtew model (Abtew, 1996) to calculate the ET_o of a study area. Salam et al., 2020 updated the ET_o of Bangladesh using several empirical models and found that the Abtew model performed best under Bangladeshi climatic conditions. We used the updated ET_o for 1980–2016 from Salam et al., 2020 to update the CWU for each year according to Eq. 2. However, the average for the same period (1980–2016) was used as the ET_o for the 2017–2019 period because of the unavailability of data for these years. On the other hand, we used the same constant ET_o [~2.98 mm/year] as applied in FAO estimate to update the CWU of Bangladesh for 1961–1979 period (Mekonnen and Hoekstra, 2011). We calculated the CWU for all 57 crops cultivated in Bangladesh. Because all the crops that were grown in Bangladesh were heavily dependent on irrigation water (~94 % of the cultivated land was under the irrigation), we considered the crop green water use to be negligible and assigned all the CWU to be crop blue water use. Crop production and yield data were collected from FAOSTAT for the period of 1961–2019 (FAOSTAT, 2021).

2.2. Estimation of the freshwater overconsumption beyond carrying capacities due to crop production

We used the WaterGAP 2.2d model (Müller Schmied et al., 2020) to calculate the freshwater overconsumption in Bangladesh. Following the approach to define the regional carrying capacity of global watersheds by Motoshita et al., 2020, we defined the regional carrying capacity of Bangladesh's watershed for anthropogenic activities by deducting the EWR from the available water at a monthly level according to Eq. 3.

$$RCC_{i,m,t} = AW_{i,m,t} - EWR_{i,m,t} \tag{3}$$

where $RCC_{i,m,t}$ (m^3) represents the regional carrying capacity for human activities in each watershed '*i*' of Bangladesh for month '*m*' in year '*t*'; $AW_{i,m,t}$ (m^3) shows the total amount of freshwater available in each watershed '*i*' of Bangladesh for month '*m*' in year '*t*', and $EWR_{i,m,t}$ (m^3) denotes the environmental water requirement of each watershed '*i*' of Bangladesh for month '*m*' in year '*t*'. The EWR varied for each watershed depending on the mean monthly water flow. We adopted the Variable Monthly Flow (VMF) method developed by Pastor et al., 2014 to estimate the EWR for each watershed in Bangladesh. The VMF method is robust, spatially and temporally explicit, and has been used in numerous assessments e.g., Boulay et al., 2018; Steffen et al., 2015.

Human water consumption (HWC) consists of domestic, industrial, livestock, and irrigation water consumption according to the WaterGAP 2.2d model (Eq. 4). In the original model, only irrigation water consumption is provided on a monthly basis, whereas the remaining three water consumption categories are provided on an annual basis. We calculated the monthly water consumption for all categories in each watershed in Bangladesh. The freshwater RCC was subtracted from the total HWC to estimate the overconsumption in each watershed according to Eq. 5.

$$HWC_{i,m,t} = Dom_{i,m,t} + Ind_{i,m,t} + Liv_{i,m,t} + Irri_{i,m,t} \tag{4}$$

$$Overconsumption_{i,m,t} = \begin{cases} HWC_{i,m,t} - RCC_{i,m,t}, HWC_{i,m,t} > RCC_{i,m,t} \\ 0, HWC_{i,m,t} \le RCC_{i,m,t} \end{cases} \tag{5}$$

where $HWC_{i,m,t}$ (m^3) represents the human water consumption in each watershed '*i*' of Bangladesh for month '*m*' in year '*t*'; $Dom_{i,m,t}$ (m^3) denotes the total amount of domestic water consumption in each watershed '*i*' of Bangladesh for month '*m*' in year '*t*'; $Ind_{i,m,t}$ (m^3) shows the total amount of industrial water consumption in each watershed '*i*' of Bangladesh for month '*m*' in year '*t*'; $Liv_{i,m,t}$ (m^3) symbolizes the total amount of livestock water consumption in each watershed '*i*' of Bangladesh for month '*m*' in year '*t*'; $Irri_{i,m,t}$ (m^3) characterizes the total amount of irrigation water consumption in each watershed '*i*' of Bangladesh for month '*m*' in year '*t*'; and $Overconsumption_{i,m,t}$ (m^3) displays the total amount of freshwater overconsumption in each watershed '*i*' of Bangladesh for month '*m*' in year '*t*'.

The overconsumption of freshwater for the production of each crop was estimated by allocating the total overconsumption of freshwater based on the total CWU of each crop produced in Bangladesh, assuming that the other sources of water use had minimal contributions to it (e.g., the total share of domestic, livestock, and industrial sources to the HWC on an average for 2000–2016 period was ~10 %). We also divided the overconsumption amount into two types: overconsumption induced by the consumption of agricultural crops and overconsumption induced by the export of crops to other nations, based on FAO crop trade matrix data (FAO, 2023). The national consumption of crops produced in Bangladesh was calculated by subtracting the exports of each crop from the production.

2.3. Analyzing the balance between nutrient density and freshwater overconsumption of crops

Balancing nutritional requirements with environmental considerations is pivotal for achieving sustainability in food consumption. Nutrient density of foods can be defined as the amount of selected nutrients per reference unit of food, which is generally expressed as 100 kcal, 100 g, or the full serving size. Here, we considered the nutrient densities of all 57 crops produced and consumed in Bangladesh. We estimated the total energy provided by total crop consumption according to Sokolow et al., 2019. Nutrient profiling is the existing standard methodology for quantifying the nutrient quality of foods. The nutrient profiling model used standard requirements set by the World Health Organization (WHO) and FAO. These guidelines recommend the nutrient intake (RNI) for males aged 19–65 years. A recent study developed a nutrient density score (NDS) for crops using the WHO and FAO guidelines of the RNI of 10 nutrients (vitamins A, C, B_6; Thiamin, Riboflavin, Niacin, Folate, Calcium, Zinc, and Iron) (Sokolow et al., 2019). The NDS of the crops denoted the average percentage RNI per 100 kcal of food. Thus, the NDS represents the efficiency of food crops in terms of nutrition. We analyzed the relationship between the overconsumption of freshwater induced by food crops grown in Bangladesh and the NDS of food crops obtained from Sokolow et al., 2019 using the FAO crop code. This analysis has us the implications towards sustainable crop consumption from the perspective of nutritional sufficiency and water resource use.

3. Results

3.1. Updating the crop water use using local data

We found a noticeable difference between the commonly used methods and our estimates for calculating the CWU. Typically, global estimates assume a static ET_o, which is the reason for the underestimated (or overestimated) CWU. The magnitude of evapotranspiration (ET_o) directly influences CWU, showing that higher ET_o results in increased CWU, and conversely, lower ET_o contributes to reduced CWU.

This relationship indicates the sensitivity of the CWU to fluctuations in ET_o. Evapotranspiration rate fluctuates depending on the climatic conditions of the country. Hence, using local climatic data could provide a better and more accurate estimate than constant reference evapotranspiration estimates as a global average. This is evident from the results shown in Fig. 1. Both the FAO Penman-Monteith and Abtew models could be useful, but the key point here is to use the updated ET_0 under local climatic conditions for each year. According to our findings, the updated CWU in 2019 was estimated at approximately 165 billion cubic meter. Notably, the FAO based estimates calculated this value as ~130 billion cubic meters, an underestimation of CWU ~35 billion cubic meters (21 % of the total). Overall, both estimates showed similar trends over the study period, albeit with different magnitudes of change during 1980–2019, owing to the different ET_0 values used for the estimation. The average CWU in Bangladesh during 1980–2019 was estimated to be approximately 144 billion cubic meter according to the updated results, while the trend of estimated CWU showed a constant increase with time (approximately 20 % increase over 40 years).

Fig. 2 shows a comparison between the FAO-based estimate and the updated estimate of the CWU for the top 11 crops in Bangladesh that have a comparatively higher CWU. It is evident that the water consumption for rice production outweighs other major crops of the country. Based on our updated results, rice production consumed ~110 billion cubic meter water on average from 1961 to 2019. This value is approximately 17 billion cubic meter higher than the FAO-based estimate. Other than rice production, the other major crops that had comparatively higher CWU were jute (~3 Bm^3), sugarcane (~2 Bm^3), wheat (~2 Bm^3), and areca nuts (~1 Bm^3). The total amount of water consumed for crop production is determined by the crop production. To understand the effects of the total crop production amount and efficiency of crop water use on the total water consumption for crop production, we show how intensity and production affect total crop water use in Supplementary Fig. 1. Rice had the highest crop water consumption, even though its production efficiency was comparatively higher than that of other crops such as areca nuts, tea, chilies, and peppers. Rubber has the lowest production efficiency in terms of crop water consumption among all crops produced in Bangladesh. We observed higher production efficiency in terms of water consumption in vegetable and fruit crops (e.g., melons, cauliflowers, broccoli, pumpkins, and potatoes).

3.2. Overconsumption of freshwater from agricultural crop production

Looking at the water consumption, we found out that the average water consumption during the period was ~107 billion cubic meter where the overconsumption amount was approximately 19 % of the total water consumption. Compared with the global freshwater overconsumption accounted for ~24 % of the total freshwater consumption, as estimated by Motoshita et al., 2020, overconsumption faced in Bangladesh was a bit lower. This overconsumption is primarily driven by a combination of factors, including low water availability and high human water consumption. Overconsumption beyond the regional carrying capacity of water resources associated with agricultural crop production in Bangladesh was approximately 20 billion cubic meter – the average value during 2000–2016. The WaterGAP 2.2d model divides Bangladesh into 16 watersheds, of which 10 face overconsumption (Fig. 3). There was variation in overconsumption, which was attributed to changes in crop production. Watersheds that experienced overconsumption also had fluctuations, as downs which is evident from Supplementary Fig. 2 that shows the coefficient of variation (CV) of freshwater overconsumption during the study period. We found that freshwater availability followed a downward trend, which is undoubtedly an alarming situation. In the context of discussing freshwater overconsumption, a specific reference was made to the consumption of crops within those regions and its correlation with the HWC metrics of those regions (Fig. 3). Noticeably, all watersheds in the coastal districts of the country experienced overconsumption, whereas watersheds that engulfed the major rivers and were located in the wetland ecosystem in the eastern region did not experience any overconsumption (Fig. 3). Some coastal districts are already facing salinity intrusion owing to numerous factors, and agricultural production has become more challenging (e.g., in the southwestern coastal districts) (Tauhid Ur Rahman et al., 2017). Owing to salinity intrusion into freshwater, the availability of freshwater decreases, while overconsumption may increase, considering the current trend of agricultural crop production.

Fig. 4 shows temporal variations in freshwater availability and overconsumption. We noticed a distinctive temporal pattern over the course of time – the freshwater availability was decreasing by 10 %,

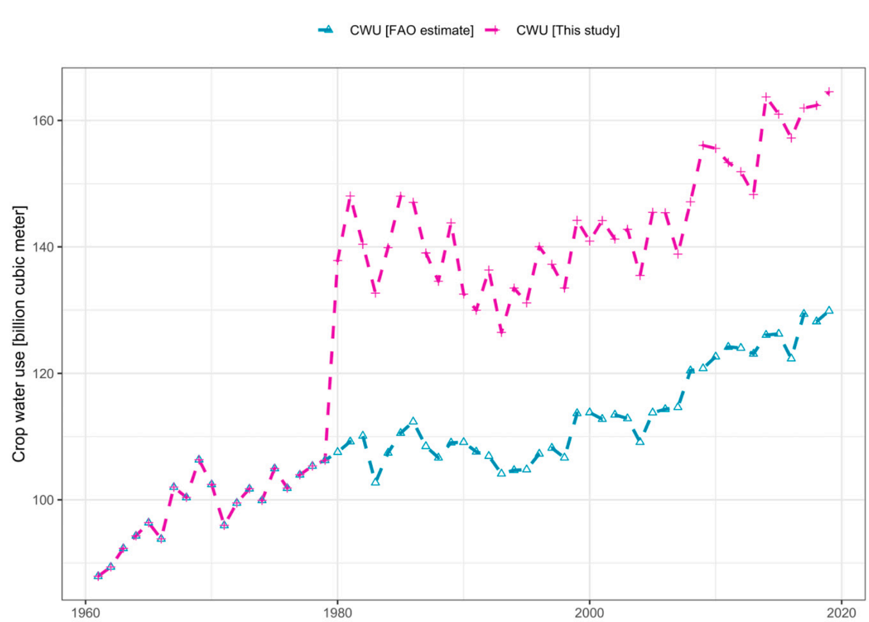

Fig. 1. The updated crop water uses in Bangladesh during 1961–2019 period. Note that the crop water use data for FAO based estimate was calculated from the crop production data provided by FAO, 2023.

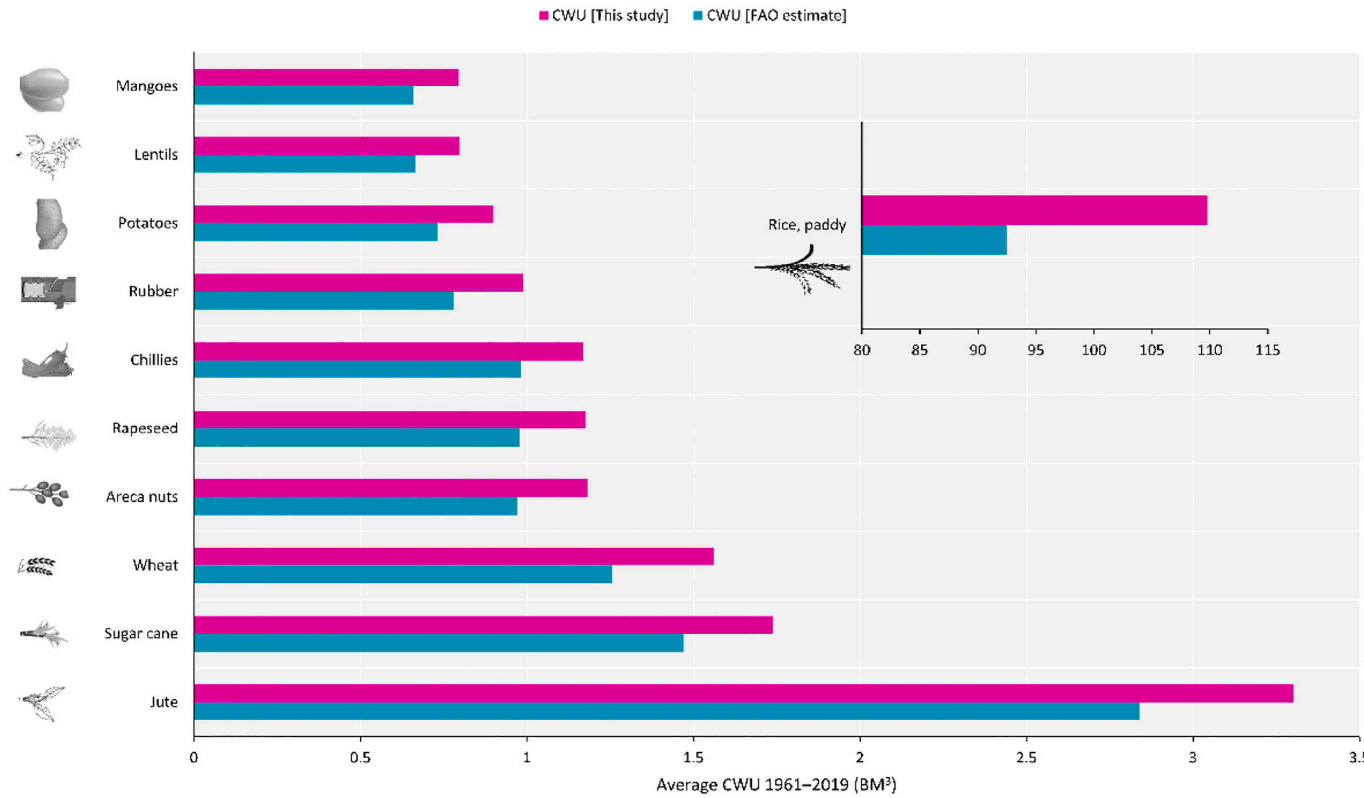

Fig. 2. Comparison between different estimates of crop water use for major crops that have comparatively higher crop water use. Note that the data is shown as an average value of crop water use during 1961–2019 period.

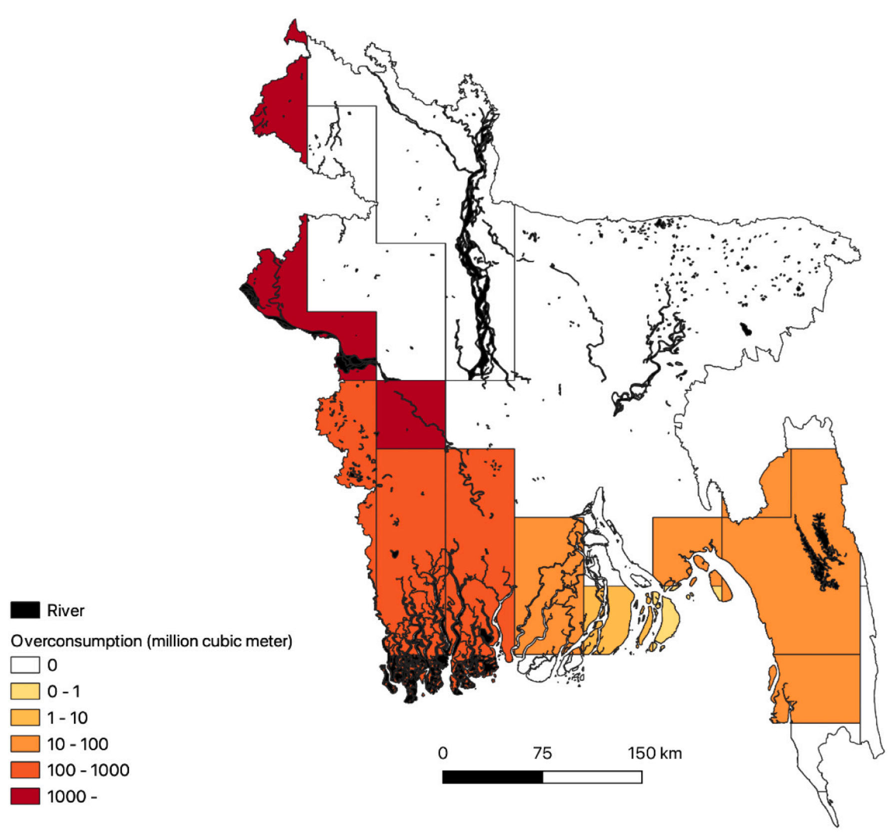

Fig. 3. Freshwater overconsumption in Bangladesh induced by the agricultural crop production. Note that the overconsumption amount is presented as the average value in million cubic meter during 2000–2016 period based on WaterGAP 2.2d model.

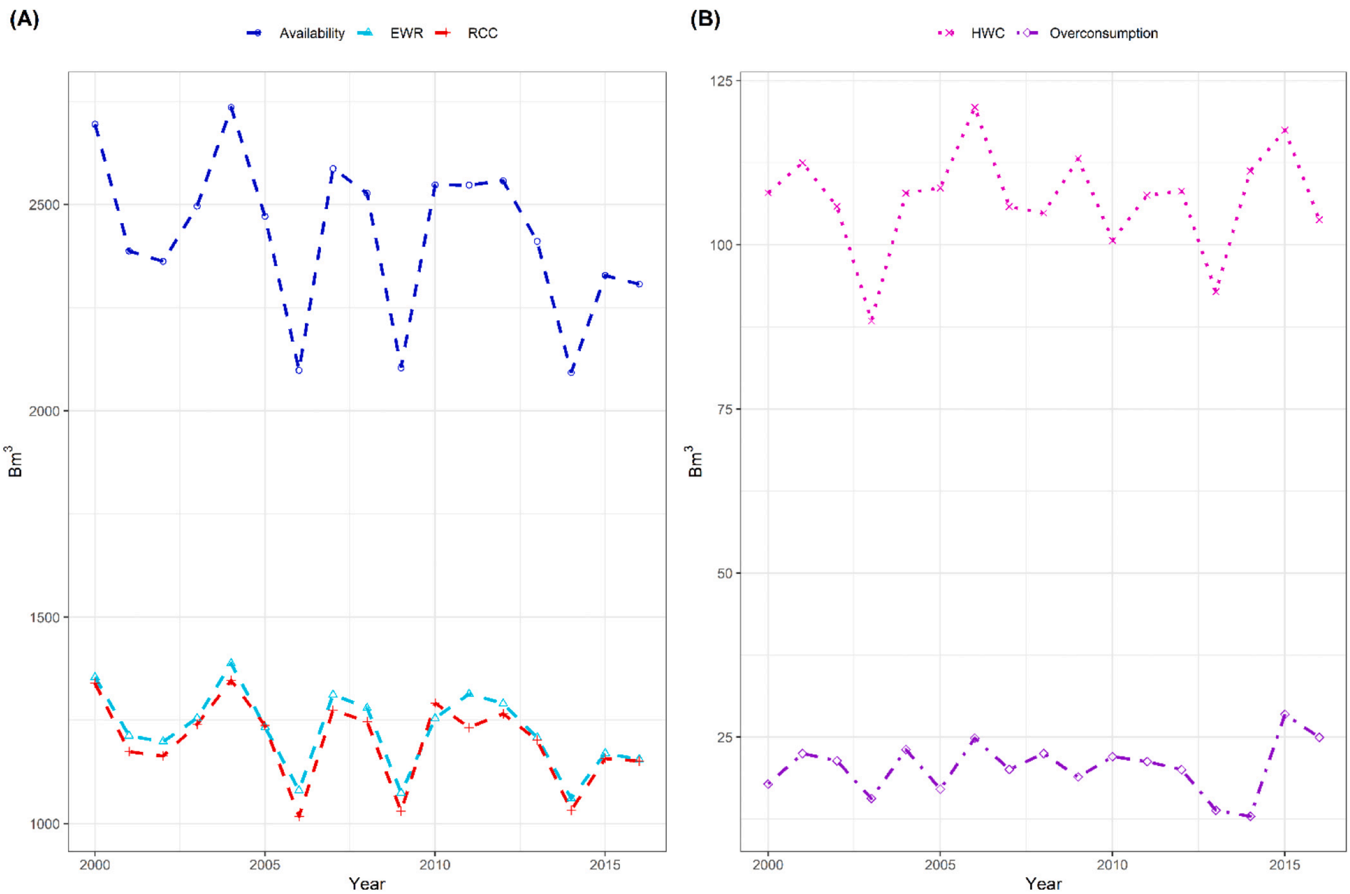

Fig. 4. The temporal variation of (A) the freshwater availability, environmental water requirements and regional carrying capacity, (B) the human water consumption (HWC) and overconsumption in Bangladesh during 2000–2016 period according to WaterGAP 2.2d model.

whereas the overconsumption was increasing by 8 % based on a three-year moving average. This is a serious concern, especially for aquatic ecosystems, because a certain amount of freshwater is required to maintain ecosystem functioning. On average, overconsumption during 2000–2016 was approximately 20 billion cubic meter. The underlying factors behind the fluctuations in freshwater overconsumption were the year-specific reference evapotranspiration of the country and the production of crops in the specific year.

The overconsumption of freshwater induced by crop production is driven mainly by its own consumption. Export related overconsumption only shared ~1 % of the total overconsumption, whereas national consumption related overconsumption shared the rest. This is due to the need to feed a large population; however, in recent years, food sufficiency has increased owing to the ongoing green revolution. According to our results, export-related overconsumption amounted to ~0.22 billion cubic meter whereas national consumption-related overconsumption of freshwater accounted for ~20 billion cubic meter on average, during 2000–2016. The export related overconsumption is mainly driven by the crops like jute (133 million m^3; 61 %), areca nuts (31 million m^3; 14 %), sesame seeds (14 million m^3; 6 %), tea (12 million m^3; 5 %), and rubber (11 million m^3; 5 %) (Supplementary Fig. 3–4). The overconsumption induced by the consumption of crops, notably rice, accounted for a substantial proportion of water use, with rice alone contributing to approximately 83 % (~16,860 million m^3) of total water use (Fig. 5). Rice is the major staple food; on a per capita basis Bangladesh is one of the top rice consumers of the world with an estimated per capita consumption of ~180 kg per year (during 2020–2021). Managing water consumption in rice production is imperative for addressing the overconsumption associated with rice cultivation, which is a key highlight depicted in Fig. 5. Moreover, recent trends indicate a gradual decrease in per capita rice consumption (Yunus et al., 2019) whereas the consumption of other crops such as wheat, potatoes, chilies, peppers, and mangoes has shown an increasing trajectory, as previously discussed. In this sense, water management for the production of these crops is also important as a prescriptive approach towards sustainable water use in future crop production.

3.3. *Causal demand inducing overconsumption of freshwater by agricultural crop production*

Fig. 6 shows the annual CWU of the major crops in 2015 by dividing the non-overconsumption and overconsumption portions to provide an overview of how much of the CWU for the production of such crops exceeded the carrying capacities. We provided the crop production of Bangladesh (rice, wheat, and sugarcane) in a unit of 1000 tons per 5-arc-minute grid cell based on the GAEZ v3.0, model for the year 2015 (IIASA/FAO, 2012) in Supplementary Fig. 5 to better understand regional crop production and induced freshwater consumption issues. Rice production was responsible for more than 77 % of the total overconsumption induced by agricultural crop production, whereas the proportion of water consumption for rice production is approximately 84 %. This indicates that rice was produced in less pressured areas for overconsumption, which can be confirmed by the comparison of the production and overconsumption maps in Supplementary Fig. 5 and 6. Overconsumption induced by rice production occurred in very limited areas (Supplementary Fig. 6), whereas rice production was widespread throughout the country. Moreover, we found the important fact that significant overconsumption of major crops (rice, wheat, and sugarcane) occurred in the same watershed. This implies that the same countermeasures for reducing overconsumption (e.g., improvement of water

Fig. 5. Overconsumption of freshwater induced by own consumption of agricultural crop during 2000–2016 in Bangladesh. Note that the unit of the freshwater overconsumption value is million cubic meter.

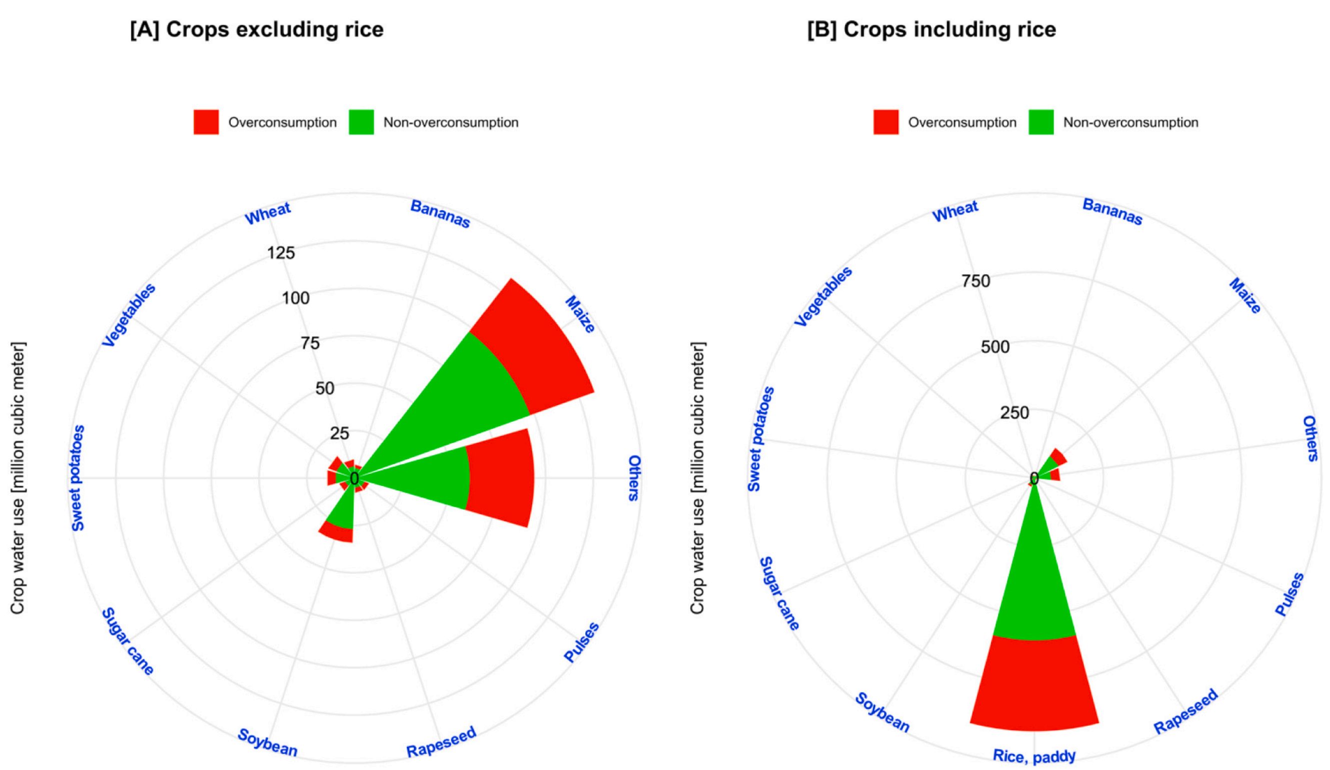

Fig. 6. Portion of freshwater non-overconsumption and overconsumption induced by major agricultural crops in Bangladesh during 2015. Palette [A] shows the overconsumption and non-overconsumption portion excluding rice, and palette [B] shows the same figure including all the crops. Note that the crop production data is based on the GAEZ v3.0 model and the overconsumption is calculated on watershed level according to WaterGAP 2.2d model.

intensity, shift of production crops, or area) in the watershed would commonly work for major crops.

Rice is still the most relevant crop that dominates the overconsumption of water in crop production; however, per capita rice consumption has been gradually decreasing, and the opposite is true for other crops, as mentioned in the previous section. If we could reduce overconsumption in such areas by avoiding rice production, the overconsumption induced by other major crop production in Fig. 6 would become more relevant. Other than rice, maize and soybean production contributed nearly 8 % and 2 % of the total overconsumption. The amount of water overconsumption by major crops, other than rice (Fig. 6) was not necessarily proportional to the amount of production (Supplementary Fig. 7). Looking at the temporal trend of water consumption by crops from 2000 to 2016 (Supplementary Fig. 8), some major crops (jute, areca nuts, potatoes, etc.) showed higher growth rates in production than rice. This implies that these major crops may be of concern in the future.

3.4. *Balance between freshwater overconsumption and nutrient density of consumed crops*

Fig. 7 shows the relationship between the nutrient adequacy of the consumed crops in Bangladesh and freshwater overconsumption. In terms of the total freshwater overconsumption induced by crop production in Bangladesh, a few crops dominate, as depicted in Fig. 7. To promote sustainability in the context of crop consumption, it is advisable for the population to favor crops that not only exhibit higher nutrient adequacy but also minimize freshwater overconsumption. Notably, rice was the single dominant crop for both freshwater overconsumption and nutrient adequacy owing to its massive consumption. In contrast, vegetables and fruits (shown as the legends colored orange and pink in Fig. 7) had lower nutrient adequacy than grain crops because their consumption was low, while they induced less freshwater overconsumption than many other crops. The nutrient adequacy compared with the overconsumption of vegetables is relatively higher than that for fruits and grains/roots/tubers/plantains on average; the ratios of the nutrient adequacy to the overconsumption for grains/roots/tubers/plantains, fruits, and vegetables are 6.4, 6.3, and 7.3, respectively. Therefore, shifting consumption patterns is key to sustainable water use while maintaining health. In terms of sustainable production and consumption (and considering that sufficient nutrition is maintained), some food crops might be key, for example, cauliflowers/broccoli, cabbage, lettuce, and spinach. In addition, the substitution of food crops within the same category with higher nutrient adequacy but lower water overconsumption should be considered. For example, within grains, wheat could be an alternative to rice, as it would contribute to the improvement of both water and nutrition. Moreover, potatoes, sweet potatoes, and maize could significantly reduce water overconsumption and improve the adequacy of nutrients per kcal of intake. Encouraging increased consumption of these efficient crops, as opposed to the current reliance on rice, presents an option for achieving a balanced approach to nutrition and sustainable water use from a consumer's perspective.

4. Discussions

Like many other productive activities, water plays a significant role in crop production. Statistically speaking, food production demands ~90 % of the consumptive water use, according to the estimates provided by D'Odorico et al., 2018. For this reason, a better understanding of agricultural water consumption is needed to identify regions where

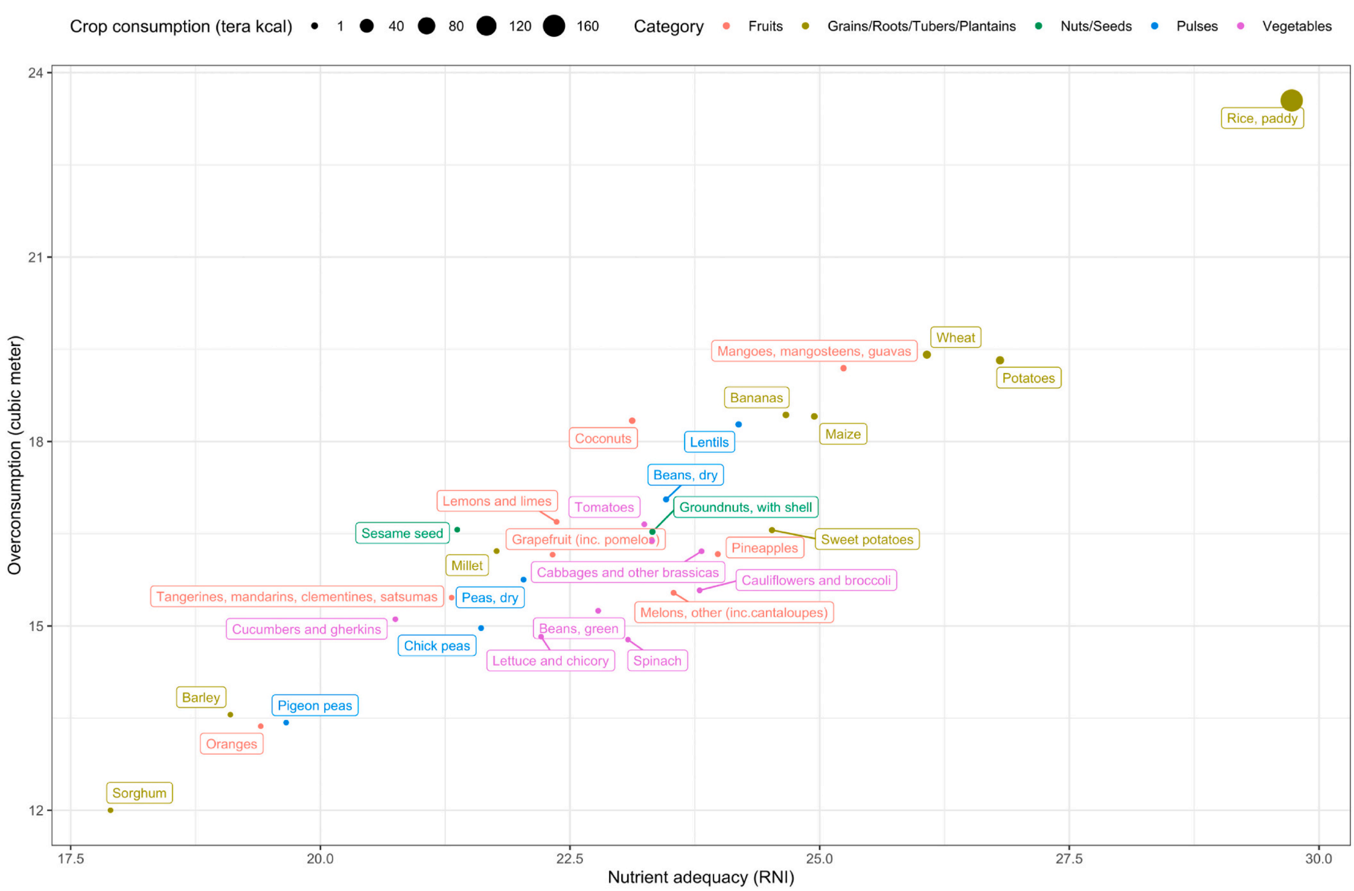

Fig. 7. The freshwater overconsumption due to national consumption of crops in Bangladesh with respect to nutrient adequacy. Note that both the horizontal and the vertical axis have been log transformed and the size of the bubble corresponds to the total crop consumption.

agricultural water demand and its spatial and temporal variations could impact the surrounding ecosystem. Overconsumption of freshwater is a regional issue that affects the local environment the most and has been identified by Motoshita et al., 2020. Though literature on the global water footprint of nations suggested that the water footprint of developing nations was smaller than that of developed countries, factoring the consumption volumes into the estimates (Hoekstra and Mekonnen, 2012), this does not necessarily suggest that such a low water footprint would have less impact on the ecosystem from the viewpoint of local sustainability. Even with a smaller water footprint, freshwater overconsumption can occur at a local scale, which may be of concern to the local population and ecosystems. Of course, the situation differs in global and local contexts. Inspecting this on a global-scale assessment, the responsibility for freshwater overconsumption is found to be linked with crop-importing countries, where international food trade reduces the pressure on the planetary boundaries of freshwater use (Motoshita et al., 2020). However, in some countries, such as Bangladesh, this is due to meeting the huge basic needs of its own population.

We identified watersheds in Bangladesh that face freshwater overconsumption. According to our findings, the southwestern part of the country is a major hotspot for freshwater overconsumption, which is mainly induced by some of the major crops that are typically cultivated in this region. Furthermore, the southwestern part of the country has been recognized to aggravate the uncertainty of water supply and escalate extreme hydrological events such as erratic rainfall and droughts (Mojid et al., 2021). In addition, there is a chance that groundwater recharge may decline in the future in this part of the country because of a smaller amount of short-span high-intensity rainfall due to climatic variability (Shah, 2009). Competition for freshwater use among various sectors will intensify in the future, which may lead to negative impacts on local water, energy, ecosystem services, food security, and overall agricultural productivity (Hong et al., 2016; Mo et al., 2017). To alleviate these impacts, improving water efficiency in crop production and production transfer to potential farms in areas with lower water overconsumption pressures is essential. The water efficiency of rice production in the southwestern areas is relatively low compared to that in other areas, whereas the ratio of water overconsumption is high in these areas. There is also plenty of arable land in Bangladesh (~60 % of the total land), which suggests the potential to shift the production area for rice production to less pressured areas in terms of water sustainability. A shift in production location cannot be achieved based only on the sustainability of water; however, the results of this study provide an additional dimension for sustainable agriculture in Bangladesh in the future.

Worldwide, balanced nutrient intake through food consumption is gaining momentum as part of an effort to reduce the number of deaths from noncommunicable diseases. Low- and middle-income countries are among the hotspots of these diseases (Gakidou et al., 2017). The World Health Organization/Food and Agriculture Organization recommends consuming at least 400 g or five servings of vegetables and fruits daily (WHO/FAO, 2003). Our findings provide evidence that fruits and vegetables contribute less to freshwater overconsumption. These findings have significant policy implications. A balanced intake of fruits, vegetables, and grains supports a healthy lifestyle and concurrently mitigates excessive freshwater consumption. However, it has been found that on an average, 75–92 % of the population of Bangladesh, both in rural and urban areas, does not consume the recommended fruits and vegetable intake. Although various socioeconomic and sociodemographic factors are responsible, affordability and low awareness are the main contributors to lower vegetable and fruit intake (Mustafa et al., 2021). The typical belief of most people in the country is that rice consumption is more important than vegetable or fruit consumption during regular meals. Therefore, to maintain a healthy and sustainable lifestyle, supportive and feasible policies must be implemented and help raise public awareness. We showed that some crops, especially vegetables and fruits, provide higher nutrient and energy densities. However, they are not widely consumed worldwide. Therefore, changes in eating habits are crucial for the sustainable management of freshwater resources while maintaining public health. On the other hand, we focused on the overconsumption of water for crop production in the context of the regional carrying capacity of water resources for the conservation of aquatic species. However, more food is needed to solve the issue of insufficient food supply in many emerging economies, which is not discussed in this study. The sufficiency of food supply in emerging economies should also be considered by balancing water use for the conservation of ecosystems and the nutrition of the population.

5. Conclusions

A comprehensive evaluation of crop water consumption identified hotspots of freshwater overconsumption, notably in the southwestern region of Bangladesh, which exacerbated environmental uncertainty and impacted local ecosystems. This overconsumption, driven by major crops, not only strains water resources, but also intensifies competition among sectors, which has negative implications for water availability. Shifts in production locations, focusing on areas with lower water overconsumption pressures, have emerged as critical strategies for sustainable crop production. Notably, encouraging a balanced approach that emphasizes higher consumption of fruits and vegetables aligns with both healthy lifestyle recommendations and the goal of reducing excessive overuse of freshwater. Promoting these shifts in food choices and addressing socioeconomic barriers could contribute significantly to sustainable water resource management in Bangladesh.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2023.11.020.

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