Status and sustainability challenges of agricultural water usage in Bangladesh

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Abstract: Maintaining sustainability in agricultural water usage is a critical concern particularly when the burgeoning population demands more food while adverse climate change affects water availability. Despite this, the climate-water-crop nexus is still poorly understood in many regions. This study was conducted to assess the current agricultural water use scenario in Bangladesh, and its sustainability challenges under the virtual water perspective. The number of crops, cropping area, yield, and water use data were used to calculate virtual water transport in terms of crops gown at the divisional scale. The long-term daily rainfall, daily river stage, and weekly groundwater level data were collected and nonparametric Mann-Kendall trend analysis was conducted to assess the water use sustainability. Findings in other recent studies were also taken into consideration to evaluate the sustainability challenges. This study revealed that the two most drought-prone northwest divisions export virtual water embedded in agricultural produce at 14086 Mm^3 yr^{-1}, whereas two urbanized divisions import 18477 m^3 yr^{-1}, to or from the national water-use budget. Rice production alone consumed ~88% of the total water used in agriculture, and the dry season rice had higher water demand than the wet season rice. The water use sustainability in the two most water-exporting divisions (Rajshahi and Rangpur) is at great stake because total rainfall in July is decreasing significantly (2.90 mm yr^{-1}) in Rajshahi and the number of rainless days in August is significantly increasing (0.033 day yr^{-1}) in Rangpur. Irrigated rice production is predicted to face water scarcity because the dry season water level in both rivers (63%) and groundwater (92%) shows a declining trend. The ratio of green (rainfed) to blue (irrigation) water use in the country was estimated at 2.5, which needs to be increased. The study findings will be useful references for developing effective agricultural water management strategies considering the diverse nature of the potential sustainability challenges.

Keywords: virtual water transport, climate change, water security, groundwater, surface water, precipitation, drought index

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1 Introduction

Water availability is a key to food security. Water-food security nexus is, however, facing enormous challenges due to high population growth, rising water demand, scarce water resources, and climate change (Yillia, 2016). Freshwater scarcity is projected to exacerbate in the future due to a significant increase in water demand, which in turn will affect water security for food production and environmental sustainability (Alcamo et al., 2003; Zakar et al., 2012; Ercin and Hoekstra, 2016). It is estimated that annual global water

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withdrawal will grow from 4,500 billion m^3 in 2009 to 6,900 billion m^3 by 2030 (Addams et al., 2009). Climate change may lead to increased water stress due to declining precipitation and higher water demand in many parts of the world (Ercin and Hoekstra, 2016). Ludwig et al. (2009) reported that climate change could affect the distribution of global water resources, by altering the timing, variability and reliability of rainfall as well as the increasing occurrence of extreme weather events. Valipour (2017) reported that 46% of global cultivable areas remained unsuitable for rainfed agriculture due to climate change and other meteorological issues. The projected temperature increase associated with climate change will imply higher evaporation and drier conditions. Consequently, water and food security nexus will become more complex to manage (Hanjra and Qureshi, 2010).

Like many other countries, Bangladesh is struggling to maintain water security for food production. Increasing water demand and competition over freshwater resources have already been felt during the previous decades (Mancosu et al., 2015; Arfanuzzaman and Rahman, 2017). The population of the country is projected to reach about 214 million by 2050, which will result in twofold increase in annual domestic and fourfold increase in industrial water demand (Ismail, 2016). Ensuring adequate water share for crop agriculture is a great challenge because of the limited water availability and its high-water footprint. Rice is the main crop in the region, which has higher water footprint than any other crops of comparable value and growth duration (Allen et al., 1998; Saha et al., 2013). Rice is farmed both during dry and wet seasons covering nearly 80% of the gross cropped area (BBS, 2012–2017). The wet-season rice is primarily rainfed, but the dry-season rice is an irrigated crop and contributes nearly 55% to the total rice production. High water-consuming, high yielding rice varieties have been predominantly cultivated in the dry-season with the expansion of irrigation facilities since the 1990s (Alauddin and Tisdell, 1991). Over time, irrigation in Bangladesh has become increasingly dependent on groundwater due to the easy availability of low-cost equipment to tap shallow aquifers, and the limited availability of surface water during dry season due to huge withdrawal at upper catchment. Although the demand for irrigated agriculture is still on the rise to meet the challenges of food security, further expansion of irrigated agriculture is questionable because of groundwater depletion (Rahman et al., 2016). The condition is likely to be worse with shortened monsoon season and less dry season rainfall under the changing climate and thereby resulting in reduced groundwater recharge (Shamsudduha, 2018).

A new paradigm shift in water management strategies is immensely felt at a national and international scale to deal with the emerging water and food security issues. For better water management, it is essential to understand the present agricultural water use scenario at a spatial and temporal scale as well as their influencing factors. Assessment of the virtual water transport among the regions of a country can provide a clear picture of the spatial distribution of water use (Hoekstra and Hung, 2005). Virtual water (VW) is the amount of water used for producing any kind of commodity, goods or service (Allen, 1998; Carr et al., 2013; Hoekstra and Hung, 2005). Identifying the amount of virtual water embedded in crops has greater implications for water management, practice, and policy (Ray et al., 2018). The concept of virtual water trade provides a novel way of exploring sustainable water use options (Carr et al., 2013; Hoekstra and Hung, 2005). If one region exports a water-intensive product to another region, it exports water in virtual form (Hoekstra and Hung, 2005; Oki and Kanae, 2004). Hence, water scarcity can be minimized in a place by importing water-intensive products instead of producing them locally (El-Sadek, 2010; Matchaya et al., 2019). Moreover, the natural water security of a state depends on whether the water used derives from green water (e.g., effective rainfall or soil moisture) or blue water (e.g., water from different surface and groundwater sources) (Wichelns, 2010). Virtual water concept has provision to separate the proportions of green and blue water used to produce crops. Overall, virtual water trade concept can help improve water use efficiency and water allocation efficiency at local or national scales (Zeitoun et al., 2010).

Studies dealing with virtual water and water footprint concept are very few in Bangladesh. Some studies have assessed the water footprint for rice production in the country (Rahman et al., 2016; Mullick and Das, 2020). However, no studies have yet explored the virtual water flows across different regions of the country considering different agricultural crops. Assessing the regional virtual water trade can help identify which parts of the country are in the virtual water surplus or deficit zones in terms of different crops grown. It is also important to evaluate the extent to which the current regional virtual water exchange pattern is sustainable in terms of pressures on water demand and availability. Therefore, this study aimed to explore the regional virtual water transport in terms of different crops grown and detect the sustainability challenges by identifying the trends of some hydro-meteorological parameters representing the green and blue water resources. Evaluating the trends of hydro-meteorological variables is indeed a key indicator for assessing the possible impacts of climate change on agriculture water usage (Valipour et al., 2020) and help develop its sustainable management (Valipour, 2016). Trend analysis of two rainfall related extremes was performed in order to evaluate the sustainability of green water availability. Similarly, long-term trends of maximum and minimum river stage and groundwater table were detected in order to assess the sustainability issues of blue water resources.

2 Materials and methods

2.1 Study area

Bangladesh is one of the most climatologically vulnerable countries in the world. It lies in the northeastern part of South Asia (20° 34'–26° 38' N and 88° 01'–92°41' E) and is bounded by India on the west, north and northeast, Myanmar on the southeast, and the Bay of Bengal on the south (Figure 1). The landscape is largely assembled into three landforms, hill areas accounting for 12%, terrace areas covering 8%, and plain and fertile floodplain areas covering 80% (BBS, 2012-2017). The country enjoys a sub-tropical monsoon climate with an average annual rainfall of 2030 mm. Amount of rainfall and its distribution throughout the year are very important for crop production. Regional hydrology and spatio-temporal distribution of water resources in the country are highly susceptible to water-related extreme events (Ahmad, 2003). Northern and western parts of the country encounter frequent drought, eastern low-lying areas face flash floods and the southern coastal zone is vulnerable to the cyclone and sea level rise. Rice is the main crop. The non-rice crops (e.g., vegetables, pulses, oilseeds, potato, and other small grains) are grown only in sequence with the rice in one or even two seasons (BBS, 2012–2017). Despite its small size, the country has spatial heterogeneity in crop diversification (0.49 in Rajshahi and 0.17 in Sylhet division, Islam and Hossain, 2015), population density, cropping intensity, climatic advantages, soil quality, and availability of different agricultural inputs (Quddus et al., 2004).

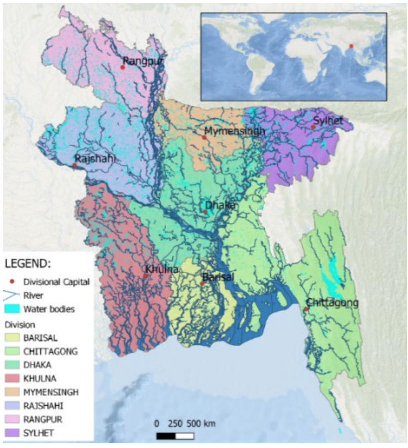

Figure 1 Divisional map of Bangladesh (Data source: Department of Public Health Engineering, Bangladesh)

2.2 Water use assessment

The virtual water transports among the eight divisions of Bangladesh, namely Dhaka, Chattogram, Rajshahi, Khulna, Sylhet, Barishal, Rangpur, and Mymensingh (Table 1), were calculated to understand the spatial crop water use scenario in the country. Division-wise crop data for the period of 2011–12 to 2015–16 were collected from the Yearbook of Agricultural Statistics (BBS, 2012–2017). Water use values for different crops were calculated using the data collected from relevant literature (Ahmed, 2018; Islam et al., 2017). Crops grown in Bangladesh were grouped into six categories: (i) rice crops, (ii) other cereal crops, (iii) pulse crops, (iv) oilseeds, (v) spices and condiments, and (vi) fruits and vegetables. Although rice is a cereal crop, it was categorized separately in this study because of its importance for food security as well as water security of the country. A few crops were not added to the list due to their negligible cultivation area. The virtual water transport (*VWT*) (surplus/export or shortage/import) in m^3 at divisional scale for each crop category was calculated by using the following equation:

$$VWT=(CP_{da}-CP_{na})\times DP\times WF \quad (1)$$

where CP_{da} and CP_{na} are the divisional and national per capita annual crop production of each category in kg, respectively, *DP* is total divisional population, and *WF* is water footprint ($m^3\ kg^{-1}$). A positive value of *VWT* will indicate food surplus or virtual water export and negative value food shortage or virtual water import.

Table 1 Area, population and climatic condition of eight divisions of Bangladesh (BBS, 2012–2017)

Division	Area (×1000 km^2)	Population per km^2	Annual rainfall (mm)	Average temperature (°C)
Dhaka	20.6	1661	2022	25.9
Chattogram	33.9	838	2794	25.7
Rajshahi	18.2	1018	1419	25.8
Khulna	22.3	704	1736	26.1
Sylhet	12.6	784	3876	24.8
Barishal	13.2	630	2184	25.8
Rangpur	16.2	975	2192	24.9
Mymensingh	10.6	1249	2249	25.3

2.3 Sustainability challenges

To assess the potential risks on the sustainability of current agricultural water use scenario, long-term trends of rainfall, river stage, groundwater level and land-use changes data were evaluated. Findings from the literature were also taken into consideration to evaluate the sustainability challenges.

2.3.1 Rainfall pattern

Daily rainfall data of fifty-one years (1965–2015) recorded at eight representative weather stations of eight divisions were collected from the Bangladesh Meteorological Department (BMD, 2019). Long-term trends of total rainfall and the longest spell of consecutive dry days (an index indicating meteorological drought) were assessed in this study. A day with precipitation <1 mm was considered as a dry day, which is a precipitation based extreme index defined by the Expert Team on Climate Change Detection and Indices (Zhang et al., 2011). Drought index and total rainfall, both at a monthly and annual basis, were computed from the daily rainfall data for each division. Average monthly effective rainfall for crop production was calculated using mean monthly rainfall and mean monthly consumptive use values by following the USDA-SCS method (Dastane, 1978).

2.3.2 Groundwater availability

Weekly groundwater level data over the period 1981–2017 of 12 different observation wells located in Rajshahi division were collected from the Bangladesh Water Development Board (BWDB, 2019). Annual maximum and minimum groundwater level data were separated from the weekly values. The long-term trends of annual maximum and minimum groundwater levels above mean sea level were analyzed. The depletion and replenishment potential of groundwater resources were investigated in this northwest region only because this region heavily contributed to the food security of the country by producing surplus crops with its groundwater as revealed in the current study. Moreover, the aquifer systems in this region are considered vulnerable due to its low recharge potential and high abstraction rate (Shamsudduha et al., 2009, 2011). However, previous studies on groundwater of other regions of the country were reviewed to qualitatively assess its spatial variation.

2.3.3 Surface water availability

Daily river stage data of eight major river sections over the country were collected from BWDB (2019). River water is usually used for dry season irrigation, so low flow analysis is needed to estimate the dependable water available from a river. The annual maximum and minimum river stage values were identified from the daily river stage data and the trend analysis of the data was performed.

2.3.4 Land use changes

Current water use scenario may face tremendous challenges due to land-use changes, such as the conversion of low water-intensive crops to high-water intensive crops, cropland to an urban area, and changes in agricultural management practices. In addition to our data, a thorough literature review was conducted to investigate the pattern of such changes in the country.

2.3.5 Data analysis model

A long-term trend analysis tool called MAKESENS model was chosen for this study. The MAKESENS is a computer software model developed by Finnish Meteorological Institute of Finland using Microsoft Excel, and the macros were coded with Microsoft visual basic (Salmi et al., 2002). The model is widely used for climatic trend analysis (Ali et al., 2012; Mojid et al., 2019). Trend analysis of rainfall, drought index, annual maximum and minimum groundwater level and river stage was accomplished by using this model. The MAKSENS performs two types of statistical analysis. It detects the presence of any monotonic increasing or decreasing trend with nonparametric Mann-Kendall test and then estimates the slope of a linear trend with the nonparametric Sen's method (Gilbert, 1987). In computing the trend, MAKESENS exploits either the so-called S statistics (for $n < 10$) or the Z statistics ($n \geq 10$).

Mann-Kendall test statistics *S* (Gilbert, 1987) is calculated using the following formula:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn\,(x_j - x_k) \quad (2)$$

where x_j and x_k are the annual values in years *j* and *k*, $j > k$, respectively, and

$$sgn(x_j - x_k) = \begin{cases} 1 & if\ x_j - x_k > 0 \\ 0 & if\ x_j - x_k = 0 \\ -1 & if\ x_j - x_k < 0 \end{cases}$$

(3)

The absolute value of *S* is compared directly to the theoretical distribution of *S* derived by Mann and Kendall (Gilbert, 1987). A positive (negative) value of *S* indicates an upward (downward) trend.

For $n \geq 10$, normal approximation test (Z statistics) is used. However, if there are several tied values (i.e. equal values) in the time series, it may reduce the validity of the normal approximation. For this, the variance of *S* is computed by the following equation, which considers that ties may be present:

$$VAR(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p-1)(2t_p+5)\right] \quad (4)$$

where *q* is the number of tied groups and t_p is the number of data values in the p^{th} group.

The values of *S* and *VAR(S)* are used to compute the test statistic Z as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}}, if\ S > 0 \\ 0, \qquad\quad if\ S = 0 \\ \frac{S+1}{\sqrt{VAR\ (S)}}, if\ S < 0 \end{cases} \quad (5)$$

The presence of a statistically significant trend is evaluated using the *Z* value. A positive (negative) value of *Z* indicates an upward (downward) trend. To test for either an upward or downward monotone trend (a two-tailed test) at different α level of significance (α: 0.1, 0.05, 0.01, and 0.001), the Sen's slope can be estimated by the following equation for all data value pairs:

$$Q_i = \frac{x_j - x_k}{j-k}, \text{ where } j>k \quad (6)$$

If there are *n* values of x_j in the time series, we get as many as $N=n(n-1)/2$ slope estimate Q_i. The Sen's estimator of slope is the median of these N values of Q_i. The *N* values of Q_i are ranked from the smallest to the largest and the Sen's estimator, *Q* is calculated as follows.

$$Q = Q_{[(N+1)/2]}, \quad if\ N\ is\ odd \quad (7)$$

$$Q = \frac{1}{2}\left(Q_{[N/2]} + Q_{[(N+2)/2]}\right), \quad if\ N\ is\ even \quad (8)$$

3 Results

3.1 Current water use scenario

3.1.1 Crop wise share

In the last five years (2011–2016), the estimated average annual water use was 110871 Mm^3 to produce different crops in Bangladesh. A major portion (88.2%) of this amount was used for rice production, whereas other cereals consumed only 3.7% (Table 2). The second-largest share (4.5%) of total water was utilized for vegetable production. Remaining 3.6% of the water produced other categories of crops, namely pulse (0.9%), oilseed (1.3%), and spices and condiments (1.4%). On an average 2.85 m^3 of water was used to produce 1 kg of rice, whereas in the case of wheat, maize, and other cereals the water foot print was only 1.29 m^3 kg^{-1} (Table 2). There is enormous scope to reduce the pressure on agricultural water use by reducing the water losses in rice production.

It may need substantial technological and social interventions to have such changes in reality.

Table 2 Water used by different crop categories in Bangladesh

Crop category	Crop water use ($m^3\ kg^{-1}$)	Total water used (Mm^3)	Percent water used (%)
Rice	2.85	97719	88.2
Cereals	1.29	4125	3.7
Fruits and vegetables	0.42	5020	4.5
Oilseeds	1.51	1481	1.3
Pulses	0.56	953	0.9
Spices and condiments	0.76	1574	1.4

Irrigation water diverted annually from groundwater and surface water (blue water) in the country was 31500 Mm^3 as reported in FAO-AQUASTAT (2011). The estimated average effective precipitation (green water) was 79371 Mm^3 equivalent to 93-cm depth (35% of total precipitation) over the agricultural land to supply the total crop water need of 110871 Mm^3. This estimated effective precipitation (93 cm) in this study is close to the effective precipitation (96 cm) calculated from the mean monthly precipitation and mean monthly consumptive use values using USDA-SCS method. The ratio of green to blue water use in the country was estimated at 2.5, which is below the average nationwide ratio of green to blue water in the U.S. for soybean (4.9) and maize (3.7). The ratio in Canada is 10.2 for wheat and 105.9 for maize (Aldaya et al., 2010).

3.1.2 Crop wise interdivisional virtual water transport

A huge amount of water was virtually transported in terms of rice because of its large production area (11.24 Mha) and higher water footprint. Six among eight divisions exported water in terms of rice to other divisions (Figure 2). Rangpur had the highest amount of surplus virtual water in the national balance, which was 5733 Mm^3, followed by Rajshahi (4610 Mm^3). Although Rajshahi had slightly higher rice area (16.2%) and yield rate (3.3 $t\ ha^{-1}$) than Rangpur (16% and yield rate 3.2 $t\ ha^{-1}$), the latter division outperformed Rajshahi in exporting rice because of its lower population density (975 km^{-2}) than that of Rajshahi (1018 km^{-2}). Both divisions have suitable soil types (clay and loamy) for rice cultivation, higher rice-cropping intensity and less industrialization (Saha et al., 2013). Sylhet, Barishal, Khulna, and Mymensingh also contributed to the national virtual water balance by exporting water embodied in rice. In contrast, Dhaka and Chattogram received virtual water in this category amounting 10433 and 5980 Mm^3, respectively. Ever-increasing population density, as well as large-scale industrialization, in these two divisions, shrank the per capita rice production area. Most populated and industrialized Dhaka received 1.75 times more virtual water than did Chattogram as the population density in the latter division was only one half of Dhaka.

In terms of cereal production, three divisions contributed to the national virtual water balance. Rangpur contributed the highest amount of water (1301 Mm^3) followed by Khulna (466 Mm^3) and Rajshahi (288 Mm^3) (Figure 2) due to the higher cereal production area (37.4, 18.4 and 25.2%, respectively) and higher yield (5.17, 5.53 and 3.58 $t\ ha^{-1}$, respectively). In contrast, Chattogram received the highest amount of virtual water in this category because of the low production area (2.5%). Dhaka, Mymensingh, Sylhet, and Barishal had to import virtual water as cereal due to their less production area and the lower yield.

Rangpur contributed the highest amount (944 Mm^3) of virtual water to the national balance for fruits and vegetable production (Figure 2) because of its largest vegetable yield rate and production area (26.6%). Rajshahi was in the second position with its 755 Mm^3 of surplus virtual water. On the other hand, Chattogram received the maximum quantity of virtual water followed by Dhaka and Sylhet. It can be explained by the lower vegetable yield in Chattogram (less than the national average) and its lower amount of per capita vegetable production area. Suitable weather and soil condition in Rangpur and Rajshahi facilitated fruits and vegetable production.

For pulse production, Khulna, Rajshahi, and Barishal contributed 137, 118 and 117 Mm^3 of virtual water, respectively, to the national balance, while rest of the divisions had taken up virtual water from the national balance (Figure 2). Although Khulna had less production area than Rajshahi, higher yield rate (1.1 t ha^{-1}) of Khulna helped secured the top position. Dhaka had 22.5% of the total national production area, but its large population warranted importing virtual water from the national water-use budget.

Rajshahi, Chattogram and Dhaka, respectively, contributed 223, 65 and 13 Mm^3 of virtual water to the national balance in terms of oilseed production (Figure 2). Among them, the contribution of Rajshahi was remarkably higher because it holds 30.8% of the total national oilseeds production area. Although Dhaka (28.7%) cultivated more oilseed than Chattogram (17.5%), high population density and lower yield rate (1.0 t ha^{-1}) refrained Dhaka from outpacing Chattogram in exporting. The rest of the divisions received virtual water from others, where Mymensingh received the highest (93 Mm^3). Sylhet and Barishal ranked second and third positions receiving 88 and 62 Mm^3 virtual water, respectively.

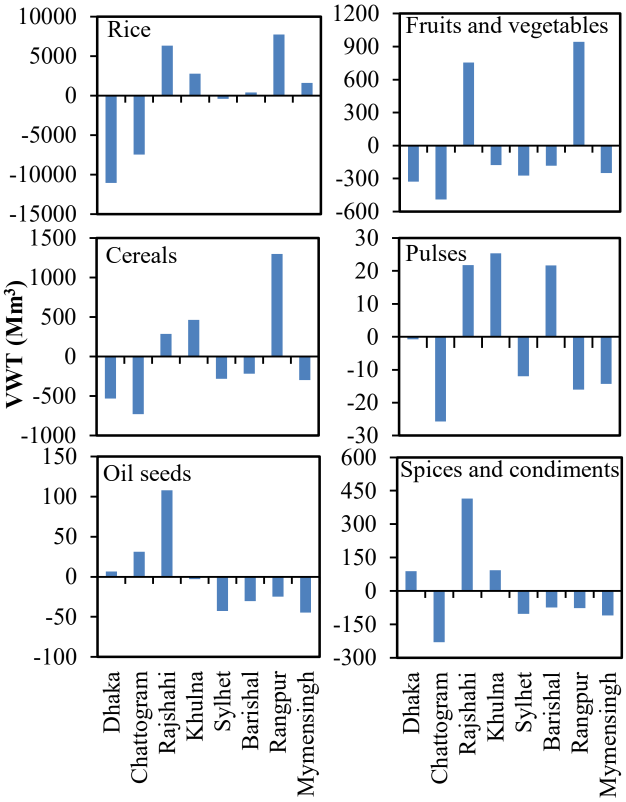

Figure 2 Interdivisional *VWT* for six crop categories in Bangladesh (Positive values indicates export and negative values import of *VWT*)

In the case of spices and condiments production, Rajshahi exported the highest amount of virtual water (415 Mm^3) to the deficit divisions (Figure 2). Although Khulna and Dhaka were in the second and third positions of exporting virtual water, the amounts were much lower (93 and 88 Mm^3, respectively) than Rajshahi. Spices and condiments cultivation area of Dhaka (26.9%) was two times more than that in Khulna (12.4%), but Dhaka contributed less virtual water due to its huge consumption and lower yield rate (6.4 t ha^{-1}) than Khulna (8.1 t ha^{-1}). Among the divisions, Chattogram was the top receiver of virtual water as spices and condiments (230 Mm^3) followed by Mymensingh (110 Mm^3).

3.1.3 Overall interdivisional virtual water transport

Rangpur added the highest amount of virtual water to the national budget, which was 7743 Mm^3 followed by Rajshahi (6343 Mm^3), Khulna (2789 Mm^3), Mymensingh (1608 Mm^3) and Barishal (393 Mm^3) (Figure 3). However, Rajshahi exported virtual water for all crop categories, whereas Rangpur had to import virtual water for oilseed, pulse, and spices and condiments. Agriculture was the main source of income in Rangpur and Rajshahi (68.5% and 60.4% of the total income, respectively). Suitable soil, weather, and availability of cheap agricultural labor triggered surplus production in these two divisions. Dhaka, Chattogram, and Sylhet were in the receiving end of the virtual water transport. Dhaka received the highest amount of virtual water (11036 Mm^3)

followed by Chattogram (7441 Mm^3) (Figure 3). This was attributed to their huge populations (34.2 and 28.4 million, respectively) and land-use changes over several decades, i.e., conversion of agricultural land to urbanized area. Besides, the geographical feature of the hilly areas of Chattogram and Sylhet was considerably different from the remaining flat part of the country (Islam et al., 2017); and as a result, cropping intensity of these areas was lower than the national average (Quddus et al., 2004).

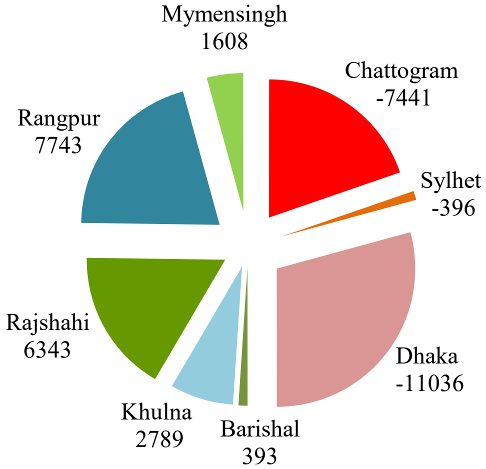

Figure 3 Divisional virtual water transport (*VWT* in Mm^3) for total national agricultural production. The left half of the circle with the blue or greenish color indicates exporting of virtual water whereas the right half with the reddish color represents importing from other divisions

3.2 Assessment of sustainability challenges

3.2.1 Rainfall pattern

Annual consecutive dry days (drought index) in different divisions showed both increasing and decreasing trends (Table 3), which were statistically significant only in Dhaka and Mymensingh, showing the probability of more frequent drought in Dhaka and less frequent in Mymensingh. However, the annual drought index does not reveal which crop will be affected more. Therefore, the monthly drought index is necessary for predicting future crop-specific water management requirement. Drought index for the dry months, e.g., December, January and February, showed no considerable trend meaning that the dry-winter season will remain mostly rainless as usual. In contrast, in the pre-monsoon months, March–May, most of the divisions experienced either increasing or decreasing magnitude of drought. The northern part, e.g., Rajshahi, Rangpur and Mymensingh, will likely be less drought-prone in April, but the southern and eastern part, e.g., Dhaka, Chattogram, Khulna, Sylhet and Barishal, had insignificant increasing trends in March and April. Drought frequency in May decreased significantly in Barishal and Mymensingh. Drought index in monsoon months, i.e. June, July, and August had no trend throughout the country except in Barishal and Rangpur (Table 3). However, the increasing drought trend for August (0.033 days yr^{-1}) in Rangpur was statistically significant. Drought condition in September remained the same in all the divisions. For October, only Mymensingh showed significant negative drought index suggesting that the number of rainless days will diminish in this month.

Table 3 Trend of monthly and yearly consecutive dry days over the period of 1965–2015

Month	Dhaka	Chattogram	Rajshahi	Khulna	Sylhet	Barishal	Rangpur	Mymensingh
Jan.	$0^{\S}$	0	0	0	0	0	0	0
Feb.	0.067	0	0	0	0	0	0	-0.04
Mar.	0.118	0.067	0	0	0.067	0	0.034	0
Apr.	0.053	0.043	-0.094	0.063	0	0.053	-0.11*	-0.074
May	0	-0.032	0	-0.032	0	-0.06^{+}	0	-0.067*
Jun.	0	0	0	0	0	0.021	0	0
Jul.	0	0	0	0	0	0	0	0
Aug.	0	0	0	0	0	0	0.033^{+}	0
Sept.	0	0	0	0	0	0	0	0
Oct.	0	0	0	0	0.043	0	0	-0.09^{+}

Nov.	0.045	0	0	0.053	0.053	0	0	0
Dec.	0	0	0	0	0	0	0	0
Yearly	0.33*	0.188	0.065	0.297	0.244	0	0.203	-0.409*

Note: §All values are in day yr^{-1}; $^{+}$ is for $p < 0.1$ and * for $p < 0.05$ level of significance; and negative sign indicates decreasing trend.

Annual total rainfall decreased insignificantly in Dhaka, Rajshahi, and Barishal but increased in others. Chattogram and Khulna, two coastal divisions, had significant increasing rates of total rainfall of 14.0 and 8.57 mm yr^{-1}, respectively (Table 4). Total rainfall in the dry months, December and January, had no trend throughout the country. February rainfall showed an insignificantly decreasing trend in Dhaka and Rajshahi whereas either increasing or no trend in other parts of the country (Table 4). Among pre-monsoon months, April rainfall in Mymensingh and May rainfall in Chattogram and Rajshahi increased significantly at 1.33, 3.58, and 1.26 mm yr^{-1}, respectively. The July rainfall significantly decreased at a rate of 2.90 mm yr^{-1} in Rajshahi, which can pose a great risk for rainfed rice production and groundwater recharge potential. On the other hand, the southwest division Khulna had an increasing rate of rainfall in July, September and October showing an agreement with the trend of its annual total rainfall.

Table 4 Trend of monthly and yearly total rainfall throughout 1965–2015

Month	Dhaka	Chattogram	Rajshahi	Khulna	Sylhet	Barishal	Rangpur	Mymensingh
Jan.	$0^{\S}$	0	0	0	0	0	0	0
Feb.	-0.03	0	-0.03	0.07	0	0	0.03	0.1
Mar.	-0.3	0	0.05	0.03	-0.60	0	-0.05	0.1
Apr.	0	0.5	0.37	-0.15	1.16	-0.13	0.82	1.33^{+}
May	-1.52	3.58*	1.26^{+}	-0.27	2.70	-0.10	-0.26	1.0
June	-0.06	2.25	-0.74	-1.70	-0.09	-0.63	1.06	3.1
July	1.11	0.63	-2.90*	3.76*	-4.78	1.18	-2.0	-0.11
Aug.	-0.80	-0.29	-1.0	-0.40	0.29	-1.32	-0.87	2.4
Sept.	-0.58	-0.24	-0.15	4.5**	-0.1	-0.12	0.28	-0.09
Oct.	-0.41	1.75	-0.19	2.2*	-0.56	-0.49	1.44	0.71
Nov.	-0.14*	0	0	0	-0.03	-0.08	0	0
Dec.	0	0	0	0	0	0	0	0
Yearly	-1.95	14.0*	-3.82	8.57*	1.14	-2.3	4.45	4.0

Note: §All values are in mm yr^{-1}; $^{+}$ is for $p < 0.1$, * for $p < 0.05$ and ** for $p < 0.01$ level of significance; and negative sign indicates decreasing trend.

3.2.2 Groundwater depletion

Annual minimum groundwater level in the northwest region usually occurred during April–May and maximum in September–October. Except well 5, all observation wells showed declining trends both in annual maximum and minimum groundwater levels (Figure 4). The results are in line with the findings of other studies in the region showing water tables declining steadily at 0.1–0.5 m yr^{-1} making the use of shallow aquifers unsustainable (Shamsudduha et al., 2009). Moreover, the declining maximum groundwater level indicates that there is not enough recharge potential to get the aquifer fully recharged (Figure 4). The unchanged gap between the maximum and minimum groundwater levels of some observation wells reveals an equal annual recharge over the years (well 3, 4 and 8; Figure 4). In other observation wells, the gap is either increasing (well 9 and 12; Figure 4) or decreasing (well 2 and 5; Figure 4) depicting increasing or decreasing annual net recharge, respectively. The findings also suggest that the problem of continual groundwater declination needs site-specific interventions.

3.2.3 Surface water availability

Annual maximum and minimum river stages of eight selected river sections were subjected to the trend analysis. The annual fluctuations of river stages ranged 3–10 m (Figure 5). The availability of surface water in 1990 fluctuated from 3710 Mm^{3} during the dry season to 111,250 Mm^{3} during the wet season (BBS, 2012–2017). Rivers in Bangladesh generally experience peak flow during July–September because of the combined effect of concentrated monsoon rainfall (80% of the annual total) and Himalayan snow melting and encounter very low flow during February–April (the rainless season) due to a large abstraction rate for irrigation throughout the watershed.

The availability of surface water in dry winter irrigation season is already very low and still decreasing in some rivers. The Ichamati (Chattogram), the Mohananda (Rajshahi), the Rupsa (Khulna) and the Old Brahmaputra (Mymensingh) showed significant decreasing trends in the annual minimum river stages (Figure 5). The annual minimum flow in other rivers did not show any trend, but flow volumes were considerably low.

4 Discussion

4.1 Crop-wise water usage and their interdivisional virtual flows

Current crop water use scenario indicates that rice holds maximum share (88.2%) of the total agriculture water use in Bangladesh followed by vegetables (4.5%), other cereals (3.7%), spices and condiments (1.4%), oil seeds (1.3%), and pulses (0.9%). The findings of the regional virtual water flows reveal that there is enormous spatial variability in crop water use. In terms of all crops grown in the country, Rajshahi, Rangpur, Khulna, Mymensingh, and Barishal divisions are in virtual water surplus zone, whereas Dhaka, Chattogram, and Sylhet are in the virtual water deficit zone. However, Dhaka division had surplus virtual water in oil seeds and spices & condiments categories. Similarly, Chattogram division had surplus water in oils seeds production. Two northern divisions (Rangpur and Rajshahi) are exporting significant portions of virtual water in almost all crop categories. It implicates that crop production in the northern Bangladesh is playing the leading role to maintain the country's food security. Different factors, such as suitable soil, water availability, weather, and availability of cheap agricultural labor, were responsible for the increased crop production in these two divisions. However, sustainability of agricultural water usage in Rajshahi and Rangpur are vulnerable according to the trends of both green and blue water availability. In contrary, huge population, conversion of agricultural land to urbanized area, and geographical features in Dhaka and Chattogram were the main factors that played the key role to keep these places insufficient in crop production.

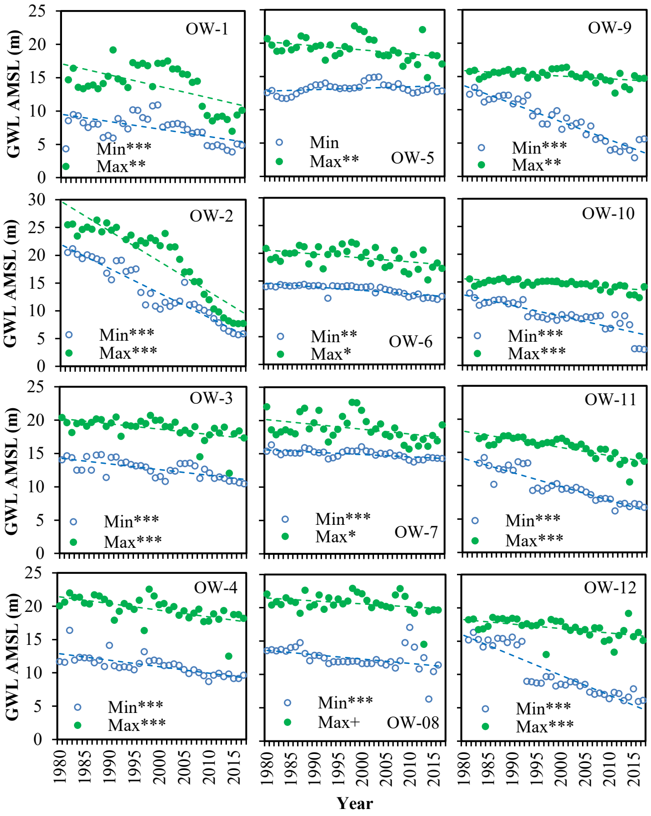

Figure 4 Changing pattern of yearly maximum (solid circle) and minimum (open circle) groundwater level above mean sea level (GWL AMSL) over the period 1981–2017 at different observation wells (OW) located in Rajshahi division

Note: Different signs with the legends, i.e. + is for < 0.1, * for < 0.05, ** for < 0.01 and *** for < 0.001 level of significance, indicate whether the trends are significant or not)

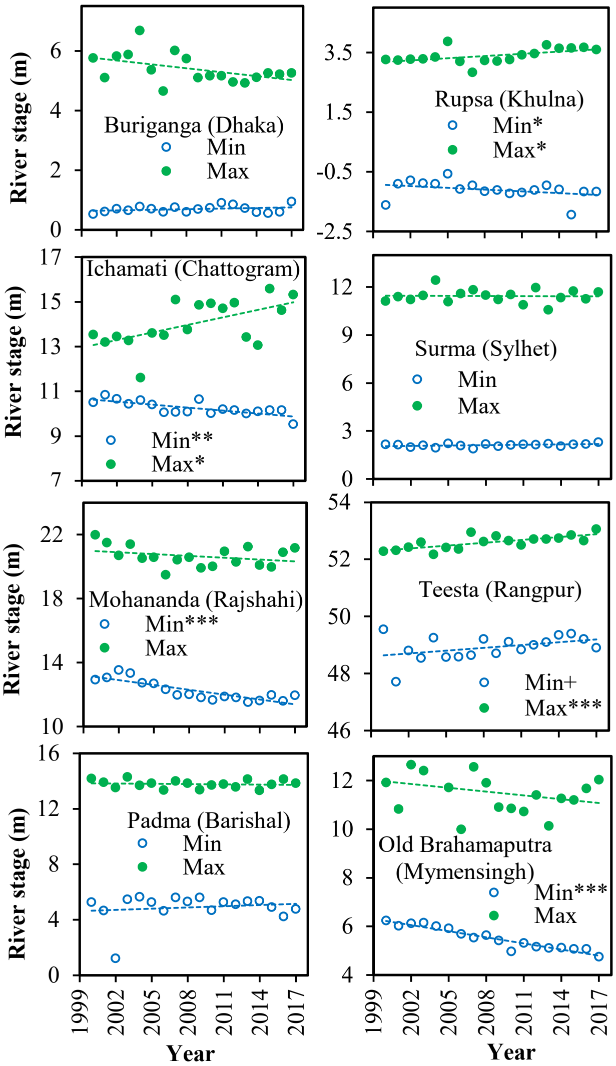

Figure 5 Trend of the annual maximum (solid circle) and minimum (Open circle) river stage above mean sea level of eight rivers representing eight divisions in Bangladesh

Note: Different signs with the legends, i.e. + is for < 0.1, * for < 0.05, ** for < 0.01 and *** for < 0.001 level of significance, indicate whether the trends are significant or not)

4.2 Sustainability challenges

4.2.1 Green water

Green water availability indicates that the rainfed crop production during June–November may increasingly face drought condition and encounters significant yield loss especially in Rangpur and Rajshahi divisions. The number of consecutive dry days in August in Rangpur division has been significantly increased for the study period. It can tremendously affect the rainfed rice production in this area because August is the peak season for rainfed rice cultivation. However, Bari et al. (2016) reported an increasing trend in total monsoon rainfall and Shahid (2011) found an increased use of effective rainfall in Rangpur. Total rainfall in July was decreasing significantly (2.90 mm yr^{-1}) in Rajshahi division. A number of studies also observed significant negative trends of monsoon and annual rainfall in the northwest region (Bari et al., 2016; Rahman et al., 2016; Islam et al., 2020; Zannat et al., 2019). Although the rainfall scenario in Rangpur is slightly better than that in Rajshahi, both divisions are generally considered as drought-prone compared with other divisions. In contrast, an increasing trend of total rainfall has been observed in Chattogram and Khulna divisions. Upal (2020) reported similar increasing annual mean rainfall in the south coastal areas of Bangladesh.

The increasing total rainfall and decreasing number of rainless days in pre-monsoon months (March–May) across the country indicates the early arrival of monsoon as also suggested by Saha et al. (2013). This result also indicates that the drought condition in the pre-monsoon months is becoming less severe. Shahid (2010) and Bari et al. (2016) also reported the increasing pre-monsoon rainfall across the country. The increasing tendency of rainfall in pre-monsoon can shorten the groundwater depletion period in April and May and thereby lessening groundwater scarcity. It will also help ease the water supply situation and reduce the irrigation demand during the second half of the dry season (January–May) rice cultivation. Increased number of rainy days in pre-monsoon also augments soil water reserve for plant water uptake, particularly for rainfed paddy and jute plant. Neither a significant reduction of total rainfall nor increasing trend of continuous rainless days was observed in the dry winter season (November–February) throughout the country. It indicates that this season will generally remain mostly rainless as usual and hence the impacts of rainfall variability on the winter crops will remain unchanged. A recent study, however, predicted that the winter season in the northwestern Bangladesh would be drier (Zannat et al., 2019).

4.2.2 Blue water

Considering the exhibited sharp declining trend in many of the observation wells, sustaining dry season irrigation projects has become a challenge in the northwest (e.g. Rajshahi) region. The declining trend of groundwater level has been attributed to the increasing trend of dry season pumping for irrigated rice cultivation in this region (Rahman et al., 2016; Shamsudduha et al., 2009). The area also experienced frequent unusual drawdown, land subsidence and tubewell failures during dry seasons (Adhikary et al., 2013). Recharge is a natural way to replenish the groundwater declination. However, the groundwater recharge potential in this northwest division is also very low because of their low permeable vadose zone (Shamsudduha et al., 2009). The Pleistocene geologic formation in these areas is markedly different from the rest of the Holocene alluvial-deposited delta area of the country (Woodman et al., 2018). The clay-rich agricultural soil restricts the irrigation return flow as well as rainfall to join saturated groundwater zone. If the declining trend in groundwater continues, the northwest region will no longer be able to export the huge virtual water to other divisions. The dry season groundwater level in some other parts of the country also continually decreased but at a slower rate than that in the northwest region (Shamsudduha et al., 2009, 2011). Many wells in Rangpur division also depicted declining trends in annual minimum water table depth (Mojid et al., 2019). Ali et al. (2012) stated that the water table depth of almost all the studied wells in the northeast region was declining slowly. The declining trend of groundwater in the Sylhet region was also attributed to the over-exploitation of groundwater resources for irrigation and domestic purpose (Zafor et al., 2017). However, a stable or slightly rising trend in groundwater level in the dry season was observed in the south coastal region (Shamsudduha et al., 2009, 2011, 2012). Groundwater in the coastal zone is largely unexploited due to salinity in shallow and lower shallow aquifers (Rahman and Bulbul, 2015). Salinity problems hampered crop production greatly in the coastal belt and these problems become acute in the dry season due to increased salinity (Huq et al., 2015; Islam and Hossain, 2015).

Both annual maximum and minimum river stages in most of the rivers studied showed declining trends indicating that the sustainability of surface water resources is at great risk. A number of studies (Mondal and Islam, 2017; Kamal et al., 2013; Billah et al., 2015) also reported similar results in case of low flow analysis. The annual maximum river stages showed significant rising trend for Chattogram, Khulna, and Rangpur divisions. The annual minimum river stages showed significant rising trend only at Rangpur division, which is good for the dry season irrigated crop production in this region, but further research is needed to quantify how much surface water can be withdrawn sustainably. The inconsistent surface water availability in Bangladesh is also associated with the trans-boundary nature of major rivers. About 95% of the flow in the river system originates outside the country (Ahmad, 2003), which introduces uncertainty in surface water management.

The minimum groundwater levels in the study area in recent years were even below the lowest river stages indicating that the groundwater contribution to surface water baseflow was negative in the dry season (Figures 4 and 5). Such a scenario throughout a watershed can cease the continuity of flow in perennial streams and dry-up water bodies leading to serious consequences on the aquatic ecosystem. Aquatic plants and animals of such environments become unable to complete their life cycles and become endangered. IUCN Bangladesh (2015) assessed that already 30 (12%) species of freshwater fishes were endangered. So, groundwater withdrawal based on the 'safe yield of an aquifer' concept only may not always be sustainable when the whole aquatic ecosystem is considered. In addition to the safe yield of groundwater, understanding the extent of groundwater-surface water interaction is needed to assess the overall effects of the water level depletion (Sophocleous, 1997; Schwartz et al., 2020). An additional complexity provided by the groundwater and surface water interaction needs to be recognized in assessing the sustainability of water use (Sophocleous, 1997). Research is needed in facilitating adaption to the worst outcome if groundwater sustainability is truly unachievable (Siegel and Hinchey, 2019; Schwartz et al., 2020).

4.2.3 General discussion and implications

Sustainability challenges of agriculture water usage in the country vary at spatial and temporal scale and are affected by different factors. Change in crop water demand induced by the climate change is another factor that would exert pressure on sustainable water use. Potential evapotranspiration and crop water requirement of dry season rice decreased in the northwest (Acharjee et al., 2017a; Islam et al., 2019) but increased in the central and southwest regions (Islam et al., 2019) due to the past climate change. In contrast, under future climate change scenarios dry season water requirement has been projected to increase in the north and northwest regions and decrease in the southwest region (Islam et al., 2018). Acharjee et al. (2017b) showed that the daily potential evapotranspiration in the northwestern Bangladesh would increase in future, but potential crop water requirement would decrease due to a shorter growing period induced by the increased temperature. Analyzing the drought events under different future climate scenarios, Kamruzzaman et al. (2019) predicted that the drought prone area will likely shift from the northwestern into the central or the southwest regions. The results indicate that uncertainties exist in the future climate change impacts in different regions of the country.

Projected climate change may have both positive and negative impacts on water availability and demands (Kirby et al., 2016), but water demand will increase and available sources of water will be scarce under the impacts of growing population and land-use change. Land use change is another important challenge for the sustainability of crop production and their water usage. Bangladesh has been experiencing rapid land-use changes during the last five decades. The yearly average loss of agriculture land was 23,391 ha (0.26%) during 1976–2000 and 56,537 ha (0.45%) during 2000–2010 (Hasan et al., 2013). In contrast, lands gained in a rural settlement, urban and industry, and aquaculture are 30,809, 4,012 and 3,216 ha yr^{-1}, respectively, during 2000–2010. Expansion of built-up areas by the transformation of agricultural lands and water areas in Dhaka, Chattogram and Rajshahi was faster than that in other divisions (Dewan and Yamaguchi, 2009; Hassan and Nazem, 2016; Hasan et al., 2013). Rajshahi, a major food-producing division, lost 15,945 ha cropland during 2000–2010 (Hasan et al., 2013; Mahbub, 2003). Hasan et al. (2017) projected a further decline in cultivated land under both environmental protection and economic growth scenarios. Loss of agricultural lands and water areas will put multifaceted pressures, such as more water demanding crop cultivation in limited agricultural land, decreased availability of water resources, and increased competition for water resources.

Development of effective water management strategies is an urgent need to reduce water loss and improve water productivity. Reducing water loss from rice fields is the first priority because irrigated high yielding rice constitutes about 60% of the country's total rice production. Technological interventions to improve the rice water productivity (Rahman and Bulbul, 2015; Alauddin et al., 2020) and/or switching from dry-season rice to other grains have been proposed in reducing agricultural water requirement and increasing higher return (Hasan et al., 2019). However, adoption of these changes needs substantial research to find out their space- and time-varying suitability. In order to improve overall crop water productivity and manage the blue water scarcity, increasing attention on rainfed agriculture is required (Saed et al., 2018; Hoekstra, 2019; Mainuddin et al., 2020). For example, Khulna, the 3rd highest virtual water contributing division, has still great potential to expand rainfed rice production based on the green water availability. Use of surface water to convert fallow or low intensity land to irrigated wheat and maize has also been reported as a possible option to augment crop production in Khulna division (Krupnik et al., 2017). Rainwater harvesting can significantly improve the production capacity of coastal saline affected soils (Bouma et al., 2012). One of the main challenges of rainfed agriculture is the unavailability of proper rainwater harvesting structures (Islam et al., 2017). Implementation of proper water harvesting and recycling system and incorporation of water conservation techniques can develop a climate resilient agriculture (Abdullah and Rahman, 2015). Strengthened agricultural research and extension and changing cropping pattern and spatial distribution would help show the path to sustainable agricultural water management. The findings will be useful references for developing sustainable agricultural water management strategies for the country and other regions with similar problems.

5 Conclusion

Two northwestern divisions, Rangpur and Rajshahi, are exporting large volumes of virtual water (7743 and 6343 Mm^3 yr^{-1}, respectively) in terms of agricultural produce to other divisions of which Dhaka and Chattogram are the major receivers (11036 and 7441 Mm^3 yr^{-1}, respectively). However, changes in rainfall pattern are statistically significant in these two northern divisions. Total rainfall in July is significantly decreasing (2.90 mm yr^{-1}) in Rajshahi and the continuous rainless days in August are getting prolonged in Rangpur, which is a threat for rainfed agriculture in these divisions. Changes in rainfall patterns in rainfed cropping seasons are not evident elsewhere in the country. In the main irrigation season, both the river stage and groundwater level are declining gradually over the years in most of the studied locations. As there was no considerable reduction of the total rainfall in the dry season (November–April), the decreased water availability observed in this period could be attributed to the overutilization of both surface and groundwater throughout the catchment. The minimum groundwater level in the study area in recent years was even below the lowest river stage indicating that the groundwater contribution to surface water baseflow was negative in the dry season, which can severely affect aquatic ecosystem. Water availability in the south coastal region in the dry season is stable, but water in this region is largely unexploited due to salinity in surface water and shallow to lower shallow aquifers. Shifting from rainfed to irrigated high-yielding cropping system has a multifaceted effect on water resources. Further research is needed to explore ways to produce more food using green water, which will lessen the sustainability challenges.

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References

Abdullah, H. M., and M. M. Rahman. 2015. Initiating rainwater harvest technology for climate change induced drought resilient agriculture: scopes and challenges in Bangladesh. *Journal of Agriculture and Environment for International Development*, 109(2): 189-208.

Acharjee, T. K., G. van Halsema, F. Ludwig, and P. Hellegers. 2017a. Declining trends of water requirements of dry season *Boro* rice in the north-west Bangladesh. *Agricultural Water Management*, 180: 148-159.

Acharjee, T. K., F. Ludwig, G. van Halsema, P. Hellegers, and I. Supit. 2017b. Future changes in water requirements of *Boro* rice in the face of climate change in North-West Bangladesh. *Agricultural Water Management*, 194: 172-183.

Addams, L., G. Boccaletti, M. Kerlin, and M. Stuchtey. 2009. Charting our water future: Economic frameworks to inform decision-making. *Munich: 2030 Water Resource Group*, McKinsey Company.

Adhikary, S. K., S. K. Das, G. C. Saha, and T. Chaki. 2013. Groundwater drought assessment for Barind irrigation project in northwestern Bangladesh. In *20th International Congress on Modelling and Simulation*, 2917-2923.

Adelaide, Australia, 1-6 December.

Ahmad, Q. K. 2003. Regional cooperation in flood management in the Ganges-Brahmaputra-Meghna region: Bangladesh perspectives. *Natural Hazards*, 28(1): 191-198.

Ahmed, U. 2018. Virtual water transport and water-related climate vulnerability in eight divisions of Bangladesh. M.S. thesis, Department of Irrigation and Water Management, Bangladesh Agricultural University.

Alauddin, M., and C. Tisdell. 1991. *The Green Revolution and Economic Development: The Process and its Impact in Bangladesh*. London: Palgrave Macmillan.

Alauddin, M., M. A. R. Sarker, Z. Islam, and C. Tisdell. 2020. Adoption of alternate wetting and drying (AWD) irrigation as a water-saving technology in Bangladesh: Economic and environmental considerations. *Land Use Policy*, 91: 104430.

Alcamo, J., P. Döll, T. Henrichs, F. Kaspar, B. Lehner, T. Rösch, and S. Siebert. 2003. Global estimates of water withdrawals and availability under current and future "business-as usual" conditions. *Hydrological Sciences Journal,* 48(3): 339-348.

Aldaya, M. M., J. A. Allan, and A. Y. Hoekstra. 2010. Strategic importance of green water in international crop trade. *Ecological Economics*, 69(4): 887-894.

Ali, M. H., I. Abustan, M. A. Rahman, and A. A. M. Haque. 2012. Sustainability of groundwater resources in the northeastern region of Bangladesh. *Water Resource Management*, 26(3): 623-641.

Allen, R. G., L. S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration — guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. Rome, Italy: Food and Agriculture Organization of the United Nations.

Arfanuzzaman, M., and A. A. Rahman. 2017. Sustainable water demand management in the face of rapid urbanization and groundwater depletion for social-ecological resilience building. *Global Ecology and Conservation*, 10: 9-22.

Bari, S. H., M. T. U. Rahman, M. A. Hoque, and M. M. Hussain. 2016. Analysis of seasonal and annual rainfall trends in the northern region of Bangladesh. *Atmospheric Research*, 176-177: 148-158.

BBS. 2012–2017. Yearbook of Agricultural Statistics of Bangladesh 2012–2017. Dhaka: Bangladesh Bureau of Statistics.

Billah, M., M. M. Rahman, A. K. M. S. Islam, G. M. T. Islam, S. K. Bala, S. Paul, and M. A. Hasan. 2015. Impact of climate change on river flows in the southwest region of Bangladesh. In *5th International Conference on Water & Flood Management* (ICWFM-2015), 581-590. Dhaka, Bangladesh, 6-8 March.

BMD. 2019. Bangladesh Meteorological Department. Available at: www.bmd.gov.bd. Accessed 4 August 2020.

Bouma, J., W. Critchley, and J. Barron. 2012. A review of the recent literature on water harvesting in Sub-Saharan Africa. In *Water Harvesting in Sub-Saharan Africa*, eds. W. Critchley, and J. Gowing, ch. 3, 32-51. London, New York: Routledge.

BWDB. 2019. Bangladesh Water Development Board. Available at: https://www.bwdb.gov.bd. Accessed 4 August 2020.

Carr, J. A., P. D'Odorico, F. Laio, and L. Ridolfi. 2013. Recent history and geography of virtual water trade. *PLoS ONE*, 8(2): e55825.

Dastane, N. G. 1978. Effective rainfall in irrigated agriculture. Available at: http://www.fao.org/3/X5560E/x5560e03.htm. Accessed 4 August 2020.

Dewan, A. M., and Y. Yamaguchi. 2009. Land use and land cover change in Greater Dhaka, Bangladesh: Using remote sensing to promote sustainable urbanization. *Applied Geography*, 29(3): 390-401.

El-Sadek, A. 2010. Virtual water trade as a solution for water scarcity in Egypt. *Water Resources Management*, 24(11): 2437-2448.

Ercin, A. E., and A. Y. Hoekstra. 2016. European water footprint scenarios for 2050. *Water*, 8(6): 226.

FAO-AQUASTAT. 2011. Irrigation in Southern and Eastern Asia in figures – AQUASTAT Survey – 2011. Available at: http://www.fao.org/nr/water/aquastat/countries_regions/BGD/index.stm. Accessed 4 August 2020.

Gilbert, R. O. 1987. *Statistical Methods for Environmental Pollution Monitoring*. New York: Van Nostrand Reinhold.

Hanjra, M. A., and M. E. Qureshi. 2010. Global water crisis and future food security in an era of climate change. *Food Policy*, 35(5): 365-377.

Hasan, M. M., M. Alauddin, M. A. R. Sarker, M. Jakaria, and M. Alamgir. 2019. Climate sensitivity of wheat yield in Bangladesh: implications for the United Nations sustainable development goals 2 and 6. *Land Use Policy*, 87: 104023.

Hasan, M. N., M. S. Hossain, M. A. Bari, and M. R. Islam. 2013. Agricultural land availability in Bangladesh., Dhaka, Bangladesh: SRDI.

Hasan, S. S., X. Deng, Z. Li, and D. Chen. 2017. Projections of future land use in Bangladesh under the background of baseline, ecological protection and economic development. *Sustainability*, 9(4): 505.

Hassan, M. M., and M. N. I. Nazem. 2016. Examination of land use/land cover changes, urban growth dynamics, and environmental sustainability in Chittagong city. Bangladesh. *Environment, Development and Sustainability*, 18(3): 697-716.

Hoekstra, A. Y. 2019. Green-blue water accounting in a soil water balance. *Advances in Water Resources*, 129: 112-117.

Hoekstra, A. Y., and P. Q. Hung. 2005. Globalization of water resources: international virtual water flows in relation to crop trade. *Global Environmental Changes*, 15(1): 45-56.

Huq, N., J. Hugé, E. Boon, and A. K. Gain. 2015. Climate change impacts in agricultural communities in rural areas of coastal Bangladesh: a tale of many stories. *Sustainability*, 7(7): 8437-8460.

Islam, A. R. M. T., M. S. Rahman, R. Khatun, and Z. Hu. 2020. Spatiotemporal trends in the frequency of daily rainfall in Bangladesh during 1975–2017. *Theoretical and Applied Climatology*, 141: 869-887.

Islam, A. R. M. T., S. Shen, and S. Yang. 2018. Predicting design water requirement of winter paddy under climate change condition using frequency analysis in Bangladesh. *Agricultural Water Management*, 195(C): 58-70.

Islam, A. R. M. T., S. Shen, S. Yang, Z, Hu, and R. Chu. 2019. Assessing recent impacts of climate change on design water requirement of Boro rice season in Bangladesh. *Theoretical and Applied Climatology*, 138: 97-113.

Islam, M. M., and M. E. Hossain. 2015. Crop Diversification in Bangladesh: Constraints and Potentials. Available at: https://bea-bd.org/site/images/pdf/057.pdf. Accessed 4 August 2020.

Islam, M. T., M. M. Ullah, M. G. M. Amin, and S. Hossain. 2017. Rainwater harvesting potential for farming system development in a hilly watershed of Bangladesh. *Applied Water Science*, 7(5): 2523-2532.

Ismail, H. 2016. Climate Change, Food and Water Security in Bangladesh. Strategic Analysis Paper, Future Directions International. Available at: https://www.futuredirections.org.au /publication/climate-change-food-water-security-Bangladesh/. Accessed 10 December 2020.

IUCN Bangladesh. 2015. Red List of Bangladesh: A brief on assessment result 2015. Available at: https://www.iucn.org/content/red-list-bangladesh-volume-5-freshwater-fishes. Accessed 4 August 2020.

Kamal, R., M. A. Matin, and S. Nasreen. 2013. Response of river flow regime to various climate change scenarios in Ganges-Brahmaputra-Meghna basin. *Journal of Water Resources and Ocean Sciences*, 2(2): 15-24.

Kamruzzaman, M., M. Jang, J. Cho, and S. Hwang. 2019. Future changes in precipitation and drought characteristics over Bangladesh under CMIP5 climatological projections. *Water*, 11(11): 2219.

Kirby, J. M., M. Mainuddin, F. Mpelasoka, M. D. Ahmad, W. Palash, M. E. Quadir, S. M. Shah-Newaz, and M. M. Hossain. 2016. The impact of climate change on regional water balances in Bangladesh. *Climatic Change*, 135(3-4): 481-491.

Krupnik, T. J., U. Schulthess, Z. U. Ahmed, and A. J. McDonald. 2017. Sustainable crop intensification through surface water irrigation in Bangladesh? A geospatial assessment of landscape-scale production potential. *Land Use Policy*, 60: 206-222.

Ludwig, F., P. Kabat, H. van Schaik, and M. van der Valk. 2009. *Climate Change Adaption in the Water Sector*. London, United States: Earthscan Publications.

Mahbub, A. 2003. Agricultural land loss and food security: An assessment. Manila, The Philippines: IRRI.

Mainuddin, M., M. Maniruzzaman, M. M. Alam, M. A. Mojid, E. J. Schmidt, M. T. Islam, and M. Scobie. 2020. Water usage and productivity of Boro rice at the field level and their impactson the sustainable groundwater irrigation in the North-West Bangladesh. *Agricultural Water Management*, 240: 106294.

Mancosu, N., R. L. Snyder, G. Kyriakakis, and D. Spano. 2015. Water scarcity and future challenges for food production. *Water*, 7(3): 975–992.

Matchaya, G., C. Nhemachena, and S. Nhlengethwa. 2019. Virtual water trade and water endowments in southern Africa. *International Journal of Food and Agricultural Economics*, 7(1): 31-45.

Mojid, M. A., M. F. Parvez, M. Mainuddin, and G. Hodgson. 2019. Water table trend—a sustainability status of groundwater development in north-west Bangladesh. *Water*, 11(6): 1182.

Mondal, M. S. H., and M. S. Islam. 2017. Chronological trends in maximum and minimum water flow of the Teesta River, Bangladesh, and its implications. Jamba: *Journal of Disaster Risk Studies*, 9(1): a373.

Mullick, M. R. A., and N. Das. 2020. Estimation of the spatial and temporal water footprint of rice production in Bangladesh. *Sustainable Production and Consumption*, 25: 511-524.

Oki, T., and S. Kanae. 2004. Virtual water trade and world water resources. *Water Science and Technology*, 49(7): 203-209.

Quddus, M. A., K. Sen, and M. Salimullah. 2004. Performance of crop production in Bangladesh: growth and regional disparities. *Bangladesh Journal of Agricultural Economics*, 27(2): 57-74.

Rahman, A. T. M. S., M. Kamruzzaman, C. S. Jahan, Q. H. Mazumder, and A. Hossain. 2016. Evaluation of spatio-temporal dynamics of water table in NW Bangladesh: an integrated approach of GIS and Statistics. *Sustainable Water Resource Management*, 2(3): 297-312.

Rahman, M. R., and S. H. Bulbul. 2015. Adoption of water saving irrigation techniques for sustainable rice production in Bangladesh. *Environmental and Ecological Research*, 3(1): 1-8.

Ray, C., D. McInnes, and M. Sanderson. 2018. Virtual water: its implications on agriculture and trade. *Water International*, 43(6): 717-730.

Saed, B., A. Afshar, M. R. Jalali, M. Ghoreishi, and P. A. Mohammadabadi. 2018. A water footprint based hydro-economic model for minimizing the blue water to green water ratio in the Zarrinehrud River-Basin in Iran. *AgriEngineering*, 1(1): 58-74.

Saha, S. K., M. S. Ali, and S. Shahid. 2013. Vulnerability to climate induced drought - scenario and impacts. Available at: https://www.bd.undp.org/content/bangladesh/en/home/library/crisis_prevention_and_recovery/vulnerability-to-climate-induced-drought--scenario---impacts.html. Accessed 4 August 2020.

Salmi, T., A. Määttä, P. Antilla, T. Ruoho-Airola, and T. Amnell. 2002. Detecting trends of annual values of atmospheric pollutants by the Mann-Kendall test and Sen's slope estimates–*the Excel template application MAKESENS*. Helsinki, Finland: Finnish Meteorological Institute.

Schwartz, F. W., G. Liu, and Z. Yu. 2020. HESS Opinions: The myth of groundwater sustainability in Asia. *Hydrology and Earth System Sciences*, 24(1): 489-500.

Shahid, S. 2010. Recent trends in the climate of Bangladesh. *Climate Research*, 42(3): 185-193.

Shahid, S. 2011. Impact of climate change on irrigation water demand of dry season *Boro* rice in northwest Bangladesh. *Climate Change*, 105(3): 433-453.

Shamsudduha, M. 2018. Impacts of human development and climate change on groundwater resources in Bangladesh. In *Groundwater of South Asia*, ed. A. Mukherjee, ch. 31, 523-544. Singapore: Springer.

Shamsudduha, M., R. E. Chandler, R. G. Taylor, and K. M. Ahmed. 2009. Recent trends in groundwater tables in a highly seasonal hydrological system: The Ganges-Brahmaputra-Meghna Delta. *Hydrology and Earth System Sciences*, 13(12): 2373-2385.

Shamsudduha, M., R. G. Taylor, and L. Longuevergne. 2012. Monitoring groundwater storage changes in the highly seasonal humid tropics: validation of GRACE measurements in the Bengal Basin. *Water Resource Research*, 48(2): W02508.

Shamsudduha, M., R. G. Taylor, K. M. Ahmed, and A. Zahid. 2011. The impact of intensive groundwater abstraction on recharge to a shallow regional aquifer system: evidence from Bangladesh. *Hydrogeology Journal*, 19(4): 901-916.

Siegel, D. I., and E. J. Hinchey. 2019. Big data and the curse of scale. *Groundwater,* 57(4): 505.

Sophocleous, M. 1997. Managing water-resources systems: Why "safe yield" is not sustainable. *Ground Water*, 35(4): 561.

Upal, M. N. H. 2020. Analysis of Spatio-Temporal Rainfall Variability over Bangladesh. *Journal of Climate Change*, 6(1): 7-14.

Valipour M. 2017. Global experience on irrigation management under different scenarios. *Journal of Water and Land Development*, 32: 95-102.

Valipour, M. 2016. How do different factors impact agricultural water management? *Open Agriculture*, 1(1): 89-111.

Valipour, M., S. M. Bateni, M. A. G. Sefidkouhi, M. Raeini-Sarjaz, and V. P. Singh. 2020. Complexity of forces driving trend of reference evapotranspiration and signals of climate change. *Atmosphere*, 11(10): 1081.

Wichelns, D. 2010. Virtual water: A helpful perspective, but not a sufficient policy criterion. *Water Resources Management*, 24(10): 2203-2219.

Woodman, N. D., W. G. Burgess, K. M. Ahmed, and A. Zahid. 2018. A partially-coupled hydro-mechanical analysis of the Bengal Aquifer System under hydrological loading. *Hydrology and Earth System Sciences*, 23(5): 2461-2479.

Yillia, P. T. 2016. Water-Energy-Food nexus: framing the opportunities, challenges and synergies for implementing the SDGs. *Österreichische Wasser-und Abfallwirtschaft*, 68(3-4): 86-89.

Zafor, M. A., M. J. B. Alam, M. A. Rahman, and M. N. Amin. 2017. The analysis of groundwater table variations in Sylhet region, Bangladesh. *Environmental Engineering Research*, 22(4): 369-376.

Zakar, M. Z., R. Zakar, and F. Fischer. 2012. Climate change-induced water scarcity: a threat to human health. *South Asian Studies*, 27(2): 293-312.

Zannat, F., A. R. M. T. Islam, and M. A. Rahman. 2019. Spatiotemporal variability of rainfall linked to groundwater level under changing climate in northwestern region, Bangladesh. *European Journal of Geosciences*, 1(1): 35-56.

Zeitoun, M., J. A. T. Allan, and Y. Mohieldeen. 2010. Virtual water 'flows' of the Nile Basin, 1998–2004: A first approximation and implications for water security. *Global Environmental Change*, 20(2): 229-242.

Zhang, X., L. Alexander, G. C. Herger, P. Jones, A. K. Tank, T. C. Peterson, B. Trewin, and F. W. Zwiers. 2011. Indices for monitoring changes in extremes based on daily temperature and precipitation data. *WIREs Climate Change*, 2(6): 851-870.