Changes in water requirements of dry season rice under climate change

Quantifying recent & future changes and developing adaptation strategies in Northwest Bangladesh

Tapos Kumar Acharjee

Changes in water requirements of dry season rice under climate change ■ Tapos Kumar Acharjee

Propositions

1. Climate change does not always cause higher agricultural water demand.
   (this thesis)
2. Stakeholders prefer higher scale *out-system dependent* adaptation strategies that are aimed at minimising the impacts of climate change on agricultural systems, despite that *in-system dependent* strategies offer ample opportunities to adapt to climate change.
   (this thesis)
3. Step-by-step assessment of changes in all factorial components of a system better reveal the consequences of changes rather than a straightforward assessment of the ultimate impact.
4. Modelling and scenario analysis of future changes exhibit new insights into existing science.
5. Self-motivation is more important than time management for successful completion of a study.
6. Universities should arrange a compulsory health care course for PhD students who work with modelling or big datasets to aware them to protect their eyes and back.

Propositions belonging to the thesis, entitled

"Changes in water requirements of dry season rice under climate change: Quantifying recent & future changes and developing adaptation strategies in Northwest Bangladesh"

Tapos Kumar Acharjee
Wageningen, 11 December 2018

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Abstract

This study focuses on quantifying the changes in water requirements of dry season *Boro* rice under recent and future climate changes. It also assessed the effectiveness of shifting trans-/planting date of *Boro* rice to adapt to climate change and prioritized adaptation options in Northwest Bangladesh. The FAO developed CropWat 8.0 model was used to quantify changes in water requirements for recent decades (1980–2013) and future moderate (RCP 4.5) and rapid (RCP 8.5) climate scenarios in 2050s and 2080s time periods. The growing degree-days method was used to quantify changes in growth duration of rice as affected by climate change. Future water requirements of *Boro* rice for early, normal and late planting and possibilities of high-temperature stress during critical periods were assessed. Furthermore, the study identified and ranked adaptation options based on local experts'/stakeholders' opinion for better agricultural water management to cope with climate change.

Both the analysis of recent trends and of future changes in water requirements yielded robust signals of a possible decrease in water requirements of dry season *Boro* rice. Declining recent trends of water requirements were found with reduction of reference crop evapotranspiration. In future, the estimated net irrigation requirement of *Boro* rice showed a reduction, despite some increase in daily reference crop evapotranspiration due to shortened *Boro* growing season. The net irrigation requirement of *Boro* rice has decreased by 11% during the last three decades at an average rate of 4.4 mm year^{-1}, despite a slight decrease in effective rainfall, mainly because of high rate of decrease of potential crop evapotranspiration (5.9 mm/year). The net irrigation requirement of *Boro* rice will decrease by 1.6% in 2050s and 7.4% in 2080s for RCP 8.5 scenarios averaged over all models and districts. This study also found that late planting can substantially reduce irrigation demand, but the option is very limited due to both day- and night-time heat stress. Early planting accounts for high water demand but ensures suitable temperatures during the critical growth stages of the crop. Transboundary co-operation, integrated water resources management and adjustment of irrigation methods are the top three adaptation measures, as ranked by stakeholders. Integrated, co-operative and advanced technological strategies are preferred by local stakeholders over simple in-field measures to cope with climate change.

This study has improved existing knowledge on changes in water requirements of dry season rice due to changes in climatic parameters. These insights are useful to understand the possible changes in regional agricultural water demand, especially for rice dominated areas. Furthermore, the study has broaden our knowledge about the effectiveness of changing trans-/planting date of dry season rice to adjust to climate change and the local stakeholders' preferences of adaptation measures. This helps to make informed decisions for future adaptation planning to cope with climate change.

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CHAPTER 1

Introduction

1.1. Background and problem outline

Impacts of climate change on global agricultural water demand

Climate is an important determining factor of crop water requirements. Therefore, climate change could have many implications for agricultural water demand. Since agriculture is the largest water using sector in the world (Raes et al., 2009), changes in agricultural water use due to climate change are likely to have large impacts on global water demand. The patterns of water demand and supply for agriculture are expected to vary due to the impacts of climate change on the global hydrological cycle (Turral et al., 2011). Higher temperatures and increased variability of rainfall will lead to changes in irrigation water demand. Most climate change impact studies related to agriculture focus on impacts on crop productivity (Schmidhuber and Tubiello, 2007; Tubiello et al., 2007). However, changes in climatic conditions not only affect productivity but also crop water demands and irrigation requirements.

Climate change will result in changes in run-off, precipitation, evapotranspiration, and in the intensity and frequency of extreme events like floods, cyclones and droughts by accelerating the hydrological cycle (Watson et al., 1996). Assessment of changes in evapotranspiration is particularly important to understand the changes in crop water demand. Evapotranspiration is an important part of water balance and a key variable in the hydrologic cycle process (Xu et al., 2006). Reference crop evapotranspiration (ET_O) is a representation of the environmental demand for evapotranspiration at a reference surface and soil conditions with abundant available water (Allen et al., 1998). ET_O has been extensively used in the research of hydrologic water balance, irrigation scheduling and water resources planning (Liu et al., 2016; Wang et al., 2017). Improved understanding of the impacts of climate change on hydrological processes can also be obtained by analysing temporal variation in reference crop evapotranspiration (Tang et al., 2011). ET_O is basically dependent on four meteorological variables, i.e. air temperature, solar radiation, wind speed and relative humidity (Allen et al., 1998). Therefore, ET_O is a conceptual entity, a parameter that cannot be measured directly (Thornthwaite, 1948). ET_O has been widely used to evaluate the impacts of climate change on irrigated agriculture (Elgaali et al., 2007; Espadafor et al., 2011; Izaurralde et al., 2003; Thomas, 2008). Irrigation water requirements do not only depend on daily ET_O, but also depends on crop characteristics, rainfall availability and management practices. The crop characteristics (due to crop's phenological response to climate) and rainfall availability are also influenced by climate change. Temperature changes are expected to affect the length of the growing season of crops (Alward et al., 1999). Changing precipitation is altering hydrological systems in many regions of the world (Field et al., 2014), and thus, affecting seasonal rainfall availability. Therefore, the evaluation of the impacts of climate change on irrigated agriculture that are only based on the changes in daily ET_O could be misleading. A detail study that takes into account the changes in ET_O and rainfall pattern due to climate change and the crop's phenological response to increased temperature may better evaluate the impacts of climate change on agricultural water demand.

The impacts of climate change on world aggregate net irrigation requirements are significant (Fischer et al., 2005). Two-thirds of the global irrigated and half of the total cultivable area will possibly suffer from increased water requirements (Döll, 2002). Fischer et al. (2007) projected an increase of irrigation water requirements over 50% in developing countries, and by about 16% in developed regions by 2080 considering climate and irrigated land area changes. However, the changes in irrigation requirement may substantially vary from one region to another and from one cropping-season to another. Döll (2002) investigated the global impacts of climate change and variability on irrigation demand and concluded that changes in precipitation, combined with increases in evaporative demands, increase the need for irrigation worldwide, with the grunt of the impacts occurring on the Indian subcontinent. Rejani et al. (2016) found that the irrigation requirements of *rabi* (winter) crops, cultivated during November–May will considerably increase, whereas the changes in irrigation requirements of *kharif* (summer) crops, cultivated during June–October will be negligible in India. Several studies reported an increasing trend of future irrigation water demand with substantial variations depending on the geographic location, the degree of global warming and associated changes in regional precipitation (Wada et al., 2013; Wang et al., 2016). Therefore, the regional scale assessment of changes in water requirement is very important. Using a combination of crop and geographic information systems, Diaz et al. (2007) predicted an increase in increase in aridity and irrigation need in Spain. Climatic change is expected to increase seasonal evapotranspiration and irrigation water requirement during April–May and decrease them during July–August in Southeastern Colorado (Elgaali et al., 2007). Tukimat et al. (2017) predicted a reduction of irrigation water demand at a rate of 0.9% per decade in Malaysia.

Impacts of climate change on rice

Changes in the climatic conditions are not evenly distributed over the globe. Therefore, the spatial and seasonal variations in climatic conditions may affect crop development, production and water requirement differently, depending on the region, the season and the crop type (Supit et al., 2010). Most studies reported a decline in rice yield due to climate change. The significance of the impact of climate change for rice in Asia is reported to be much larger than that for wheat in Europe (Masutomi et al., 2009).

The fertility of spikelet in rice plant is very sensitive to temperatures. High temperature stress reduces grain yield of rice by reducing the percentage of ripened grains as a result of spikelet sterility (Oh-e et al., 2007). However, the temperature tolerance capacity of rice may considerably vary depending on cultivars (Satake and Yoshida, 1978). The duration of the rice growing season and the time of flowering are also influenced by temperature. Higher temperatures usually result into a shorter rice growing season and to earlier flowering, which consequently affect the crop production and seasonal water use (Nonhebel, 1996; Wheeler et al., 2000; Yoshida, 1981). A shortening of growing season and an early flowering of various crops due to accelerated crop development as a result of higher temperatures has been reported for several regions (Estrella et al., 2007; Guereña et al., 2001; Supit et al., 2010; Williams and Abberton, 2004). Increased temperature accelerates phenological development of plant and may decrease the length of the grain filling period and thus, reduce yield (Amthor, 2000; Bachelet and Gay, 1993; Vaghefi et al., 2013). The shortening of growth duration of a crop not only affects yield, but also the water requirements of crop. Therefore, the consideration of changes in growth duration of rice due to climate change is also very important to quantify water requirement of rice.

The crop water requirements mainly depend on the climate, the crop type and the growth stage. The crop water requirements gradually change from one stage of development to another. The growth stages of rice are distinguished as initial, development, mid-season and late-season. The crop co-efficient values (Kc) changes from one stage to another. The Kc values are lowest during the entire initial stage. During the development stage the Kc values gradually increases. The maximum crop coefficient is reached at the end of the crop development stage, which is the beginning of the mid-season and Kc values are highest for the entire mid-season stage. After mid-season, the Kc values gradually declines throughout the late-season stage. Therefore, a careful estimation of changes in different growth stage days of rice is very important for precise quantification of changes in crop water demand.

Elevated atmospheric CO_2 concentrations increase resource use efficiencies for radiation, water and nitrogen and thus increase productivity of plant (Olesen and Bindi, 2002). Elevated CO_2 concentration would increase rice yield due to an increase in net assimilation rate and photosynthesis (Vaghefi et al., 2013). Saseendran et al. (2000) reported that the increase in rice yield due to fertilisation effect of elevated CO_2 and increased rainfall may nearly makes up for the negative impact of temperature rise. However, most studies indicate that the increase in yield of rice due to elevated CO_2 would be offset by the effect of the expected temperature rise (Baker et al., 1995; Horie et al., 1996; Ziska et al., 1997).

Impacts of climate change on rice productivity have been simulated extensively for Asia (Aggarwal and Mall, 2002; Li et al., 2015; Matthews et al., 1997; Matthews et al., 1995; Tao et al., 2008). Karim et al. (2012) assessed the impacts of climate change on dry season rice productivity in Bangladesh and predicted a 33% reduction of average yields combining the periods 2046–2065 and 2081–2100. Basak et al. (2009) predicted significant reduction (over 20–50%) in yield of *Boro* rice due to climate change. Faisal and Parveen (2004) reported that overall impact of climate change on food grain production in Bangladesh would probably be small in 2030 due to strong positive impact of CO_2 fertilization, but would be noticeable in 2050. Most of the studies during recent decades focused on impacts of climate change on rice productivity, while impacts of climate change on irrigation requirement is similarly important, or even more important in water-stressed regions. Some studies have also addressed adaptation strategies to cope with the impacts of climate change on rice productivity. The decrease of rice yield can be offset by using salinity-tolerant, drought-tolerant and temperature-tolerant rice varieties (Jagadish et al., 2012; Mackill et al., 2010), and altering the transplanting dates (Shrestha et al., 2016). International Rice Research Institute has developed rice with improved tolerance to drought, submergence, cold, salinity, and sodicity in recent years (IRRI, 2018).

Climate change and the Northwest Bangladesh

Climate change is potentially a major threat to the sustainable growth and development of Bangladesh. The country has already been recognized as one of the worst victims of climate change (IPCC, 2007). Different parts of the country are susceptible to different risks, e.g. salinity, salt-water intrusion and cyclone risks in Southern coastal zone, flood risks in central and Northeast zone, and drought and heat-stress risks in Northwest zone.

Temperatures will increase faster than the average global rate of warming due to climate change in Bangladesh. Winter temperature is expected to increase faster than summer temperature in Bangladesh (Rajib et al., 2011). Temperature in summer will increase 2.7 °C whilst winter temperature will increase 4.2 °C during the 2050s (Hasan et al., 2013). The variation of rainfall and temperature is quite large from one location to another in Bangladesh (Climate Change Cell, 2009b). Shahid (2009) indicated a moderate variation in inter-annual and high variation in intra-annual rainfall in Bangladesh. Most of the climate models project a decrease in precipitation in dry season and an increase during the monsoon in South Asia (Christensen et al., 2007; Shahid and Behrawan, 2008). Tanner et al. (2007) reported the possibility of future increase in rainfall during summer monsoon by around 2–7% and decrease in dry winter months by around 3–4% by the 2050s in Bangladesh. The present geographical distribution of drought-prone areas shows that the Northwest part of the country is at greater risk of droughts (Fig. 1.1). ATM et al. (2013) identified that drought shows a very chronic pattern during the pre-monsoon season in the Northwest districts while during monsoon it shows a more random behaviour. For some sectors, the impact of drought can become more unfavourable than flood and cyclones in the future (Shahid, 2008; Shahid and Behrawan, 2008). Frequent droughts in Northwest Bangladesh cause greater yield losses relative to flooding and submergence (World Bank, 2013). Islam et al. (2017) evaluated the *Boro* growing season drought hazard and predicted a marginal increase in the Northwest and a decrease in the Southwest Bangladesh in the mid-century period. Negative impacts of climate change on agricultural water demand could be more detrimental for drought-prone regions. Therefore, understanding of changes in water demand due to climate change is particularly more important for drought-prone regions of the world, and thus, for Northwest Bangladesh.

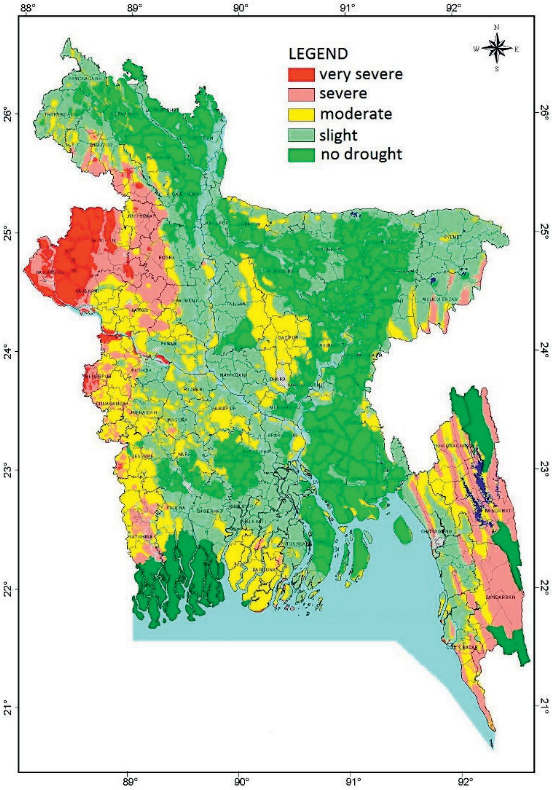

Fig. 1.1. Winter season drought prone areas of Bangladesh (source: Bangladesh Agricultural Research Council).

Rice cultivation in Bangladesh

Crop agriculture in Bangladesh is dominated by rice, almost 80% of the net cropped area, which accounts for more than 90% of total grain production in Bangladesh (Alauddin and Tisdell, 1987, 1991; Asaduzzaman et al., 2012; BBS, 2009). Three season rice crops namely, (i) *Aus* – planted in March or April and harvested in June or July, (ii) *Aman* – sown in July or August and harvested in November or December, and (iii) *Boro* – planted in December or January and harvested in May or June constitute the total rice production (Islam, 1988). Only 5% of Aman rice and 8% of Aus rice are irrigated (Ahmed, 2001). *Boro* rice, cultivated in the dry winter and the hot summer, is completely dependent on irrigation (Mahmood, 1997).

High-yielding variety *Boro* rice is the highest contributors of total rice production in Bangladesh. The rapid growth of irrigation equipment and facilities has inspired the farmers to substantially increase the irrigation-based *Boro* cultivation area. Cultivation areas of *Aus*, *Aman* and *Boro* rice in greater Bogra, Rajshahi, Pabna and Dinajpur regions from 1960-61 to 2012-13 has been shown in Fig. 1.2. The population of Bangladesh is increasing and the country will require more rice grain to feed the increased population. A large portion of this required production is expected to meet from expansion of irrigation-based *Boro* rice cultivation (Wahid et al., 2007). *Boro* rice needs large amounts of irrigation during the dry season. The overall irrigated area in Bangladesh increased from 16 to 56% from 1981-82 to 2006-07, due to rapid expansion of groundwater dependent *Boro* rice cultivation which alone consumes 73% of total irrigation (Parvin and Rahman, 2009).

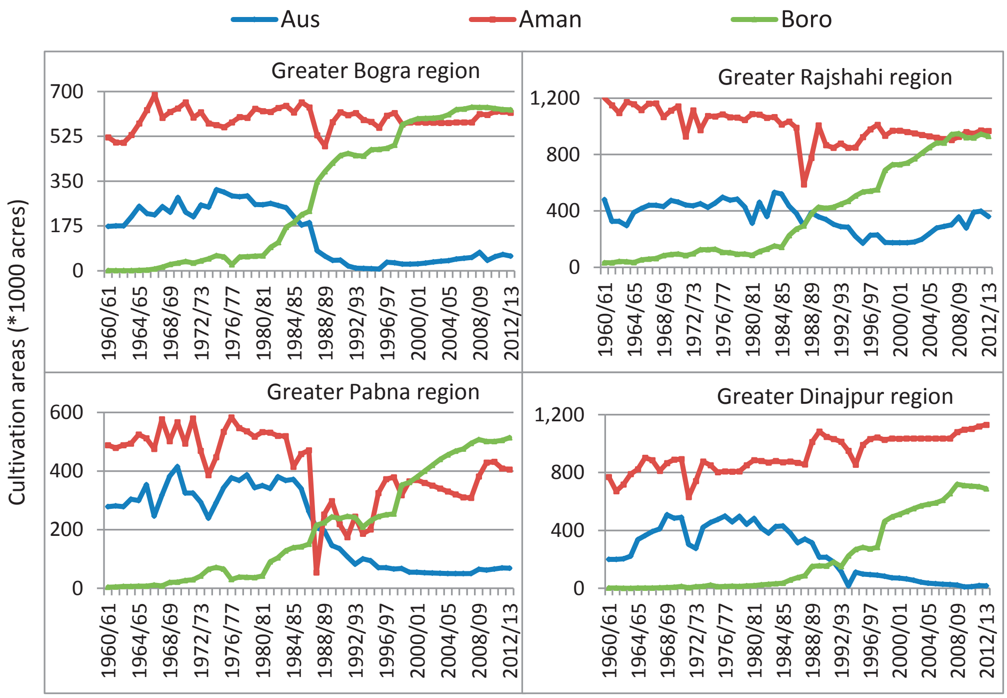

Fig. 1.2. Cultivation areas of *Aus*, *Aman* and *Boro* rice in greater Bogra, Rajshahi, Pabna and Dinajpur regions from 1960-61 to 2012-13 (Data source: Bangladesh Bureau of Statistics).

Challenges to manage water demand for irrigated agriculture in Northwest Bangladesh

Bangladesh has become increasingly dependent on groundwater irrigation for *Boro* rice cultivation. Groundwater levels in drought-prone areas are already declining due to over-exploitation and low recharge potentiality. During recent years, a prolonged absence of groundwater within the operating range of shallow tube-wells during dry season was identified as a common problem in the Northwest Bangladesh (Shahid and Hazarika, 2010). According to FAO (2007), a temperature increase of 1.3°C and a precipitation decrease of 9% in 2050 would reduce runoff into the Ganges, Brahmaputra, and Meghna Rivers by 27%, 21% and 15%, respectively. Although water scarcity in Bangladesh is still economic in nature, some Northwest districts may be approaching physical water scarcity due to a lack of sufficient water to meet all demands, including environmental flows (Alauddin and Sharma, 2013). Since expansion of irrigated agriculture could lead to a critical depletion of groundwater levels and surface water availability in the dry months is projected to reduce in the future, agricultural water demand management needs more attention.

Due to population growth and development of living standard of people, there will be higher demand of water for domestic use in the future. Water demand for industrial use may also increase since industrial growth will be accelerated with the economic growth of the country. Imbalance between water demand and availability may have enormous impacts on agriculture, socio-economic aspects and ecological conditions. Faisal and Parveen (2004) predicted that nearly 40–50% of the seasonal water would be claimed by agriculture alone in 2050, resulting in significant negative impacts on in-stream flow, environmental demand and water supply for domestic and industrial needs. In case of water shortages, it is likely that the domestic and major industrial water needs are satisfied first, while only the remaining water can be used for agriculture. Water scarcity is expected to be a major challenge for most parts of Asia due to increased water demand and lack of good management (Hijioka et al., 2014). To cope with the changing demand-availability situation, understanding of the possible changes in water requirements and exploration of the water demand management options are essential.

Adaptation to climate change for water demand management in Bangladesh

A number of activities have been initiated in Bangladesh to cope with the adverse effects of extreme natural events in recent years. Since 1960s, the government of Bangladesh employed both structural and non-structural measures that significantly reduced damages and losses from extreme climatic events over time (World Bank, 2010). About 100 small and medium scale adaptation projects were implemented between late 1990s and 2005 (BCAS, 2008). There were major investments over the last two decades in the *Barind* area to raise agricultural productivity. However, most of these efforts will be challenged by predicted increasing drought in the Northwest Bangladesh (Rahman et al., 2007).

Adaptation to climate change can potentially reduce its adverse effects, protect the livelihoods of poor farmers and reinforce any potential advantages of a changing climate (Gandure et al., 2013). It is essential to understand the direction of changes in water demand and the reason for those changes for proper agricultural water management. Planning for future development requires to prepare water projections for the future (Wada et al., 2016). Adaptation is highly context specific because it depends on the conditions of the target region and sector, and the planning for adaptation requires close collaboration of climate and impact scientists, sectoral practitioners, decision-makers and other stakeholders, and policy analysts (Füssel, 2007). The local or regional scale changes in climatic conditions could be quite different from global scale change and may have different patterns of impacts on water demand for agriculture. Therefore, different techniques are required for different regions for adaptation to climate change. Adaptation of agricultural techniques will be central to limit potential damages under climate change (Fischer et al., 2005). Understanding of changes in water requirements of crops may help to assess the agricultural adaptation techniques based on water management practices. Adaptation measures based on improved land and water management practices will be fundamental in enhancing overall resilience to climate change (Turral et al., 2011). Also, it is essential to understand the effectiveness and limits to adaptation measures. At present the picture of the limits to adaptation is not clear, partly because effective adaptation measures are highly dependent on specific geographical and climate risk factors as well as institutional, political and financial constraints (IPCC, 2001).

Knowledge gaps and research focus

The water crisis has been considered as a critical challenge for global food production and have recently received considerable attention (Li et al., 2011). It has become a key issue for the drought-prone Northwest Bangladesh. A number of studies have been carried out to understand the effects of climate change on agricultural water use worldwide (De Silva et al., 2007; Diaz et al., 2007; Döll, 2002; Doria et al., 2006; Elgaali et al., 2007; Espadafor et al., 2011; Fischer et al., 2007; Gao et al., 2017; Rejani et al., 2016; Supit et al., 2010; Tang et al., 2011; Tukimat et al., 2017; Woznicki et al., 2015). Studies by different authors mainly concluded that agricultural water demand will increase in most parts of the world due to increases in evapotranspiration. However, the changes in irrigation water demand vary widely according to local climate. The understanding of future changes in irrigation water demand due to climate change is still not very clear in many parts of the world including Bangladesh. However, some studies in Bangladesh attempted to understand the effects of climate change on agricultural water demand (Hossain et al., 2017; Karim et al., 2012; Khan, 2013; Mainuddin et al., 2015; Shahid, 2010).

Despite some studies in recent years, two important knowledge gaps about understanding and managing water demand for crop agriculture exist. The first research gap relates to quantifying future water requirements for dry season crops considering both the changes in climatic parameters and crop's phenological response to the changed conditions. To address the changes in water demand, a large number of studies in Bangladesh estimated only the impact of climate change on reference crop evapotranspiration (Ali et al., 2005; Ayub and Miah, 2011; Kader, 2012; Mojid et al., 2015; Shopan et al., 2013). However, for a complete understanding of the impacts of climate change on agricultural water demand, the findings about the reference crop evapotranspiration is insufficient. Adaptation planning of irrigated crop agriculture based on only the identified changes in reference crop evapotranspiration could be misleading. A few recent studies estimated the impact of climate change on irrigation water requirement of *Boro* rice in Northwest zone (Islam et al., 2018; Mainuddin et al., 2015; Shahid, 2010). Shahid (2010) concluded that there will be no appreciable change in irrigation requirement of *Boro* rice due to climate change. The study by Mainuddin et al. (2015) also found similar results and concluded that the water requirement for irrigation may slightly increase in the future due to climate change. However, Mainuddin et al. (2015) did not consider the impacts of climate change on crop phenology. Crop's phenological response to changed climate condition could be an important aspect for water requirements estimation. Therefore, a detailed study including crop's phenological responses to climate change is needed. Moreover, it is essential to understand the consequences of climate change on all water requirement components.

The second research gap relates to assessing the effectiveness of simple adaptation strategies like shifting of trans-/planting dates etc. and prioritizing suitable measures to cope with the impacts of climate change on agricultural water demand. Most of the studies on shifted planting dates mainly focused on rice yield. However, a study to assess the effectiveness of shifting planting dates with focus on water demand and temperature threshold during critical stages is required. A number of studies have been carried out in Bangladesh on climate change adaptation in response to floods (Brouwer et al., 2007), flash floods (Climate Change Cell, 2009a), salinity (Climate Change Cell, 2009a), droughts

(Habiba et al., 2012a) and natural hazards (Alam et al., 2012). However, the ranking of adaptation measures are rarely developed with main focus on agricultural water demand management in Bangladesh.

1.2. Research objectives and questions

The main objective of this thesis is two-fold:

1. To quantify the historical and future changes in water requirements of dry season rice in Northwest Bangladesh; and
2. To identify and develop strategies to improve water demand management under future agro-climatic changes.

The first research objective was achieved through a quantitative analysis method, where modelling approaches were used to quantify historical and future possible changes in water requirements of dry season *Boro* rice in four Northwest districts. Historical daily climate data on maximum and minimum temperature, rainfall, wind-speed, humidity and sunshine hour were used to quantify historical changes in water requirements of *Boro* rice. To quantify the future possible changes in water requirements, first we developed climate scenarios using five global circulation models and two RCPs by downscaling and bias correction. Thereafter, the developed climate scenarios were used to estimate future possible changes in water requirements of *Boro* rice. The second research objective was achieved through quantitative and qualitative methods. First, we used the modelling approach to test the effectiveness of a simple strategy 'shifting trans-/planting date of *Boro* rice' as an adaptation strategy to cope with possible future climate change. Second, we took opinions of local experts/stakeholders and used the multi-criteria analysis method to rank a set of identified adaptation options for Northwest Bangladesh. Four corresponding research questions were formulated:

Question 1: What are the impacts of recent climate change on water requirements of dry season *Boro* rice in Northwest Bangladesh? (Chapter 2)

Question 2: What are the impacts of future climate change on water requirements of dry season *Boro* rice in Northwest Bangladesh? (Chapter 3)

Question 3: How effective is the shifting of trans-/planting date of *Boro* rice to adapt to future climate change? (Chapter 4)

Question 4: What are the priority measures for the drought prone Northwest Bangladesh to cope with climate change? (Chapter 5)

1.3. Methodological framework

The first three research questions (Q1–Q3) were addressed by a quantitative method and the last research question (Q4) was addressed by a qualitative method (Fig. 1.3). Research questions 1–3 concern about the changes in water requirements of dry season *Boro* rice under historical & future climate changes and shifted trans-/planting conditions. The first research question was addressed using observed daily climate data for four Northwest districts in a crop water requirement model. The growth stage days (initial, development, mid-season and late-season stages) of *Boro* rice for each year (from 1979-80 to 2012-13) were estimated applying a dynamic modelling of growing degree-days in response to temperature. This research further focused on understanding the future consequences of climate change by employing five global circulation model outputs for two RCPs to address the second research question. Water requirements were quantified for moderate (i.e. RCP 4.5) and rapid (i.e. RCP 8.5) climate change conditions. The future water requirements of *Boro* rice for early, normal and late planting and possibilities of high temperature stress during critical periods were quantified to address third research question. A qualitative analysis which involve stakeholders consultations, literature review and multi-criteria analysis was applied to address the 4th research question.

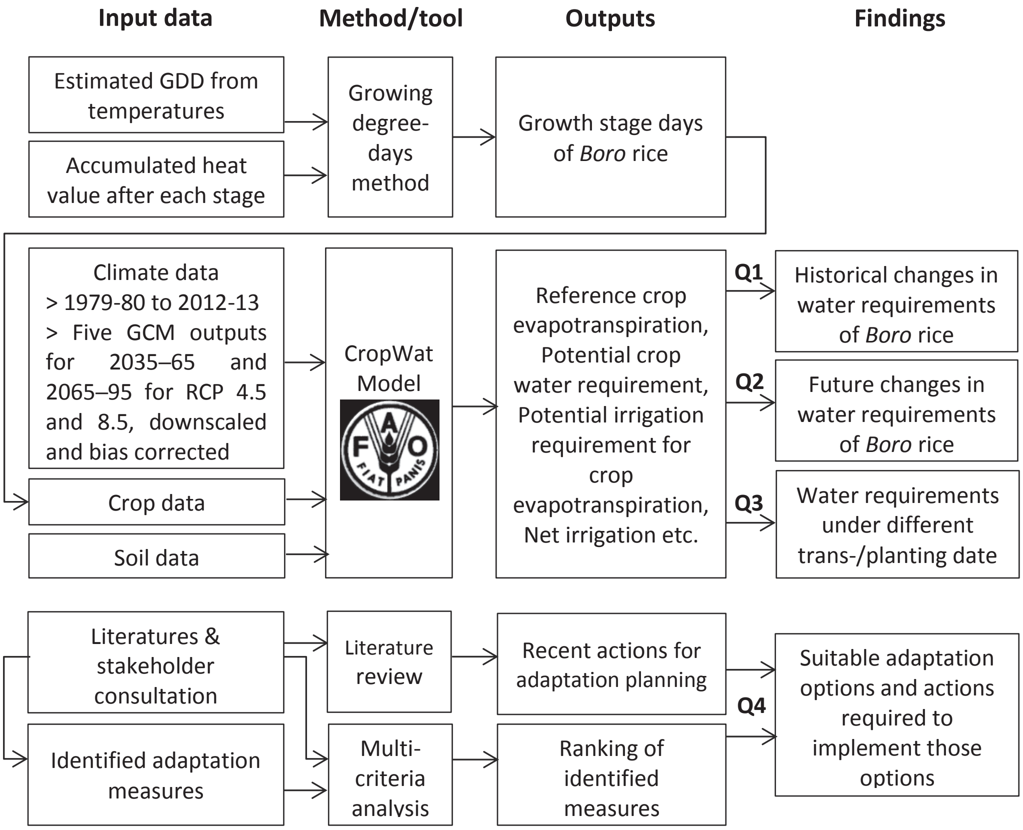

Fig. 1.3. Methodological framework of this study.

CropWat 8.0 for water requirements estimation

Crop water requirement modelling in this study covers both climatic influence on water requirement components and phenological response of crop. The climatic influence on water requirement components of rice is illustrated in Fig. 1.4. The daily reference crop evapotranspiration (ET_O) is influenced by temperature, humidity, wind speed and sunshine hours. The potential crop water requirement (ET_C) is estimated using estimated daily ET_O, crop coefficient values at different growth stages and number of days under each growth stages. The actual crop water requirement (ET_A) differs from ET_C due to the influence of water stress at root-zone. However, for rice cultivation with continuous standing water, there is no water stress at root-zone, hence, ET_A is equal to ET_C. Crops receive some water from rainfall. If we substitute the effective rainfall (ER) from crop water requirement we get the potential irrigation requirement for crop evapotranspiration (ET_C–ER). The sum of potential crop water requirement for crop evapotranspiration, amount of percolation loss throughout the growing season and amount of water required for nursery and field preparation is the net irrigation requirement. For modelling the water requirements as described here, the FAO developed CropWat 8.0 model had been used in this study.

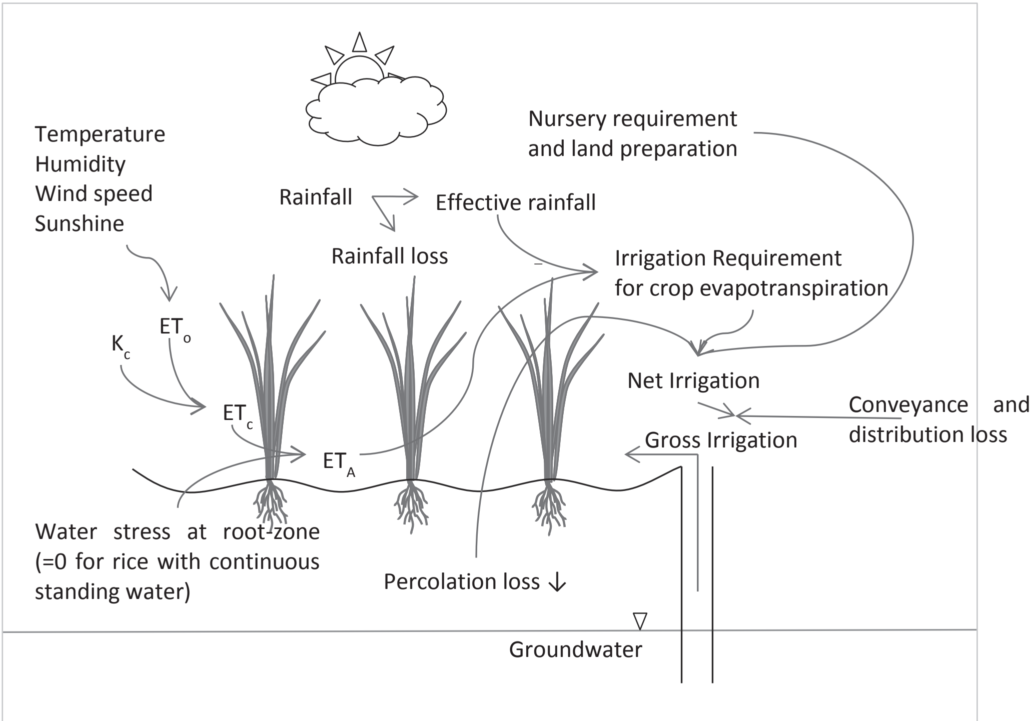

Fig. 1.4. Schematic representation of different components of water requirements.

Climate models and data

For the quantification of historical changes in water requirements of *Boro* rice, daily climate data collected from the Bangladesh Meteorological Department were used. To address the 2nd and 3rd research questions, first the future climate scenarios were constructed using five Global Circulation Model (GCM) outputs for RCP 4.5 and 8.5 for 2050s (2035–65) and 2080s (2065–95) and thereafter, the developed climate scenarios were used in crop water requirement modelling. GCMs are the key tools to assess future climate change at large-scale (Xu, 1999). GCMs provide data on coarse horizontal resolution, which limits their capability to resolve processes at local scale (Wilby and Wigley, 1997). Therefore, it is essential to adjust the large-scale predictions of GCMs to the local-scale climate variables. The downscaling methods are generally used to convert GCM outputs into local climate variables. There are various methods available for downscaling GCMs outputs which fall into two main categories: (i) dynamic and (ii) statistical downscaling (Fowler et al., 2007). The statistical downscaling method was followed in this study. After downscaling, a bias correction to climate model outputs was applied using the WATCH forcing data for the period of 1971–2001.

Growing degree-days method for growth duration estimation

The development of plant is dependent on temperature and requires a specific amount of heat to progress in life cycle. The growth or development of a plant is linearly related to temperature or the total amount of heat to which it is exposed (Yoshida, 1981). The growing degree-days (GDD) method was followed in this study to address the crop’s phenological response to increased temperature. Growing degree-days is a way of assigning a heat value to each day and the values are added to give an estimate of amount of seasonal growth that plants have achieved. GDD has vastly improved prediction of phenological events compared to other approaches (Cross and Zuber, 1972; Gilmore and Rogers, 1958; Klepper et al., 1984; McMaster and Smika, 1988; Russelle et al., 1984).

Multi-criteria analysis for ranking adaptation measures

To address the 4th research question, first the suitable adaptation options for the drought-prone Northwest part of Bangladesh were identified from literature review and stakeholder consultations. Thereafter, identified measures were scored by local experts/stakeholders to assess the priority based on importance, urgency, no-regret and co-benefit criteria and the complexity based on technical, social and institutional complications. The multi-criteria analysis method was followed to rank the identified measures.

1.4. Thesis outline

The thesis is arranged into six chapters. Chapter 1 presents the general introduction to study area, problem definition, research gaps, research objectives and questions and overall methodological framework used in this study. Chapter 2–5 is the core of the study; present the scientific research addressing four research questions. Chapter 2 presents the impacts of recent/historical climate change on water requirements of dry season *Boro* rice in Northwest Bangladesh. The results highlight the trends of recent changes in water requirements and its connection to different climatic parameters. Chapter 3 presents the consequences of future climate change on water requirements of *Boro* rice. The results highlight the possible changes in water requirements of *Boro* rice under a moderate and rapid climate change including a comparison with base period and a characterization of consequence of future climate change on different water requirement components. Chapter 4 presents the effectiveness of 'shifting trans-/planting date' of *Boro* rice to adapt to climate change. The results highlight the compatibility of changed planting dates in terms of variation in water requirements for early, normal and late planting and possibility of exceeding the threshold temperatures during critical period. Chapter 5 presents the prioritization of adaptation measures for better agricultural water management to cope with climate change. The results highlight the top listed adaptation measures for the Northwest Bangladesh. Finally, Chapter 6 synthesizes the main results of this study and discusses the study's limitations, scientific contributions, recommendations and future research perspectives.

CHAPTER 2

Declining trends of water requirements of *Boro* rice

ABSTRACT

The drought prone Northwest Bangladesh is vulnerable to the impacts of climate change, particularly because of less water availability in the dry period and high water requirement for crop production. Improved understanding of recent changes in crop water demand in the dry season is important for the water resources management in the region. A study was carried out to determine the potential impacts of recent climate change during last three decades on trends of water requirements of *Boro* rice. The reference crop evapotranspiration (ET_o), potential crop water requirement ($\sum ET_C$), effective rainfall during the crop growing period (ER), potential irrigation requirement for crop evapotranspiration ($\sum ET_C$–ER) and net irrigation requirement of *Boro* rice were estimated using observed daily climate data in the CropWat model for the period of 1980 to 2013 for four Northwest districts. Significant decreasing trends of ET_o were observed in most of the dry months due to increasing relative humidity and decreasing wind-speed and sun-shine hours. The results showed decreasing trends of potential crop water requirement, i.e. the total crop evapotranspiration ($\sum ET_C$), of *Boro* rice due to decreasing reference crop evapotranspiration and shorter crop growing periods. The variations in trends of potential irrigation requirement for crop evapotranspiration ($\sum ET_C$–ER) found among different districts, are mainly linked to variations in trends of changes in effective rainfall. The net irrigation requirement of *Boro* rice has decreased, by 11% during the last three decades at an average rate of 4.4 mm year^{-1}, despite decreasing effective rainfall, mainly because of high rate of decrease of crop evapotranspiration (5.9 mm year^{-1}). Results indicate that a warming climate does not always result in higher agricultural water use and that climate change can also result in reduced water demands because of changes in humidity, wind-speed and sun-shine hours.

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2.1. Introduction

Irrigation requirement for crop production is the highest water demand sector in Bangladesh. The total water withdrawal in 1990 was estimated at about 14.64 km^3, of which about 86 percent for agriculture (FAO, 2016). Irrigation requirement is highly related to the climatic condition of a region. The world climate is changing, and Bangladesh is considered as one of the most vulnerable countries due to the impacts of anthropogenic climate change (Intergovernmental Panel on Climate Change, 2007). Water related impacts of climate change will likely be the most critical for Bangladesh, including enhanced possibility of dry season drought (Agrawala et al., 2003). An investigation of potential impacts of recent climate change on water demand by crops is important for water resources management of the region. Globally, the amount of water for irrigated agriculture accounts for 70 percent of the fresh water withdrawal (Fischer et al., 2007). Hence, studies on impacts of climate change on water demand for agriculture is important. Such studies which are performed on large spatial scales (e.g. global, continental, or basin) are not detailed enough for understanding the consequences of climate change on regional water management. The regional studies on impacts of recent climate change, involving the major crop of that region, is important from local water management perspective (Woznicki et al., 2015). Moreover, trends of water requirement, estimated from observed recent long-term daily climate data (which is already affected by anthropogenic impacts) and comparison with the trends of local climatic parameters could provide a better insight of climate change induced changes in water demand and related recent water management situations.

The rainfall distribution pattern is very seasonal in Bangladesh. The country receives almost 90% of the total rainfall during May to October (Shahid, 2009). *Boro* is the dry season rice in Bangladesh, which needs irrigation during January to April. The annual average rainfall in Northwest Bangladesh ranges from 1400 to 2000 mm, with 93 percent of the rainfall occurring during May to October, and only about 6 percent during *Boro* rice growing months (Shahid, 2010). Hence, dry season crops that require water during November to April, fully dependent on irrigation. As the surface water flows during the dry period in the Northwest Bangladesh are not adequate to support crop cultivation, the irrigation systems mostly depend on groundwater resources. Several studies indicate that groundwater levels in drought prone regions of Bangladesh are declining because of over-exploitation for irrigating dry period *Boro* rice and reduced recharge potentiality due to urbanization. The groundwater table in the Northwest Bangladesh has declined between 2.3 to 11.5 m from 1981 to 2011 (Dey et al., 2013). About 85 percent of the area in Rajshahi district has low recharge potentiality and only 8.6 percent of total average annual rainfall percolates into subsurface to recharge groundwater (Adham et al., 2010). Analyses of groundwater hydrographs and rainfall time-series by Shahid and Hazarika (2010) indicate that, groundwater level is declining in the Northwestern districts, because of increasing groundwater extraction for irrigation in the dry season and recurrent droughts. The amount of water extracted in any region for cultivating crops depends on net irrigation requirement of cultivating crops, cultivation area and irrigation efficiency. The potential change in water extraction due to change in net irrigation requirement of cultivating crops can distinctly vary from region to region considering the regional changes in climatic condition.

Because, changes in climatic conditions can impact differently in different regions of the world depending on different present existing climate condition and different rate of changes in various climatic parameters that affect water demand by crops.

Some studies indicate a decrease in climatic water requirement (ET_o) of crops in the Northwest districts of Bangladesh due to change in climatic conditions during last few decades. A study by Mojid et al. (2015) indicates a decreasing trend of ET_o in most of the months in Dinajpur and Bogra due to changes in climatic conditions from 1990 to 2010. Irrigation water requirement is very sensitive to climate change (Schlenker et al., 2007). Demand for irrigation water is particularly sensitive to changes in precipitation, and temperature (Frederick and Major, 1997). An investigation based on an irrigation model by McCabe and Wolock (1992) indicates a change in annual mean water requirement is strongly associated with the change in temperature. Most of the studies regarding the effects of climate change on crop water requirement have treated evapotranspiration as a function of temperature or as a function of the impact of elevated CO_2 on stomatal conductance (Gleick, 1987). However, not only temperature, but also humidity, wind speed and solar radiation affect evapotranspiration. A sensitivity analysis by Eslamian et al. (2011) indicates that evapotranspiration estimation using *Penman–Monteith* formula is very sensitive to temperature and humidity compared to wind speed and sunshine duration. Findings by Yu et al. (2002) indicated that, solar radiation is the most sensitive variables of the modified Penman formula and wind-speed the least sensitive. However, estimation of irrigation requirements involving all climatic parameters as input could provide a better insight of consequences of climate change on water demand.

To completely understand the impacts of climate change on agricultural water requirements, only studying changes in ET_o is not sufficient. Changes in temperature not only affect evapotranspiration but also affect the length of the growing season. Higher temperatures results in more rapid plant development and thus shorten the growing season and total seasonal plant water use. Further, changes in the length of growing season of a crop could change the total percolation loss during that crop growing season. Also, changes in rainfall amount and distribution patterns, especially the changes in effective rainfall affect irrigation requirements. Thus, analysis of the changes in irrigation requirement of the major crop of a region, involving the relative changes in growth stage days and effective rainfall during growing days is important for a complete understanding of the impacts of climate change.

Boro rice is the economically most important and most cultivated dry period crop of Bangladesh. High yielding variety of *Boro* rice is cultivated on more than 70 percent of the total cultivable area during December to May. Out of 33.83 million metric tons of total rice production in 2012-13, 18.78 million metric ton was from *Boro* rice. During the past few decades, the area under *Boro* rice cultivation has been increased by almost tenfold in the Northwest districts of Bangladesh. *Boro* rice needs large amounts of irrigation during the dry season. According to Parvin and Rahman (2009), the overall irrigated area in Bangladesh increased from 16 to 56 percent from 1981-82 to 2006-07, due to rapid expansion of groundwater dependent *Boro* rice cultivation which alone consumes 73 percent of total irrigation. Increased groundwater withdrawal for irrigating dry period crops and frequent drought events are causing prolonged absence of groundwater within the operating range of shallow tube-wells during dry season in some Northwest districts (Shahid and Hazarika, 2010).

Climatic water requirement is the reference crop evapotranspiration (ET_o), which represents the environmental demand for evapotranspiration, defined as the evapotranspiration rate from a reference surface, which is a surface of short grass-like cover, completely shading the ground, of uniform height and with adequate water status in the soil profile. The crop evapotranspiration (ET_C) differs distinctly from the ET_o as the ground cover, canopy properties and aerodynamic resistance of the actual field crop are different from the reference grass. The effects of those characteristics that distinguish field crops from reference grass are integrated into the crop coefficient (Kc). In the crop coefficient approach, ET_C is calculated by multiplying ET_o by Kc. The *potential crop water requirement* is the total crop evapotranspiration ($\sum ET_C$) during the crop growing period. Actual evapotranspiration (ET_A) takes into account both climatic water demand of the field crop and soil water stress in the root zone. Hence, ET_A differs from ET_C in situation of water stress in the soil root-zone. *Potential irrigation requirement for crop evapotranspiration* is the total crop evapotranspiration amount in excess of effective rainfall, i.e. $\sum ET_C - ER$. Here, effective rainfall is the amount of rainfall that is effectively added and stored in the soil for later use by the crop. *Net irrigation requirement* takes into account the irrigation needed for crop evapotranspiration, percolation loss (PL) and water required for nursery and land preparation (N&LP), i.e. $\sum ET_C - ER + PL + N\&LP$.

A regional study on trends of recent climatic parameters, reference crop evapotranspiration, potential crop water requirement or crop evapotranspiration, potential irrigation requirement for crop evapotranspiration and net irrigation requirement, involving the changes in growing days that affects the crop water requirement and the changes in effective rainfall during the crop growing period that affects the potential irrigation requirement, and the changes in overall net irrigation of the major crop, is required for a better understanding of the impacts of recent climate change on water requirement for agriculture. Thus, this study, with an objective to quantify the impacts of recent climate change, i.e. changes in maximum and minimum temperature, relative humidity, wind-speed, sun-shine hour and rainfall, on trends of water requirements of *Boro* rice, has applied CropWat model using observed daily meteorological data as input for the period of 1979-80 to 2012-13 for four Northwest districts. This study will be beneficial for local water managers and policy makers for understanding the consequences of climate change and taking decision on local water management planning related to water demand management for agriculture. Further, this study will broaden the understanding of scientific community about the regional consequences of recent climate change in relation to water demand for agriculture, which can significantly vary from certain issues on global perspective.

2.2. Materials and Method

2.2.1. Study area

The Northwest region of Bangladesh consists of 16 administrative districts. Only five of the 16 districts have weather stations to record climatic data. Four districts, namely Rajshahi, Dinajpur, Pabna and Bogra were selected for this study (Fig. 2.1). This region is also referred as the *Barind* tract. This area extends from 23°47′ N to 25°50′ N latitude and from 88°01′ E to 89°48′ E longitude. A typical dry climate with comparatively high temperature prevails in this area. Rainfall occurs from mid-June to October and the magnitude of annual rainfall varies from 1400 mm to 2000 mm. The average rainfall is comparatively low in this region compared to the rest of the country. The mean and standard deviation of monthly maximum and minimum temperature, rainfall, relative humidity, sun shine hours and wind speed of the study districts for the period of 1979–2013 are illustrated in Fig. A.1 of Appendix A. The region is usually classified as medium to highland, normally flood-free. This part of Bangladesh is most vulnerable to droughts (Shahid, 2008; Shahid and Behrawan, 2008). The economy of the region is largely agriculture based. The major crops are *Boro* rice, *Aman* rice, wheat, potato, jute, sugarcane, mustard, maize and vegetables. *Boro* rice, wheat, potato, maize and vegetables are cultivated during dry winter period. *Boro* rice is the dominant dry period crop cultivated on more than 70% of the cultivable area during December to May.

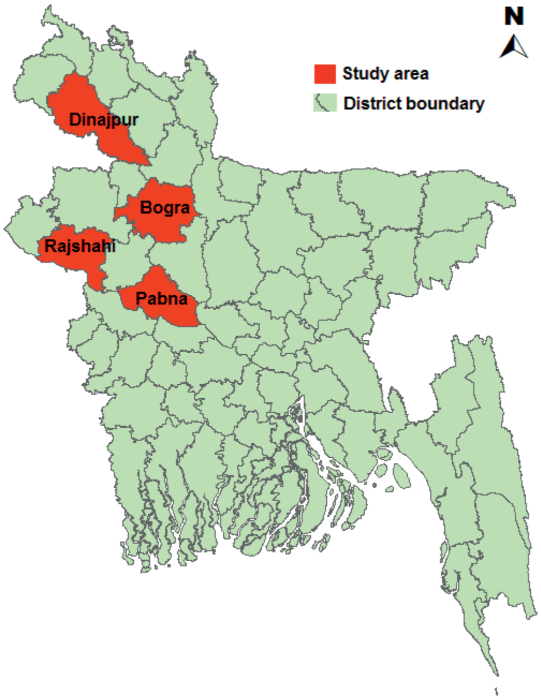

Fig. 2.1 The location of the study areas, i.e. Bogra, Rajshahi, Pabna and Dinajpur districts in the map of Bangladesh.

2.2.2. Data collection

The historical climate data for the period of 1979–2013 for Bogra, Rajshahi and Pabna, and for the period of 1981–2013 for Dinajpur were collected from Bangladesh Meteorological Department. The collected meteorological data includes daily minimum and maximum temperature, average relative humidity, wind speed, sunshine hours and rainfall. Crop data related to crop co-efficient (i.e. dry and wet Kc values for nursery, land preparation, initial, mid-season and late season stage), rooting depth, crop height, critical depletion and yield response factor at different stages of crop growth for dry season *Boro* rice have been collected from Bangladesh Agricultural Research Institute (BARI). Soil data, including available soil moisture, maximum rain infiltration rate, maximum rooting depth, initial soil moisture depletion, initial available soil moisture, drainable porosity, critical depletion for puddle cracking, maximum percolation rate after puddling, water availability at planting and maximum water depth, were standardized for medium average soil for those districts from FAO standard soil parameter values.

2.2.3. Estimation of growth stage days

The growth stage days (initial, development, mid-season and late season stages) of *Boro* rice for each year (from 1979-80 to 2012-13) has been estimated from growing degree-days (GDD) by following the method as described by Miller et al. (2001). The following equation has been used for estimating GDD:

$$\boldsymbol{GDD = \left[\frac{T_{max}+T_{min}}{2}\right] - T_{base}} \qquad (2.1)$$

$$\boldsymbol{Stage\ (days) = \frac{Accumulated\ heat\ at\ the\ end\ of\ the\ stage}{GDD\ for\ corrosponding\ period}} \qquad (2.2)$$

Where, T_{max} is the maximum temperature, T_{min} is the minimum temperature, and T_{base} is the base temperature. The values of accumulated degree-days at the end of each stage for *Boro* rice in the Northwest zone of Bangladesh were obtained from the studies of Mahmood (1997). The accumulated heat values (for the base temperature of 15 °C) at the end of initial, vegetative, flowering and maturing stages for Bogra, Rajshahi and Pabna were 80, 528, 1052 and 1291 °C, respectively and for Dinajpur were 80, 515, 1032 and 1273 °C, respectively. The method of growing degree-days can consistently predict the growth stage days (Miller et al., 2001).

2.2.4. Estimation of water requirements

The FAO developed CropWat model is a simple and effective tool for estimating water requirement and related field water balance. This model has been successfully applied to estimate water requirement under climate change by several studies (Chowdhury et al., 2013; Doria and Madramootoo, 2012; Doria, 2010; Shrestha et al., 2013). The time series of reference crop evapotranspiration (ET_O), potential crop water requirement or total crop evapotranspiration ($\sum ET_C$), potential irrigation requirement for crop evapotranspiration ($\sum ET_C - ER$) and net irrigation requirement ($\sum ET_C - ER + PL + N\&LP$) of *Boro* rice for 33 years for Bogra, Rajshahi and Pabna, and 31 years for Dinajpur were estimated using FAO developed CropWat 8.0. In order to assess the climate impacts on the water requirements of *Boro* rice, the influence of management practices were excluded by modelling the rice growth in CropWat under a standardized schedule that provides irrigation water as required.

Potential crop water requirement, $\sum ET_C$, is the amount of water required for total crop evapotranspiration (ET_C) during the crop growing period. Crop evapotranspiration was estimated from reference crop evapotranspiration and crop co-efficient ($ET_C = K_C * ET_o$). The K_C predicts ET_C under standard (no water stress) conditions. For water stress condition in the soil root-zone, the actual crop evapotranspiration becomes different, and stated as actual evapotranspiration (ET_A). CropWat model estimates the ET_A considering the soil moisture balance to adjust for water stress in the soil root-zone. Generally, ET_A becomes equal to the amount of water required for crop evapotranspiration (ET_C) of rice when continuous irrigation is applied to maintain standing water to avoid stress in crop root zone. Hence, for no water stress, $ET_A = ET_C$.

CropWat follows FAO *Penman-Monteith* formula to estimate reference crop evapotranspiration (Allen et al., 1998) . The inputted meteorological data in CropWat were in a seasonally arranged format (October to next year September) for the period of 1979-80 to 2012-13. The local Kc values of *Boro* rice inputted in CropWat were collected from BARI. The Kc values under dry condition were 0.7, 0.3, 0.5, 1.05 and 0.65, under wet condition were 1.2, 1.05, 1.1, 1.2 and 0.95 for nursery, land preparation, initial, mid-season and late-season, respectively. Effective rainfall is equal to the amount of rainfall effectively stored and in the root-zone and field, and available for crop consumption. Effective rainfall was assessed in CropWat through modelling of the irrigation and weather; estimated from the output of the water balance simulation in CropWat, and defined as water effectively stored in and on the field. As rainfall patterns change, effective rainfall may change, where increases in effective rainfall lead to further declines in net irrigation requirements or vice versa.

To identify these changing potential crop water requirements, the irrigation water was provided (in CropWat) as required by crop. Hence, these are the set according to the same irrigation scheduling principles for all simulations for standard medium soil for those districts following FAO soil parameter values and standard local crop parameters as collected from BARI. In essence, irrigation requirements, that change due to changes in ET_C (climate driven changes in ET_O and phenology) and due to changes in Rainfall patterns, were assessed. The transplanting date of *Boro* rice was taken as 10^{th} of January. For *Boro* rice, water requirements were calculated taking into account the water required during nursery (10% nursery area) and land preparation. The length of nursery and land preparation stage were taken as 35 days of nursery raising, 20 days of pre-puddling and 5 days of puddling. Puddling depth was taken as 0.4 m. Water required for land preparation of rice were calculated following FAO formula for calculating maximum percolation rate after puddling and daily decrease in maximum percolation rate during puddling. As rice crop needs standing water, substantial amounts of irrigation water are returned to the water table due to percolation. Due to the shortening of the growth cycle (phenological accelerated growth due to GDD impact) less days are available in which percolation can occur, and thus less irrigation water is required to meet that percolation. According to FAO formula, the maximum percolation rate after puddling is equal to 0.33

powers of maximum percolation rate of non-puddled soil. The daily decrease in maximum percolation rate during puddling:

$$(1/days\ puddling) * \ln\left(\frac{Max.percolation\ rate\ after\ puddling}{Max.percolation\ rate\ of\ nonpuddled\ soil}\right) \quad (3.3)$$

Soaking requirement on day 1 was taken as the amount of water required to fill soil to saturation up to puddle depth plus 10 cm. The pre-puddling scheduling was irrigation at 20 percent depletion of field capacity with a refill of soil moisture content to 100 percent saturation. The puddling scheduling was irrigation at 0 mm water depth with a refill of water depth to 50 mm. The percolation losses depend on the type of soil. They will be low in heavy and well-puddled clay soils, and will be high in the case of sandy soils. The percolation losses vary between 4 and 8 mm/day. Scheduling criteria to estimate the net irrigation requirement for rice was irrigation at 5 mm water depth with a refill to 100 mm standing water.

2.2.5. Trend analysis

Parametric methods, such as moving average or running mean (Salinger et al., 1995; Sneyers, 1992), linear regression (Gregory, 2014; Lanzante, 1996), etc. and non-parametric methods, such as Mann-Kendall test (Kendall, 1948; Mann, 1945), Spearman's test, etc. can be used for trend analysis. In this study, the time series trends of reference crop evapotranspiration (ET_O), growth stage days, potential crop water requirement or total crop evapotranspiration ($\sum ET_C$), effective rainfall (ER), potential irrigation requirement for crop evapotranspiration ($\sum ET_C$–ER) and net irrigation ($\sum ET_C$–ER+PL+N&LP) of *Boro* rice were estimated by the non-parametric Mann-Kendall test for testing the presence of the monotonic increasing or decreasing trend. The non-parametric Sen's method (Sen, 1968) was applied for estimating the slope of a linear trend. In Mann-Kendall test, the data are evaluated as an ordered time series and each data value is compared to all subsequent data values to calculate the Mann-Kendall statistic. To quantify the statistical significance of the trend, the probability associated with Mann-Kendall statistic was computed. Sen's estimator of slope is simply given by the median slope and this method calculates the slope as a change in measurement per change in time. Sen's slope method is not sensitive to outliers and gives a robust estimation of trend (Yue et al., 2002). Investigation of trends and persistence in historical meteorological data are helpful in understanding the effect of climate change on evapotranspiration in the region under study (Eslamian et al., 2011). Trend analyses were also performed for climatic parameters (i.e. for average monthly maximum and minimum temperature, sun-shine hours, relative humidity, wind speed and rainfall) to investigate how changes in different climatic parameters are affecting the water requirement components.

2.3. Results

2.3.1. Trends of reference crop evapotranspiration

During March–August, the reference crop evapotranspiration (ET_o) is higher than the yearly average (3.71, 3.81, 3.94 and 3.52 mm day^{-1} for Bogra, Rajshahi, Pabna and Dinajpur, respectively) for all the study districts (Fig. 2.2). The Mann-Kendall test for ET_o over the study period (1979–2013) indicates significant decreasing trends during the dry period (November–April) in the Northwest Bangladesh (Table 2.1). The Sen's rate of decrease of ET_o during the dry months (0.018, 0.020, 0.037, 0.025 mm day^{-1} year^{-1} for Bogra, Rajshahi, Pabna and Dinajpur, respectively) is comparatively higher than the yearly average rate of decrease (0.010, 0.014, 0.023, 0.012 mm day^{-1} year^{-1} for Bogra, Rajshahi, Pabna and Dinajpur, respectively). The rate of decrease of ET_o during dry months in Pabna is comparatively higher than other districts. ET_o exhibited insignificant increasing or decreasing trends in most of the wet months. Increasing trends were found only for July, September and October in some districts.

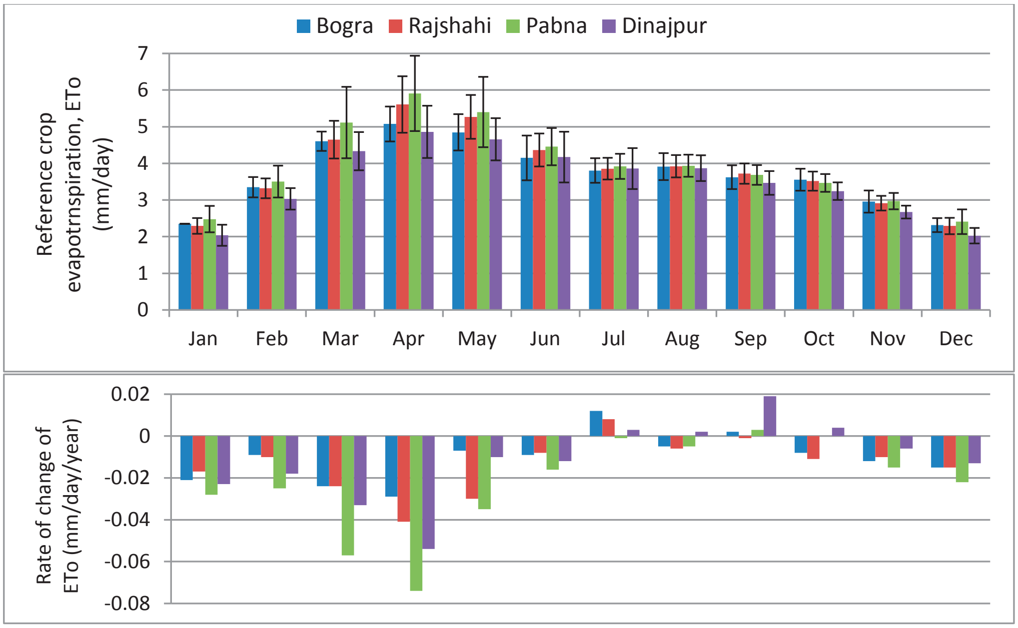

Fig. 2.2 Mean, standard deviation and Sen's rate of change of monthly average reference crop evapotranspiration in four Northwest districts for the period of 1979–2013.

Table 2.1

Mann-Kendall test for reference crop evapotranspiration in four Northwest districts of Bangladesh for the period of 1979–2013.

Month	Mann-Kendall test values of ET_o			
	Bogra	Rajshahi	Pabna	Dinajpur
January	**–4.93*** **	–**5.19*****	–**5.09*****	–**4.47*****
February	–**2.07***	–1.92[+]	–**3.26****	–**3.39*****
March	–**3.38*****	–**2.81****	–**4.60*****	–**3.92*****
April	–**3.40*****	–**4.28*****	–**4.34*****	–**4.32*****
May	–0.70	–**3.42*****	–**2.82****	–0.73
June	–1.88[+]	–1.71[+]	–**2.33***	–1.78[+]
July	**2.09***	1.83[+]	–0.12	0.25
August	–0.91	–1.09	–0.91	0.31
September	0.28	–0.26	0.63	**2.77****
October	–1.38	–**3.26****	0.04	1.16
November	–**3.78*****	–**3.03****	–**3.86*****	–1.72[+]
December	–**2.70****	–**4.75*****	–**4.60*****	–**3.35*****

[+], *, ** and *** signs indicate significant at 0.10, 0.05, 0.01 and 0.001 level of significance, respectively.

The minimum temperature during the dry months (November–April) over the study period showed increasing trends except in January (Table A.1, Appendix A) which was significant in February (except in Rajshahi), March and April (except in Bogra and Pabna). Insignificant decreasing trends of minimum temperature were found for January (except in Dinajpur). The maximum temperature was significantly decreasing in January (except in Rajshahi) while the changes in other dry months were insignificant. The increase in relative humidity was significant in November (except in Bogra and Dinajpur), December (except in Bogra), January, February (except in Bogra), March and April (Table A.2, Appendix A). The decrease in wind speed was also significant ($p < 0.001$) all over the year in Rajshahi, Pabna and Dinajpur (Table A.2, Appendix A). At Bogra, a smaller decreasing trend in wind speed was observed. Significant decreasing trends in sun-shine hours were found in December, January, February (except in Rajshahi and Pabna), March (except in Rajshahi) and April (Table A.3, Appendix A). Over the study periods, the change in rainfall was not significant except in December (Table A.3, Appendix A). Rainfall showed a significantly decreasing trend in December (except in Pabna) and insignificant decreasing trends in November, January, February (except in Dinajpur), March and April (except in Dinajpur). For further understanding of how changes in rainfall affected irrigation requirement of *Boro* rice, effective rainfall during *Boro* rice growing period was estimated (see section 2.3.3).

2.3.2. Trends of potential crop water requirement

The estimated potential crop water requirement, i.e. the total crop evapotranspiration ($\sum ET_C$) of *Boro* rice significantly decreased in all four districts (Fig. 2.3). The rates of decrease of potential crop water requirement by Sen's method were 2.75, 5.38, 9.48 and 6.15 mm year^{-1} for Bogra, Rajshahi, Pabna and Dinajpur, respectively. The estimated values of potential crop water requirement exhibited highly significant ($p < 0.001$) decreasing trends for Rajshahi, Pabna and Dinajpur (Table 2.2). The potential crop water requirement indicates a less decreasing, yet significant ($p < 0.01$), trends for Bogra district in comparison to other Northwest districts (Fig. 2.3). Both the mean and rate of decrease of potential crop water requirement are highest for Pabna district.

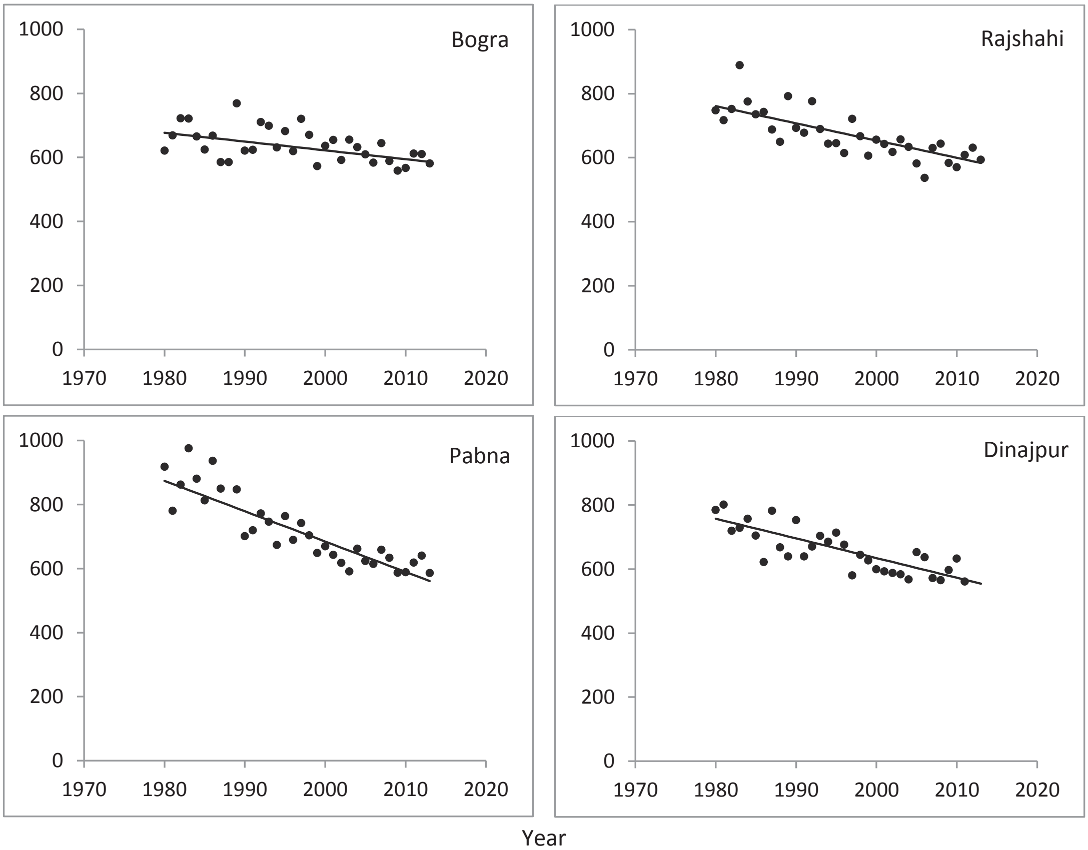

Fig. 2.3 Sen's slope of potential crop water requirement, $\sum ET_C$, (mm) of *Boro* rice at four Northwest districts of Bangladesh.

Table 2.2

Statistics of potential crop water requirement by *Boro* rice for the period of 1979-80 to 2012-13 for four Northwest districts.

District	Potential crop water requirement ($\sum ET_C$)					
	Mean (Standard deviation), mm	Mann-Kendall test	Sen's rate of change, mm year^{-1}	Decrease over the study period, mm	Value at first year, from Sen's line, mm	% decrease over the study period
Bogra	638 (52)	–**3.11****	–2.75	90.8	683	13.3
Rajshahi	671 (75)	–**5.25*****	–5.38	177.5	760	23.4
Pabna	720 (111)	–**6.15*****	–9.48	312.8	876	35.7
Dinajpur	657 (70)	–**5.01*****	–6.15	190.7	752	25.3

** and *** signs indicate significant at 0.01 and 0.001 level of significance, respectively.

The estimated potential crop water requirement of *Boro* rice takes into account both the changes in reference crop evapotranspiration (ET_O) and changes in growth stage days due change in temperature. The decrease in reference crop evapotranspiration (ET_O) during January–May decreased the crop evapotranspiration (ET_C) of *Boro* rice (as $ET_C = Kc \times ET_O$). In addition, the reduction in the number of growth stage days due to change in temperature further decreased the potential crop water requirement ($\sum ET_C$) by decreasing the number of days under crop evapotranspiration. The analysis of estimated growth stage days showed insignificant decreasing trend for Bogra and Rajshahi, and significant decreasing trend ($p < 0.05$) for Pabna and Dinajpur (Table 2.3). As the growth stage days were estimated from growing degree-days, the change in minimum and maximum temperature and their rate of change during different months of *Boro* season affected the duration of the different growth stages. The rate of reduction of *Boro* growth stage were –0.1, –0.2, –0.35 and –0.38 day year^{-1} for Bogra, Rajshahi, Pabna and Dinajpur, respectively (Fig. 2.4). Both the mean and rate of decrease of growing days over the study period is highest for Dinajpur district. Relatively a lengthy growing period in Dinajpur compared to other districts is because of relatively low maximum and minimum temperature during *Boro* rice growing season in Dinajpur.

Table 2.3

Statistics of estimated growth stage days of *Boro* rice for the period of 1979-80 to 2012-13 for four Northwest districts.

District	Mann-Kendall test value					Sen's rate of change, day year^{-1}				
	Initial	Vegetative	Flowering	Maturing	Total	Initial	Vegetative	Flowering	Maturing	Total
Bogra	**2.3***	–1.9⁺	–0.1	–**2.5***	–0.7	0.16	–0.19	–0.01	–0.06	–0.1
Rajshahi	1.8⁺	–1.5	–0.7	–1.5	–1.3	0.0	–0.15	–0.04	–0.04	–0.2
Pabna	0.0	–**2.3***	–0.8	–1.9⁺	–**2.0***	0.0	–0.24	–0.05	–0.05	–0.4
Dinajpur	0.0	–**2.7****	–0.5	–**2.2***	–**2.1***	0.0	–0.24	–0.04	–0.07	–0.4

+, * and ** signs indicate significant at 0.10, 0.05 and 0.01 level of significance, respectively.

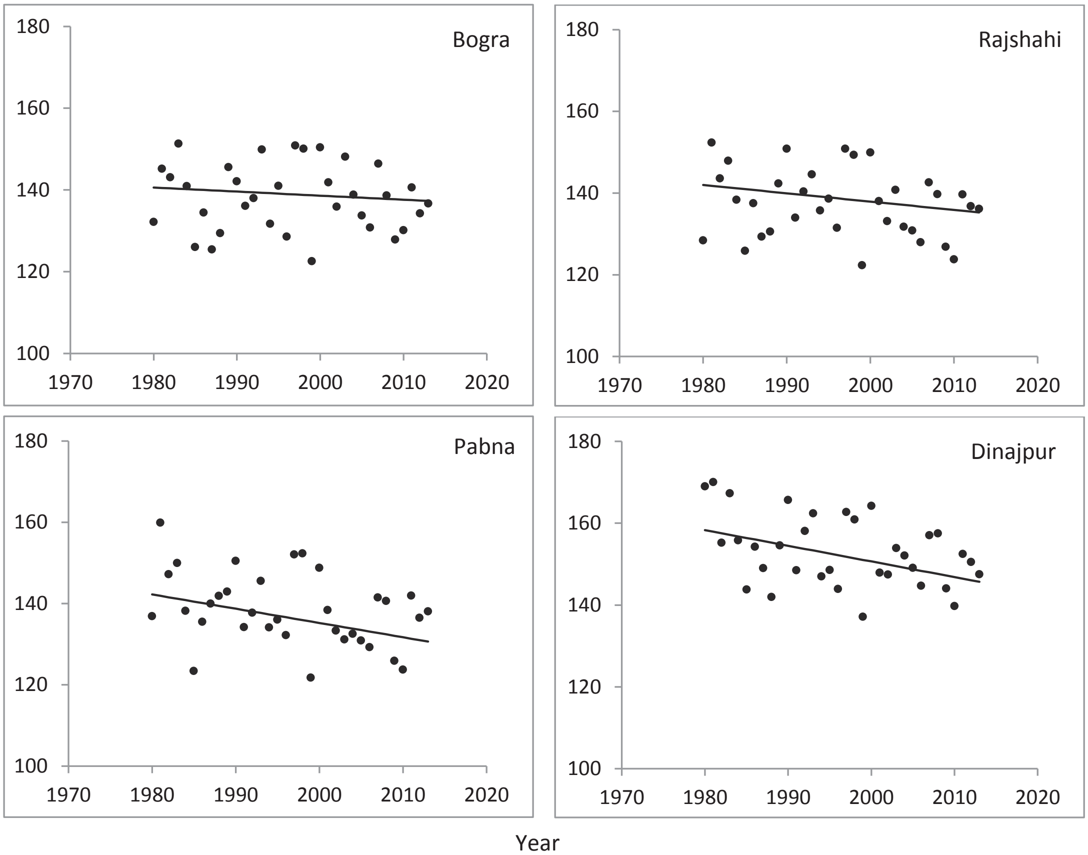

Fig. 2.4 Sen's slope of estimated total growing days of *Boro* rice at four Northwest districts of Bangladesh.

2.3.3. Trends of potential irrigation requirement for crop evapotranspiration and net irrigation requirement

As crops get a proportion of the required water from effective rainfall, irrigation requirement for the crop evapotranspiration ($\sum ET_C$–ER) is usually less than the crop water requirement or the total crop evapotranspiration ($\sum ET_C$). The estimated potential irrigation requirement for crop evapotranspiration, $\sum ET_C$–ER, showed decreasing trends in Rajshahi ($p < 0.05$), Pabna and Dinajpur (Fig. 2.5). The mean potential irrigation requirement is lowest for Dinajpur and highest for Rajshahi (Table 2.4). Effective rainfall during *Boro* growing season indicate an increasing trend in Dinajpur and decreasing trends for other Northwest districts. Also, the mean effective rainfall over the study period is much higher in Dinajpur in compared to other districts. A significant ($p < 0.05$) decreasing trends of effective rainfall were found in Bogra and Pabna.

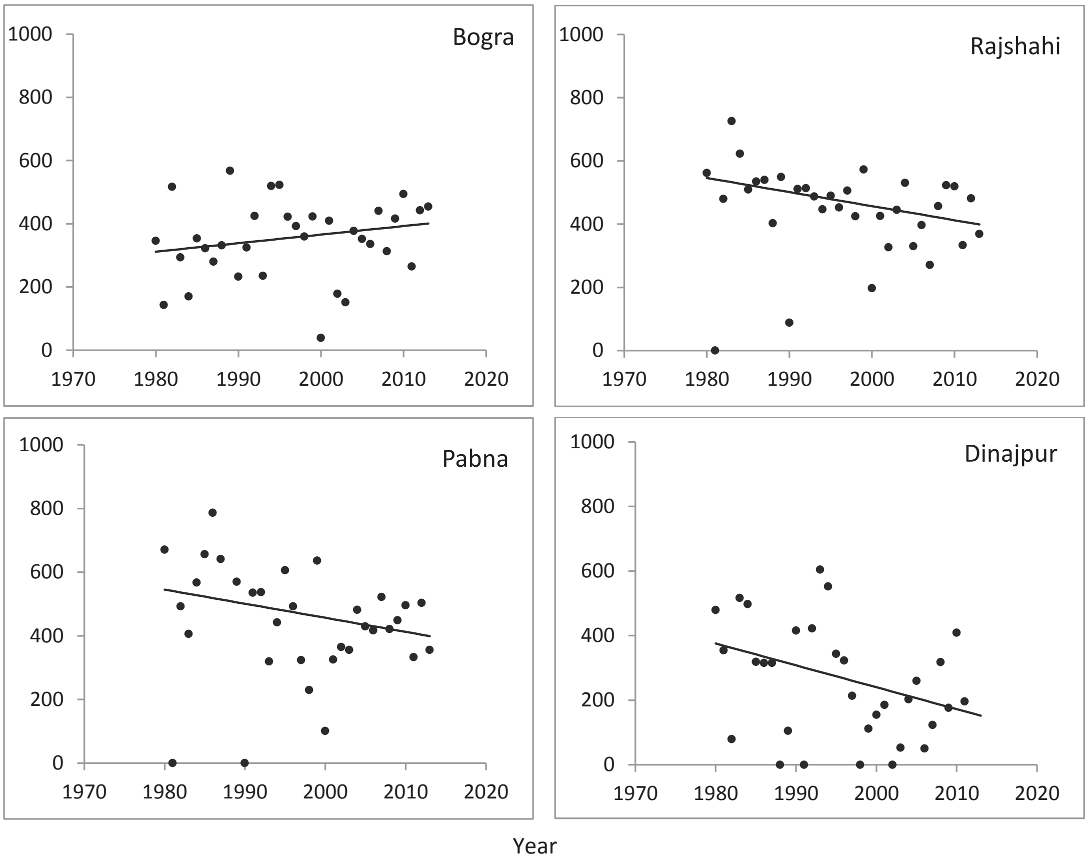

Fig. 2.5 Sen's slope of potential irrigation requirement for crop evapotranspiration, $\sum ET_C - ER$, (mm) of *Boro* rice at four Northwest districts of Bangladesh.

Table 2.4

Statistics of potential irrigation requirement for crop evapotranspiration and effective rainfall for the period of 1979-80 to 2012-13 for four Northwest districts.

District	Potential irrigation requirement for crop evapotranspiration ($\sum ET_C - ER$)			Effective rainfall (ER)		
	Mean (Standard deviation), mm	Mann-Kendall value	Sen's rate of change, mm year^{-1}	Mean (Standard deviation), mm	Mann-Kendall value	Sen's rate of change, mm year^{-1}
Bogra	348 (123)	1.22	2.70	290 (128)	–**2.19***	–5.00
Rajshahi	442 (143)	–**2.08***	–4.45	231 (145)	–0.95	–1.52
Pabna	438 (179)	–1.32	–4.42	288 (195)	–**2.34***	–5.24
Dinajpur	253 (177)	-1.70^{+}	–6.78	417 (174)	0.32	1.38

* sign indicate significant at 0.05 level of significance.

Due to percolation loss from the crop field and water requirement for land preparation and nursery, the net irrigation requirement ($\sum ET_C$–ER+PL+N&LP) of *Boro* rice is always higher than the potential irrigation requirement of crop evapotranspiration ($\sum ET_C$–ER). The mean net irrigations over the study period (average of 33 years) for *Boro* rice were 1126, 1164, 1165 and 1114 mm for Bogra, Rajshahi, Pabna and Dinajpur, respectively. The net irrigation showed a significant decreasing trends in Pabna and Dinajpur districts, and insignificant trends in Bogra and Rajshahi districts (Table 2.5). In comparison to other districts, the mean net irrigation requirement in Dinajpur is comparatively lowest with highest rate of decrease of net irrigation requirement over the study period.

Table 2.5

Statistics of net irrigation requirement and percolation amount for the period of 1979-80 to 2012-13 for four Northwest districts.

District	Net irrigation requirement ($\sum ET_C$–ER+PL+N&LP)			Percolation loss (PL)		
	Mean (Standard deviation), mm	Mann-Kendall value	Sen's rate of change, mm year^{-1} (total change, mm)	Mean (Standard deviation), mm	Mann-Kendall value	Sen's rate of change, mm year^{-1}
Bogra	1126 (106)	–1.2	–0.57 (–18.81)	588 (34)	–0.86	–0.40
Rajshahi	1164 (125)	–1.6	–3.50 (–115.5)	574 (34)	–1.60	–1.02
Pabna	1165 (170)	**–2.3***	–6.17 (–203.61)	576 (33)	**–2.11***	–1.32
Dinajpur	1114 (146)	**–2.6****	–7.19 (–222.89)	627 (30)	–1.69^{+}	–1.07

+, * and ** signs indicate significant at 0.10, 0.05 and 0.01 level of significance, respectively.

2.4. Discussion

2.4.1. Recent climate change impact on reference crop evapotranspiration

The main aim of this paper was to estimate recent changes in crop water requirement. Results show that, due to climate change, the reference crop evapotranspiration has reduced over the last three decades. The increase in minimum and maximum temperature would under non-altering conditions contribute to increases in the reference crop evapotranspiration (ET_o). However, changes in other climatic parameters in the dry season lead to a decrease in the ET_o. Especially, significantly increasing relative humidity and decreasing wind speed and sun shine hours during the dry months (see Appendix A) are contributing to a significant decrease in ET_o. The results of this study are consistent with the study of Chattopadhyay and Hulme (1997) who reported a reduced ET_o in recent decades over the Indian region despite a general increase in temperature. Their study indicated that, increasing relative humidity and decreasing solar radiation are important factor for decreasing trends of ET_o. Also, the study by Xu et al. (2006) in the Changjiang river catchment of China has showed that both pan evaporation and reference evaporation have significant ($p < 0.05$) decreasing trends, despite significantly increasing air temperature, because of significant decreasing trends in wind-speed and net radiation. You et al. (2007) has also found a decreasing trend of annual and seasonal potential evapotranspiration in the Yarlung Zangbo river basin, especially after 1980s, and most in winter and spring. Annual actual evapotranspiration in the Haihe river basin of China has also exhibited decreasing trends (Gao et al., 2012).

The result of our study is also consistent with Mojid et al. (2015) who also found decreasing trends of ET_o during 1990–2010 for Bogra and Dinajpur district of Bangladesh. Their study also indicated that, a change in ET_o is highly ($p < 0.01$) correlated with net radiation in the dry months than compare to temperature. Thus, if ET_o estimation considers only the changes in temperature then it could be far different from the actual change which involves changes in other climatic parameters. The rate of decrease of reference crop evapotranspiration is comparatively high during the *Boro* growing season, from January to May. A highly decreasing sun shine hours and a highly increasing relative humidity could be observed during *Boro* growing season than compare to other months of the year. The decrease in sun shine hours could be because of increasing cloud coverage in respective months. Increasing cloud coverage not always decrease the surface temperature of Earth by reducing incoming solar radiation, as the anthropogenic increase in temperature is mainly because of greenhouse effect of the atmosphere which traps the heat, but necessarily affects the plant system and decreases the reference crop evapotranspiration. A review by Wild (2009) indicates a widespread decrease in solar radiation during 1950s to 1980s, not only because of cloud but also changes in aerosol emission accelerated by economic development and air pollution. This study shows that such potential anthropogenic decrease in surface solar radiation can potentially decrease evapotranspiration despite ongoing global warming.

2.4.2. Recent climate change impact on potential crop water requirement

The crop-coefficient at different stages of crop growth and the duration of the different growing stages affect the amount of water required by a crop. The estimated changes in growth stage days of *Boro* rice are almost identical in all four districts (Fig. 2.4). *Boro* rice is transplanted during early January. So, the initial stage of *Boro* rice in the Northwest Bangladesh was usually affected by an insignificant decreasing minimum and a significant decreasing maximum temperature in January. Later stages were mainly affected by a significant increase in minimum and an insignificant change in maximum temperature from February and later on. Overall, the total growth stage days was decreasing due to increase in temperature during vegetative, flowering and mature stages. On an average for the Northwest Bangladesh, the growing period decreased by 5.7 percent over the study period. The study by Rani and Maragatham (2013) shows that elevated temperature of 2 °C and 4 °C results in a 6 day and 12 day shortening to reach maturity of *Kharif* rice. However, the study of Shahid (2010) figures out that only the shortening of irrigation period of *Boro* rice due to future climate change in the Northwest Bangladesh, without considering changes in ET_o will not cause appreciable change in total irrigation water demand. However, this study shows that, the potential crop water requirement ($\sum ET_C$) in the Northwest districts are significantly reducing due to the combine impacts of decrease in ET_o and a shorter growing season. The potential crop water requirement is showing the highest rate of decrease for Pabna and the lowest rate of decrease for Bogra district. Pabna showed a high decreasing rate of growing period (0.351 day year^{-1}) compared to Bogra (0.099 day year^{-1}), which is mainly because of changes in maximum and minimum temperature in the *Boro* growing period in those districts. Thus, considering both the changes in ET_o and growing days, a highest rate of decrease of potential crop water requirement is logical for Pabna. On an average, the potential crop water requirement by *Boro* rice during last three decades has been decreased by 24.43 percent in the Northwest Bangladesh.

2.4.3. Recent climate change impact on potential irrigation requirement for crop ET and net irrigation requirement

Both changes in magnitude and distribution of rainfall affect the amount of rainfall that can be effectively utilized by crops. The estimated effective rainfall during *Boro* growing season from daily rainfall data over the study period indicate a reduction for Bogra, Rajshahi and Pabna, and an increase for Dinajpur. The potential irrigation requirement for crop evapotranspiration, $\sum ET_C$–ER, in Bogra showed increasing trends mainly because of a combination of less decreasing rate (2.75 mm year^{-1}) of potential crop water requirement compared to other districts and a significant decreasing ($p < 0.05$) effective rainfall (5.0 mm year^{-1}) during *Boro* growing period. While in Pabna, though the rate of decrease of effective rainfall is high (5.24 mm year^{-1}), potential irrigation requirement for crop still showed decreasing trend, because of comparatively high rate of decrease of potential crop water requirement (9.48 mm year^{-1}). An increasing trend of effective rainfall (ER) accelerated the rate of decrease of potential irrigation requirement for crop evapotranspiration ($\sum ET_C$–ER) compared to potential crop water requirement ($\sum ET_C$) in Dinajpur only. Thus, the high variations in potential irrigation requirements among different districts are because of high variations in changes in effective rainfall during the *Boro* growing season. The zero potential irrigation requirement for crop

ET indicates more effective rainfall than crop evapotranspiration, i.e. $ER \geq \sum ET_C$. More incidents of zero potential irrigation requirement in Dinajpur compared to other districts indicate comparatively better effective rainfall occurrences in Dinajpur.

For most of the districts, the net irrigation requirement ($\sum ET_C - ER + PL + N\&LP$) showed a higher rate of decrease than the potential irrigation requirement of crop evapotranspiration ($\sum ET_C - ER$), because of decreasing percolation loss from the crop field. Due to the shortening of the growth cycle (phenological accelerated growth due to GDD impact) less days are available in which percolation can occur, and thus percolation loss decreased over time. For Rajshahi, a lower rate of decrease of net irrigation requirement than the potential irrigation requirement for crop ET, while percolation loss showed decreasing trends could be because of an increase in potential water requirement during nursery or land preparation. Thus, the Mann-Kendall test value showed a significant ($p < 0.05$) decrease in potential irrigation requirement for crop evapotranspiration, but insignificant for net irrigation requirement in Rajshahi. Overall, a significant decreasing trend of net irrigation requirement in Pabna and Dinajpur indicates a better evolving situation than an insignificant decreasing trend of net irrigation requirement in Bogra and Rajshahi from water requirement perspective. Overall, the net irrigation requirement by *Boro* rice during last three decades has been decreased by 11.19 percent in the Northwest Bangladesh.

The estimated values of net irrigation requirement using CropWat can differ from the actual field situation because of changes in variety of crop, water application method, specific soil condition, and crop density in the field. However, the trends are not very sensitive to those changes. The planting date of the crop also affects the net irrigation requirement. As the purpose of this study was not to identify most suitable planting time, rather to identify impacts of climate change, the most common standard planting time has been used for the analysis.

For identifying impacts of future climate change on water demand of crops, good prediction of future climatic parameters, including not only temperature but also solar radiation, humidity and wind-speed are important. Otherwise, the management decision based on the future scenarios of water demand could be misleading. Also, the shortening of growth stage could be an important aspect to consider for future agricultural and water management decisions, including the possibility to increase the cropping intensity in some areas.

This study has not investigated the changes in water requirements as affected by the changes in atmospheric CO_2 concentration. The global CO_2 concentration increased from 339 ppm to 396 ppm during 1980 to 2013 (Tans and Keeling, 2016). Several studies indicate that, increase in CO_2 concentration decreases evapotranspiration and increases water use efficiency (Baker and Allen Jr, 1993; Morison, 1985). Since, water requirements by *Boro* rice in the Northwest districts of Bangladesh are showing decreasing trends without considering the impacts of elevated CO_2 in the atmosphere, consideration of impacts of changes in CO_2 concentration in the atmosphere is probably not contradictory, but could strengthen the conclusion of this study.

Several studies indicate that extensive *Boro* rice cultivation is responsible for recent depletion of groundwater levels in the Northwest Bangladesh that cause a prolonged absence of groundwater within the operating range of shallow tube-wells during dry season, without a clear indication about whether only the changes in the amount of *Boro* cultivation area or both the changes in cultivation area and water requirement have caused this problem. This study clearly showed that, during the last few decades, the overexploitation of groundwater in the Northwest Bangladesh is not because of any increase in actual crop water requirement or net irrigation need, but could be because of expansion of the *Boro* cultivation area and low recharge potential due to urbanization. For better water management of this region, especially to conserve groundwater resources, only crop water demand management would not be a good solution. Rather, a combined policy that takes into account the crop water demand management, the crop area and pattern management and conservation of recharge potential areas could be a better solution.

2.5. Conclusion

This study assessed the recent trends of water requirement of *Boro* rice to understand the impacts of regional climate change on local agricultural water demand during dry season. The potential crop water requirement or the total crop evapotranspiration ($\sum ET_C$) by *Boro* rice during last three decades have been decreased by 24%, at an average rate of 5.9 mm year^{-1} and the net irrigation requirement decreased by 11%, at an average rate of 4.4 mm year^{-1} in the Northwest Bangladesh. Hence, the consequence of recent climate change on water demand is not adverse in relation to agricultural water demand. Rather, changes in climatic conditions during the last few decades have not only decreased the climatic water requirement (ET_O), but also the potential irrigation required for crop evapotranspiration and the net irrigation requirement of *Boro* rice during dry season. Therefore, this study supports that climate change can reduced water demands in some regions because of positive changes in humidity, wind-speed and/or sun-shine hours, regardless of global warming. Management decisions related to agriculture need to consider recent changes in water requirement to beneficially utilize the changes.

CHAPTER 3

Future changes in water requirements of *Boro* rice in the face of climate change

ABSTRACT

Understanding future changes in crop water requirements and irrigation demand in the context of climate change is essential for long-term water resources management and agricultural planning. This study investigates the impacts of climate change on future water requirements of dry season *Boro* rice. Climate scenarios for four Northwest districts of Bangladesh were constructed from the outputs of five global circulation models using a combination of statistical downscaling and bias correction. The generated climate data were used as input for CropWat to estimate water requirements of *Boro* rice for 2050s and 2080s (using 30 year average climate data). Reference crop evapotranspiration (daily ET_o) is increasing in the future, mainly due to higher temperatures. Potential crop water requirement ($\sum ET_C$) of *Boro* rice, however, will reduce by 6.5% and 10.9% for RCP 4.5 and 8.5, respectively for 2050s; and by 8.3% and 17.6% for RCP 4.5 and 8.5, respectively for 2080s compared to the reference period (1980–2013). $\sum ET_C$ will decrease because of a lower number of growing days due to the phenological response of rice to higher temperatures. Low rainfall accessibility under a shortened *Boro* season leads to an increase in the amount of irrigation water required to satisfy crop evapotranspiration demand. Although daily water requirements will increase, the total net irrigation requirement of *Boro* rice will decrease by 1.6% in 2050s and 7.4% in 2080s for RCP 8.5 scenario on average for all models and districts. Estimated net irrigation requirements showed high variations for different climate models, mainly due to a high variation in the projected rainfall. For improved water management planning, close monitoring and periodic evaluations are necessary to understand future directions of change in rainfall amounts and distribution.

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3.1. Introduction

Human activities since industrialization have resulted in increased CO_2 emissions causing anthropogenic climate change. Global surface temperature change is projected to likely exceed 1.5 °C for RCP 4.5 and 2 °C for RCP8.5 by the end of the 21st century, relative to the average from 1850 to 1900 (IPCC, 2013). In addition to global warming, climatic variables such as precipitation, solar radiation and wind speed will change. Although climate change is a global phenomenon, there are large regional differences in the impacts. Projections show large regional variations in future climate change. Hence, the consequences of climate change will also be regionally specific. Bangladesh is considered as one of the most vulnerable countries to the impacts of climate change (IPCC, 2007). Not only flood risks will increase, but also projected increases in rainfall variability and lower dry season rainfall will affect future crop production. Moreover, climate change is likely to affect future crop water requirements. Irrigation requirement is very sensitive to climate change (Schlenker et al., 2007) and particularly sensitive to changes in precipitation, and temperature (Frederick and Major, 1997). The change in annual mean water requirements is strongly associated with the change in temperature (McCabe and Wolock, 1992). Estimations of evapotranspiration using the *Penman–Monteith* formula are more sensitive to temperature and humidity compared to wind speed and sunshine hours (Eslamian et al., 2011). Yu et al. (2002) indicated that solar radiation is the most sensitive and wind-speed the least sensitive variables of the modified Penman formula. However, the use of all climatic variables to estimate crop water and irrigation requirement could provide a better insight of consequences of climate change on agricultural water requirement. As the consequences of climate change are regionally specific, studies conducted at large spatial scales (e.g. global, continental, or basin) often lack sufficient details to understand the impacts of climate change on regional water management. A study of potential impacts of inevitable climate change on future water requirements, using several global circulation model outputs to estimate water requirements of the major crop of a region, is important from local water management perspective (Woznicki et al., 2015).

Future changes are always uncertain. Therefore, it is difficult to predict the future climate. Using a range of possible future climate change scenarios, rather than a single projection is one way of dealing with uncertainties (Asseng et al., 2009). As scenarios provide information for different possible future changes, it can provide a better insight rather than a single prediction. Global Circulation Models (GCMs) are the basis for generating future climate change scenarios and are used for regional impact studies after applying downscaling techniques to identify the regional climate variables (Smith and Pitts, 1997). GCMs consider a wide range of processes, including atmosphere, ocean and land surface processes that characterize the climate system and are used to examine the impact of increasing greenhouse gas concentrations on global climate (Houghton et al., 1990). GCMs are the best source of information about regional climate change estimating changes in meteorological variables in regional climate in grid boxes of typically 3 or 4 degrees in latitude and as much as 10 degrees in longitude (Smith and Pitts, 1997). However, GCMs do not always accurately represent the climate at a regional scale and misrepresent the seasonal patterns of precipitation in many cases (Robock et al., 1993). Moreover, not all GCMs give a realistic scenario for a particular region or country. Hence, it is wise to use several GCMs to generate future climate change scenarios for impact studies. Use of a larger number of GCMs' outputs better represent the structural uncertainty in climate models (Tebaldi and Knutti, 2007).

Climate change induced changes in the crop water requirements is a major concern for Bangladesh. Bangladesh is facing challenges of rapid population growth, declining cultivable land, inadequate water availability during the dry season, declining ground water table (Ahmad et al., 2014; Salem et al., 2017) and extreme events such as floods and droughts. The possible impacts of climate change could add additional pressure to existing problems. Bangladesh will need to produce more food for its increasing population. Therefore, cultivation of more irrigated high yielding crops could solve the problem. However, a high water demand or lack of water availability due to climate change may not support the expansion of irrigated crop cultivation. Groundwater levels in the Northwest part of Bangladesh are declining due to increasing groundwater extraction for irrigation in the dry season and recurrent droughts (Shahid and Hazarika, 2010). Considering these different aspects, it is important to identify the possible future changes in water requirements of dry season crops to understand the consequences of climate change on the longer run and at regional scale.

Boro rice is the major dry season crop of Bangladesh, which requires irrigation from January to April. The annual average rainfall in Northwest Bangladesh ranges from 1400 to 2000 mm, with 93 percent of rainfall occurring from May to October, and only about 6 percent during *Boro* rice growing season (Shahid, 2010). *Boro* rice thus fully depends on irrigation. The total amount of water used for crop agriculture has increased substantially over the last few decades because of intensive irrigated agriculture, especially in the North-western part of Bangladesh. Intensive irrigated agriculture is resulting in water shortages during dry periods (Shahid, 2008). The excessive use of groundwater for irrigation, along with declining groundwater recharge potential due to urbanization, are causing a drop in groundwater levels throughout the country. A study by Dey et al. (2017) indicates a declining trend in groundwater levels in Northwest Bangladesh, with most depletion in Rajshahi followed by Pabna, Bogra, Dinajpur and Rangpur because of increased *Boro* cultivation area and reduced recharge. Now, it is essential to understand the future possible changes in agricultural water requirements to improve water resources management in Bangladesh.

Several studies have assessed the impact of climate change on reference crop evapotranspiration (ET_O) in Bangladesh. The study by Mojid et al. (2015) indicated a decreasing trend of ET_O during most of the months of the year for the period 1990–2010 in two Northwest districts. From 1980 to 2013, water requirements of *Boro* rice have decreased because of increases in humidity and decreases in wind-speed and sunshine hours, despite a warming of the climate in Northwest Bangladesh (Acharjee et al., 2017a). Shahid (2010) argued that there will be no appreciable changes in total irrigation water requirement of *Boro* rice due to climate change in Northwest Bangladesh. However, more in-depth studies are required to assess the consequences of climate change on crop water requirements and irrigation requirements during dry season, based on different climate scenarios.

For a complete understanding of the impacts of climate change on agricultural water requirements, the study of reference crop evapotranspiration is insufficient. Changes in temperature not only affect evapotranspiration, but also affect the length of the growing season. Estimations and analyses of changes in potential crop water requirements, number of growing days, potential irrigation requirements for crop evapotranspiration and net irrigation requirements will expand our understanding of the impacts of climate change on regional water resources management. So in this study, in which we aim to quantify the impacts of future climate change on water requirements of *Boro* rice, we applied the CropWat model in combination with downscaled and bias corrected GCM outputs of different climatic parameters, for four Northwest districts. This study will be beneficial for local water managers, agriculturists, researchers and policy makers in understanding the future consequences of climate change and developing adaptation strategies for local agricultural water management.

3.2. Materials and method

3.2.1. Study area

Only five of the 16 administrative districts in Northwest Bangladesh have a weather station. Four of these, namely Bogra, Rajshahi, Pabna and Dinajpur were included in this study. The Northwest region extends from 23°47' N to 25°50' N latitude and from 88°01' E to 89°48' E longitude. This part of the country belongs to the sub-humid agro-climatic class. As the total annual evapotranspiration is equal to annual rainfall in some places, this region is defined as very close to dry (Shahid et al., 2005). Annual rainfall varies from 1400 to 2000 mm. Meteorological drought is a very common phenomenon during the dry months in this region (Shahid and Behrawan, 2008). Recent drought events have had a severe impact on the economy of the whole country. The Northwest region, with its prolonged dry season, was affected more severely than the rest of the country (Shahid, 2008). The economy of this area is mostly agriculture based, with 75% of the land under crop cultivation. About 31% of the land is used for single cropping, 56% for double cropping and 13% for triple cropping (Shahid and Hazarika, 2010). *Boro* rice is the main dry season crop in the study area, and is cultivated on more than 70% of the cultivable area from December to May.

3.2.2. Data collection

Crop data related to dry season *Boro* rice has been collected from Bangladesh Agricultural Research Institute (BARI). Collected data on dry and wet crop co-efficient (Kc) values for different growth stages (nursery, land preparation, initial, mid-season and late season), rooting depth, crop height and critical depletion factor have been used as input into the CropWat model. Soil data on available soil moisture, maximum rainfall infiltration rate, maximum rooting depth, initial soil moisture depletion, initial available soil moisture, drainable porosity, critical depletion for puddle cracking, maximum percolation rate after puddling, water availability at planting and maximum water depth, were standardized for a medium average soil for the study districts from FAO standard soil parameter values.

3.2.3. Climate models and scenarios

Five General Circulation Models (GCMs) and two emission scenarios (RCPs) were used to construct future climate scenarios. Maximum and minimum temperatures, rainfall, wind speed and solar radiation for the time series of 2035–2065 and 2065–2095 were prepared. The GCMs used were the

CNRM-CM5 model, described as developed by CNRM-GAME (Centre National de Recherches Météorologiques—Groupe d'études de l'Atmosphère Météorologique) and Cerfacs (Centre Européen de Recherche et de Formation Avancée) to contribute to phase 5 of the Coupled Model Inter-comparison Project (CMIP5) that includes atmospheric, ocean, land surface scheme and sea ice models (Voldoire et al., 2013); the **EC-Earth** model, is a seamless (forecasting and climate change studies into a single framework) Earth System Model (Hazeleger et al., 2010); the **HadGEM2-ES** model, is as a coupled Earth System Model that was used by the Met Office Hadley Centre for the CMIP5 centennial simulations; the **IPSL-CM5A-LR** model, includes 5 model components representing the Earth System climate and its carbon cycle: LMDz (atmosphere), NEMO (ocean, oceanic biogeochemistry and sea-ice), ORCHIDEE (continental surfaces and vegetation), and INCA (atmospheric chemistry), coupled through OASIS; the **MPI-ESM-LR** model, is a comprehensive Earth-System Model that consists of component models for the ocean, the atmosphere and the land surface. These models were selected for this study because of their important criteria in evaluating the impacts of climate change, such as ocean-atmosphere couple, their documentation in literature, multi-century simulation capability, and participation in the Coupled Model Inter-comparison Project (CMIP) (Barrow et al., 2004).

Two different emission scenarios, RCP 4.5 and 8.5 were used in this study. RCP 4.5 represents stabilization without overshoot pathway to 4.5 W/m^2 (~650 ppm CO_2 eq.) at stabilization after 2100 and RCP 8.5 represents rising radiative forcing pathway leading to 8.5 W/m^2 (~1370 ppm CO_2 eq.) by 2100 (Van Vuuren et al., 2011). These two RCPs were selected for this study because they represent realistically low and high future climate change scenarios.

A statistical downscaling technique was used to generate the future climate data for maximum and minimum temperatures, rainfall, wind speed and solar radiation. The downscaled model data were bias corrected by comparing the past model data with historical observed data. For bias correction, the monthly average WATCH Forcing data (Weedon et al., 2011) of maximum and minimum temperatures, sunshine hours and wind speed and monthly total WATCH Forcing data of rainfall were compared to monthly observed station data. Since, the relative humidity predictions were not available from the GCM outputs, they were estimated following the ratio between actual water vapour pressure and saturation vapour pressure. The actual and saturation vapour pressure is a pure function of temperature and can be calculated by a common empirical interpolation function (Holbo, 1981; WMO, 1979). For humid temperate climates, when temperature is at its daily minimum, water vapour is saturated. Hence, the general assumption to estimate relative humidity from temperature data is to consider dew temperature as equal to the minimum temperature of the day (Eccel, 2012).

3.2.4. Estimation of growth stage days

The length of the four distinguished growth stages of *Boro* rice were estimated for different climate scenarios following the growing degree-days (*GDD*) method. The following equation was used to estimate *GDD*:

$$\boldsymbol{GDD} = [(\boldsymbol{T_{max}} + \boldsymbol{T_{min}})/\boldsymbol{2}] - \boldsymbol{T_{base}} \quad (3.1)$$

Where, T_{max} is the maximum temperature, T_{min} is the minimum temperature , and T_{base} is the base temperature. First, the GDD was estimated for four study districts under five climate models and two scenarios. Later, the growth stage duration was estimated from growing degree-days and accumulated heat values at the end of each stage.

$$\textit{Growth stage duration (days)} = \frac{\textit{Accumulated heat value at the end of the stage } (°C)}{\textit{GDD for the corresponding period } (°C)} \quad (3.2)$$

The accumulated heat values (for the base temperature of 15 °C) at the end of the growth stages of *Boro* rice in the Northwest zone of Bangladesh were obtained from the studies of Mahmood (1997). The accumulated heat values at the end of initial, vegetative, flowering and maturing stages for Bogra, Rajshahi and Pabna were 80, 528, 1052 and 1291 °C, respectively and for Dinajpur were 80, 515, 1032 and 1273 °C, respectively. The method of growing degree-days can consistently predict the growth stage days (Miller et al., 2001).

3.2.5. Estimation of water requirements

CropWat model developed by FAO was used to estimate water requirements of *Boro* rice. CropWat is used to compute crop water requirements and irrigation requirements based on climate, crop and soil data. It has been used extensively as a decision support tool in an international context to calculate regional irrigation requirements (Clarke et al., 2001). This model has also been successfully applied to evaluate impacts of climate change on water requirements in several previous studies (Chowdhury et al., 2013; Doria et al., 2006; Doria, 2010; Shrestha et al., 2013).

The FAO *Penman-Monteith* equation was used to determine reference crop evapotranspiration for different combinations (5 models, 2 scenarios and 4 stations) from 2035 to 2095. The statistical significance of future trends in reference crop evapotranspiration (daily ET_o) for the periods 2035–2065 and 2065–2095 was tested using the non-parametric Mann-Kendall test. In a Mann-Kendall test, the data are evaluated as an ordered time series and each data value is compared to all subsequent data values to estimate the Mann-Kendall statistic. The probability associated with the Mann-Kendall statistic was computed to quantify the statistical significance of the trend.

Water requirements of *Boro* rice were estimated in CropWat using statistically downscaled bias-corrected daily climate data from GCMs outputs. The following equation represents the estimated net irrigation requirement:

$$\textit{Net irrigation requirement} = \sum ET_C - ER + PL + N\&LP \quad (3.3)$$

Where, $\sum ET_C$ is the potential crop water requirements or total crop evapotranspiration, ER is the effective rainfall during *Boro* growth duration, PL is the amount of percolation loss, and N&LP is the amount of water required for nursery and land preparation. $\sum ET_C$–ER denotes the potential irrigation requirement for crop evapotranspiration.

Water requirements were estimated for 4 districts, 5 models and 2 RCPs for 2050s (average of 2035–65) and 2080s (average of 2065–95). *Potential crop water requirement* is calculated as total crop evapotranspiration ($\sum ET_C$) during the crop growing period and takes into account the changes in the length of the growing season. The *Potential irrigation requirement for crop evapotranspiration* is the total crop evapotranspiration amount in excess of effective rainfall, i.e. $\sum ET_C - ER$. Here, effective rainfall is the amount of rainfall that is effectively added and stored in the soil for later use by the crop, and is derived as a simulation output from CropWat. *Net irrigation requirement* takes into account the amount of irrigation required for crop evapotranspiration, percolation loss and water required for nursery and land preparation. All values are derived from CropWat simulations.

In order to assess the climate change impacts on the water requirements of *Boro* rice, the influence of management practices were excluded by modelling the rice growth in CropWat under a standardized schedule that provides irrigation water as required. The crop co-efficient values under dry condition were 0.7, 0.3, 0.5, 1.05 and 0.65, and wet condition were 1.2, 1.05, 1.1, 1.2 and 0.95 for nursery, land preparation, initial, mid-season and late-season, respectively. The transplanting date of *Boro* rice was taken as 10^{th} of January for all estimations (i.e. for base period, 2050s and 2080s). The scheduling criteria to estimate the net irrigation requirement was to provide irrigation at 5 mm water depth above ground with a refill to 100 mm standing water. The estimation procedure of percolation amount, water required for nursery and land preparation, etc. for a standard schedule in CropWat were discussed in detail in the study by Acharjee et al. (2017a).

3.3. Results

3.3.1. Future changes in reference crop evapotranspiration

All models show increasing trends of reference crop evapotranspiration for most of the dry months for both the 2035–65 and 2065–95 time series in Rajshahi (Table 3.1). The HadGEM2-ES model shows a more pronounced increase of ET_o in comparison to other model estimates. For the 2065–95 time series, HadGEM-2ES model returns higher increasing trends of ET_o for RCP 8.5 scenario in comparison to RCP 4.5 scenario. For RCP 4.5 scenario, the trends of ET_o are more pronounced for 2035–2065 in comparison to the trends during 2065–95. But, for RCP 8.5 scenario it is the opposite, with more pronounced increases of ET_o for the period 2065–95 compared to those for the 2035–65 time series. Other climate models mainly show non-significant trends, but similar kind of characteristics; e.g. for RCP 8.5, higher values of Mann-Kendall trends during 2065–2095 in comparison to the trends of 2035–65 time series. Similar results have been found for trends of reference crop evapotranspiration for Bogra, Pabna and Dinajpur (see Appendix B, Table B1–B3).

The results also indicate that, for a moderate climate change scenario (RCP 4.5) the rate of increase in reference crop evapotranspiration will reduce, or even decrease in some months (e.g. CNRM-CM5, January–March) during 2065–95 in comparison to the rate of increase during 2035–65. For a rapid climate change scenario (RCP 8.5), the rate of increase in ET_o will accelerate during 2065–95. However, for both scenarios the ET_o will mainly increase in all study districts of Northwest Bangladesh.

Table 3.1

Mann-Kendall trends of estimated reference crop evapotranspiration during dry months for 2035–2065 and 2065–2095 time series in Rajshahi.

Trends during	Month	CNRM-CM5		EC-Earth		HadGEM2-ES		IPSL-CM5A-LR		MPI-ESM-LR	
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
2035 to 2065	Jan	**2.96****	0.41	1.77⁺	0.61	**2.41***	**2.28***	–1.60	0.82	**2.14***	1.26
	Feb	1.12	–0.34	1.53	0.27	**3.50*****	**2.92****	**2.24***	1.53	**2.31***	1.26
	Mar	1.29	–1.29	0.85	0.48	**2.07***	**2.35***	0.85	**2.48***	1.09	1.50
	Apr	0.99	0.68	0.99	–0.41	1.73⁺	**3.43*****	–1.22	1.87⁺	**2.79****	**2.45***
	Nov	0.85	–0.03	1.09	0.68	**2.96****	**1.97***	0.88	0.71	1.56	1.33
	Dec	**2.35***	–0.95	1.26	0.17	**3.03****	**2.99****	0.17	1.29	–0.51	1.43
2065 to 2095	Jan	–0.41	1.63	1.26	1.53	**1.97***	**4.08*****	1.12	0.17	0.51	**2.21***
	Feb	–1.43	0.92	0.17	1.87⁺	0.68	**3.40*****	0.51	0.61	0.00	1.63
	Mar	–0.27	–0.88	1.50	–0.10	0.88	**3.30*****	0.41	0.75	–0.85	1.46
	Apr	0.68	0.10	1.26	0.58	**2.07***	**2.04***	0.54	1.36	–0.37	**2.11***
	Nov	0.48	1.19	**2.55***	0.20	**2.69****	**4.69*****	**1.97***	0.92	**2.21***	0.82
	Dec	1.36	**2.55***	1.05	0.88	**2.45***	**4.49*****	0.31	–0.20	1.63	0.92

⁺, *, ** and *** signs indicate significant at 0.10, 0.05, 0.01 and 0.001 level of significance, respectively.

3.3.2. Future changes in potential crop water requirement of Boro rice

The model estimates show a decrease in potential crop water requirement ($\sum ET_C$) of *Boro* rice in all study districts for both RCP 4.5 and RCP 8.5 compared to the base period (Fig. 3.1). The potential crop water requirement was highest during the base period for all districts. Also, the potential crop water requirement is comparatively higher during 2050s (average for 2035–65 climate) than during 2080s (average for 2065–95 climate). RCP 8.5 shows a steeper decrease in potential crop water requirement in compared to RCP 4.5. Therefore, a high end climate change scenario (RCP8.5) indicates a stronger decrease in potential crop water requirements compared to a moderate scenarios (RCP4.5).

Estimates of the potential crop water requirement takes into account both the changes in reference crop evapotranspiration (ET_o) and the changes in growth period. The duration of growth stage days of *Boro* rice will reduce as a result of increased temperatures because, the rice plant matures more quickly at higher temperatures. All the estimates from different climate models show a decrease in the number of total growing days of *Boro* rice in the future for both RCP 4.5 and RCP 8.5 (Fig. 3.2). The total growing period was shorter for RCP 8.5 compared to RCP4.5 due to higher temperatures under RCP8.5.

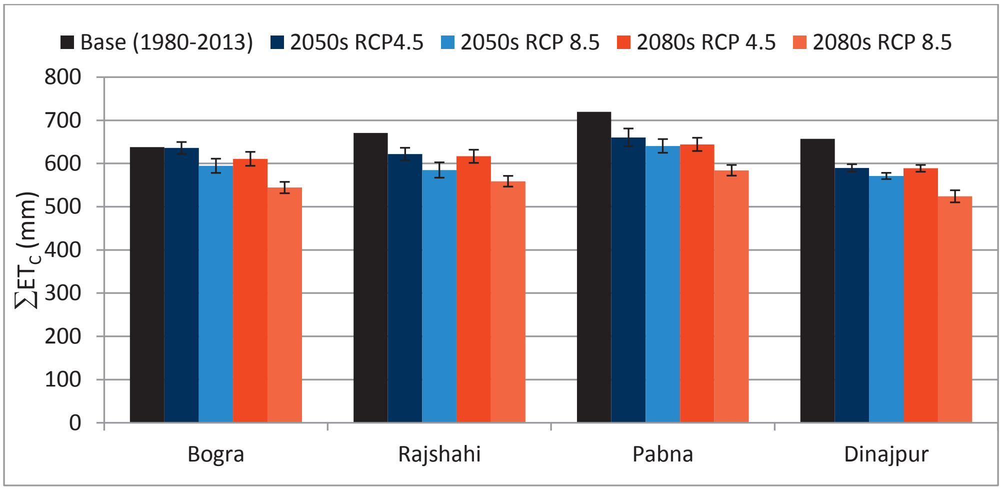

Fig. 3.1 Potential crop water requirement of *Boro* rice in four Northwest districts of Bangladesh for the base period, 2050s and 2080s using two different RCPs. Each bar show the average for five models, and error bar indicates the standard deviation of different model estimates.

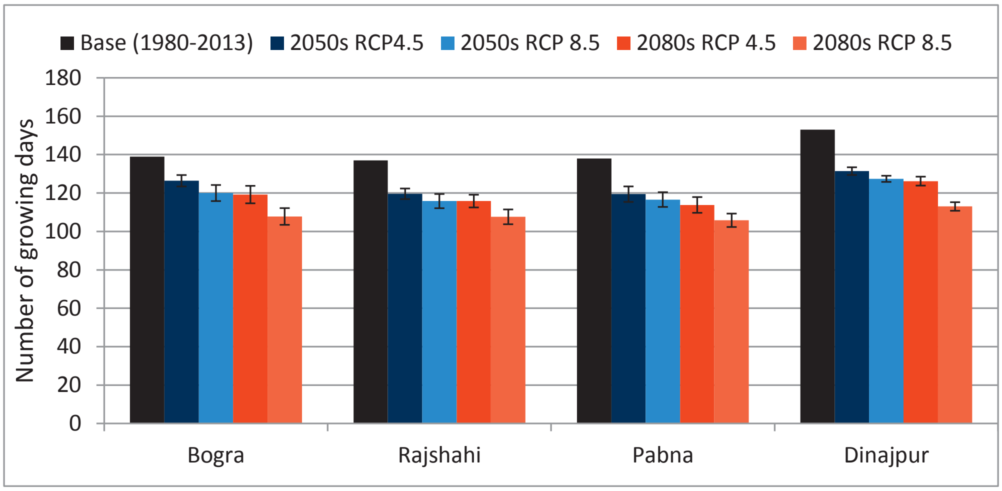

Fig. 3.2 Duration of growing days of *Boro* rice in four Northwest districts of Bangladesh for the base period, 2050s and 2080s using two different RCPs. Each bar show the average for five models, and error bar indicates the standard deviation of different model estimates.

3.3.3. Future changes in irrigation requirement of Boro rice

The model estimates indicate an increase in future potential irrigation amount required to satisfy crop evapotranspiration ($\sum ET_C$–ER) compared to the base period for both RCP 4.5 and 8.5 scenarios (Fig. 3.3). However, some variations in changes between different districts were observed. For Bogra and Dinajpur, '∑ETC–ER' showed the highest values during 2080s (2065–2095), which indicates a continuous increase till the end of the century. While for Rajshahi and Pabna, there is an increase during 2035–65, followed by a decrease during 2065–2095, which indicates a peak during the mid of the century. The variations in different districts are mainly caused by the variations in rainfall or rainfall availability during the *Boro* growing season.

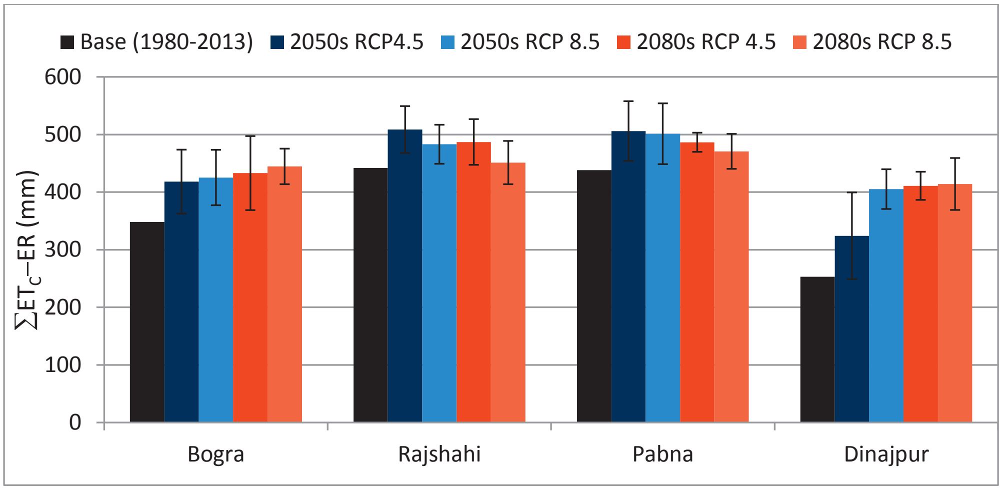

Fig. 3.3 Potential irrigation requirement for crop evapotranspiration of *Boro* rice in four Northwest districts of Bangladesh for the base period, 2050s and 2080s using two different RCPs. Each bar show the average for five models, and error bar indicates the standard deviation of different model estimates.

Analysis of monthly rainfall distribution for future climate scenarios indicates a considerable decrease in the amount of rainfall that is available during the *Boro* growing season (Fig. 3.4). High variations (see the error bars in Fig. 3.4) in available rainfall amount during the *Boro* growing season can be observed in different model estimates. These high variations in projected rainfall represent a big challenge for anticipatory irrigation and water management planning.

However, the considerable reduction of available rainfall amount during the *Boro* growing season is not only the result of reduced rainfall during the dry months. The reduction in total rice growth length has a more pronounced effect, as it shortens the total growth season with the effect that the “late periods” of high rainfall (during May) start to fall outside the rice growth period as crop growth cycles decrease (due to the described GDD effect) and the planting date is kept fixed. The green area in the graph (Fig. 3.5) indicates the approximate amount of rainfall available for *Boro* cultivation in 2080s with same planting date as now, and the red area indicates the amount of approximate rainfall that is not available for *Boro* rice cultivation in the 2080s because of shortening of growing days with fixed planting date for RCP 8.5.

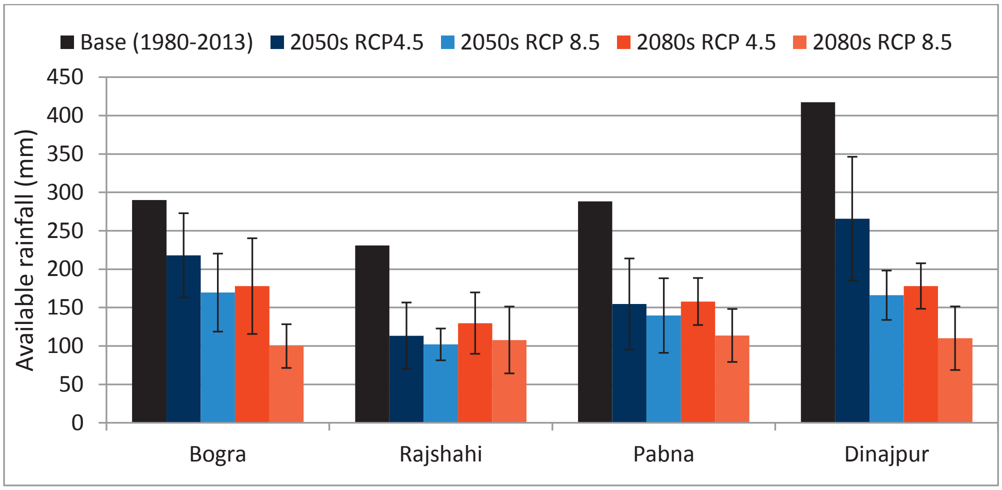

Fig. 3.4 Effective rainfall amount during *Boro* growing duration in four Northwest districts of Bangladesh for the base period, 2050s and 2080s using two different RCPs. Each bar show the average for five models, and error bar indicates the standard deviation of different model estimates.

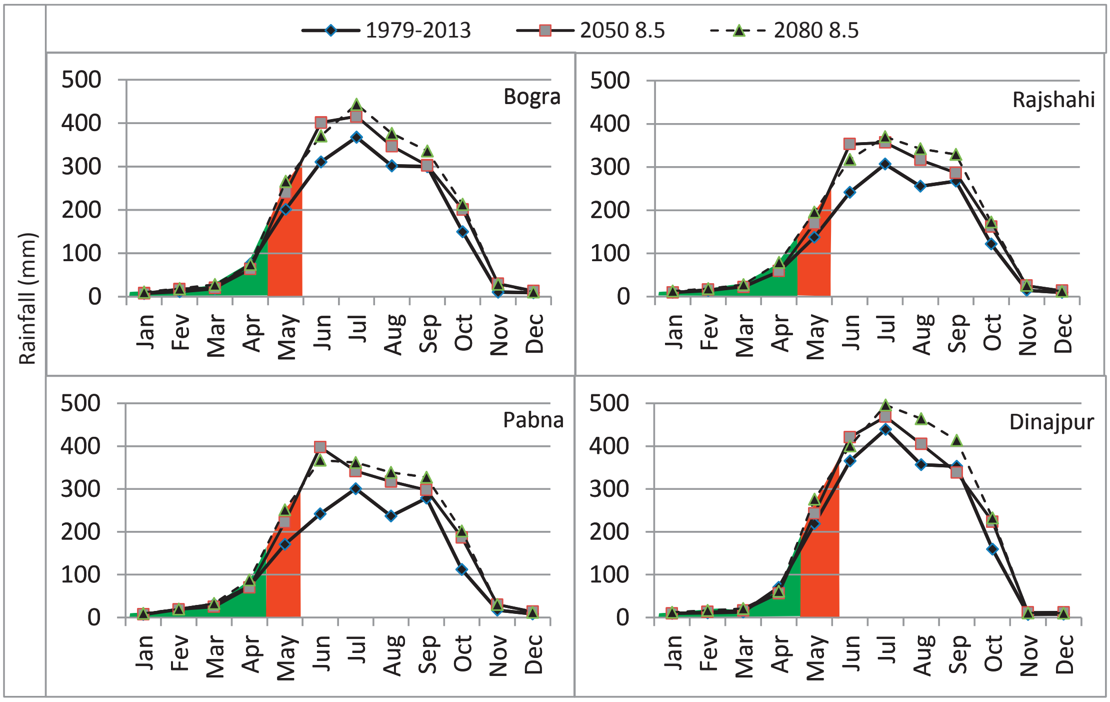

Fig. 3.5 Monthly rainfall distribution for the base period, 2050s and 2080s in four Northwest districts of Bangladesh for RCP 8.5. The green area indicates the amount of rain water available for *Boro* rice, and red area indicates the amount of rain water not available in 2080s compared to base period.

Estimations of net irrigation requirements ($\sum ET_C - ER + PL + N\&LP$) show an overall decrease in the future (Fig. 3.6). However, there are high variations in the change between the different districts, RCPs, models and time periods. For all study districts, results indicate an initial increase (i.e., during 2050s) but a later decrease (i.e., during 2080s) in net irrigation requirement for RCP 4.5, and an initial low decrease and later high decrease in net irrigation requirement for RCP 8.5. Therefore, both moderate and rapid climate change indicate a direction towards a long term decrease in the net irrigation requirements. A decreased amount of total net irrigation requirement indicates a possible reduction of percolation amounts and/or water requirements for nursery and land preparation. Further analysis indicates a decrease of total percolation during the crop growth period of *Boro* rice (Fig. 3.7). Due to a shorter duration of growth stages (phenological accelerated growth due to GDD impact) less days are available in which percolation can occur, and thus less irrigation water is required to meet that percolation.

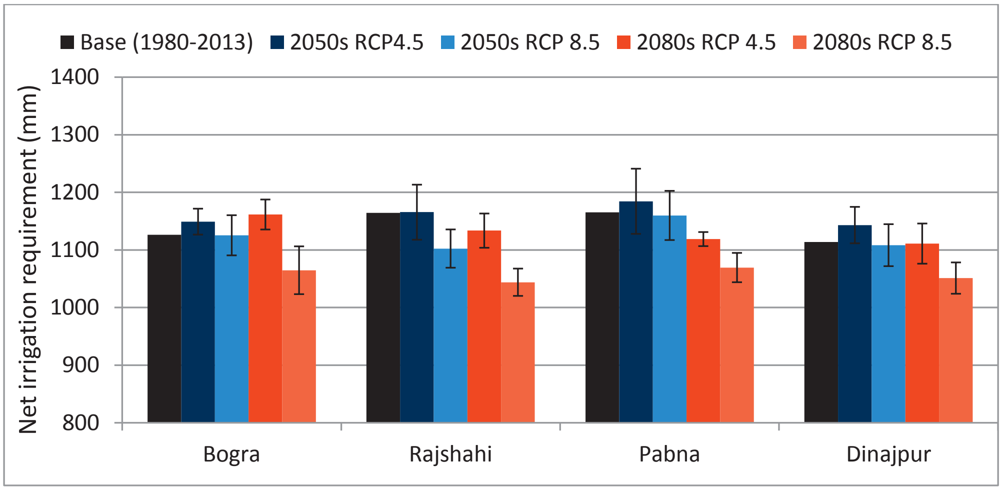

Fig. 3.6 Net irrigation requirement of *Boro* rice in four Northwest districts of Bangladesh for the base period, 2050s and 2080s using two different RCPs. Each bar show the average for five models, and error bar indicates the standard deviation of different model estimates.

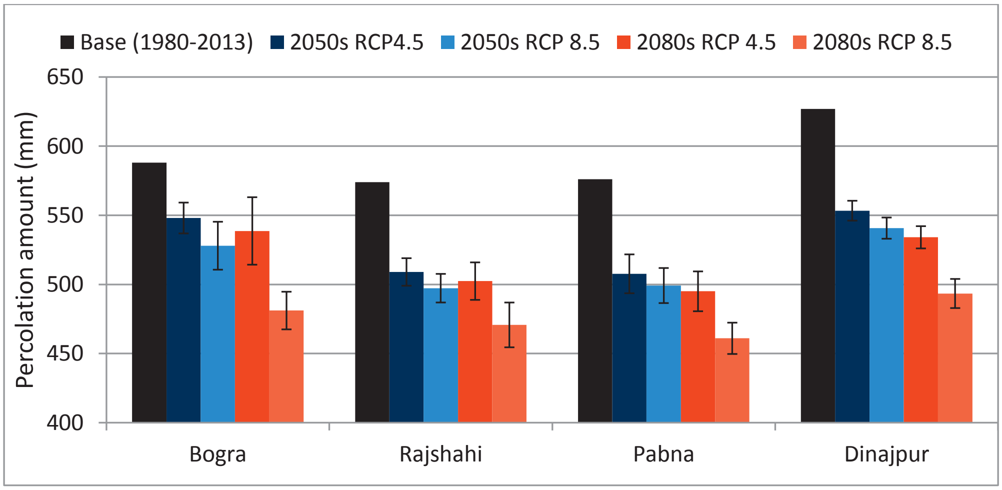

Fig. 3.7 Percolation amount during *Boro* growing season in four Northwest districts of Bangladesh for the base period, 2050s and 2080s using two different RCPs. Each bar show the average for five models, and error bar indicates the standard deviation of different model estimates.

3.3.4. Impacts of climate change on water requirement components

The impacts of changes in different climate variables on different water requirement components of *Boro* rice are shown in Fig. 3.8. A reduction in number of growing stage days (GSD) not only reduces potential crop water requirement ($\sum ET_C$), but also reduces the amount of percolation from the rice field and amount of rainfall available for *Boro* rice.

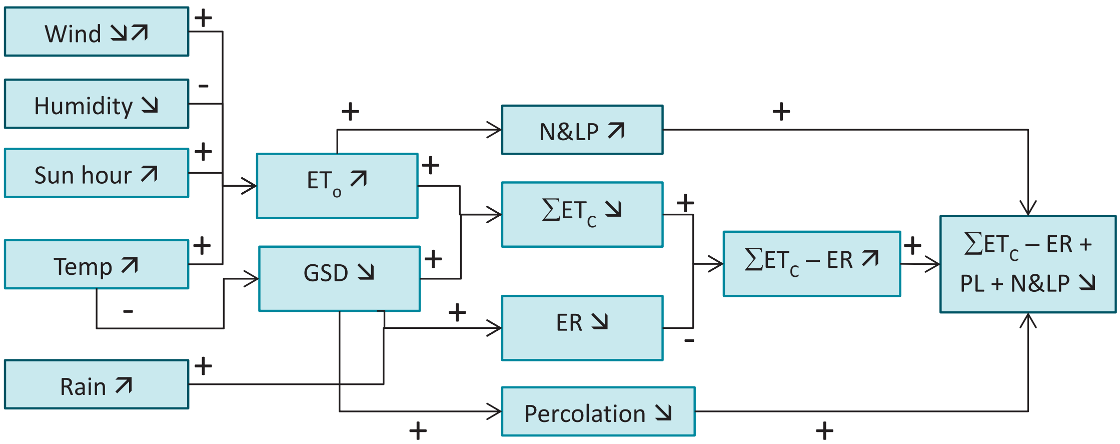

Fig. 3.8 Consequences of climate change on water requirement components for *Boro* rice in Northwest Bangladesh. The "↗"sign indicates an increase and "↘" indicates a decrease of the parameter. A "+"sign indicates that an increase in a parameter will contribute to an increase in the linked next parameter, or a decrease will contribute to decrease. A "–"sign indicates that an increase in a parameter will contribute to decrease in the linked next parameter, or a decrease will contribute to increase.

During recent decades, the potential crop water requirements ($\sum ET_C$) decreased due to both a reduction in ET_o and in the number of growing days of *Boro* rice (Acharjee et al., 2017a). In the future, $\sum ET_C$ will continue to decrease because of shortening in growing days despite a slight increase of daily water requirements. During recent decades, $\sum ET_C$–ER showed an increasing trend only for Bogra, and a decrease for other studied districts. In the future, $\sum ET_C$–ER will increase for all districts because of a decrease in rainfall availability during the *Boro* growing season. Therefore, the estimated trend in future reduction of net irrigation requirement for *Boro* rice is lower than the reducing trend observed over the last decades (1980–2013) as reported by Acharjee et al. (2017a). The percentage change (averaged across all climate models) in potential crop water requirement ($\sum ET_C$), growing stage days (GSD), effective rainfall during *Boro* growing season (ER), potential irrigation requirement for crop evapotranspiration ($\sum ET_C$–ER), percolation loss (PL) and net irrigation requirement ($\sum ET_C$–ER+PL+N&LP) are reported in Table 3.2. For both time periods and RCPs, the decrease in $\sum ET_C$ and growing stage days were lowest for Bogra and Rajshahi, and highest for Dinajpur and Pabna; which is in line with the assessment of changes over the last three decades (Acharjee et al., 2017a).

Table 3.2

The percentage change in different components for average of five climate models.

Scenarios	Comparison from base period	District	Changes in different parameters, %					
			$\sum ET_C$	GSD	ER	$(\sum ET_C - ER)$	PL	Net irrigation
RCP 4.5	by 2050s	Bogra	−0.34	−9.06	−24.85	20.05	−6.80	2.03
		Rajshahi	−7.30	−12.70	−50.89	15.10	−11.32	0.09
		Pabna	−8.21	−13.48	−46.38	15.52	−11.86	1.63
		Dinajpur	−10.25	−14.12	−36.30	28.03	−11.75	2.62
		Average	**−6.52**	**−12.34**	**−39.61**	**19.68**	**−10.43**	**1.59**
	by 2080s	Bogra	−4.29	−14.24	−38.63	24.3	−8.39	3.13
		Rajshahi	−8.07	−15.47	−43.80	10.23	−12.48	−2.66
		Pabna	−10.45	−17.54	−45.20	11.05	−14.06	−4.00
		Dinajpur	−10.40	−17.52	−57.32	62.29	−14.82	−0.27
		Average	**−8.30**	**−16.19**	**−46.24**	**26.97**	**−12.44**	**−0.95**
RCP 8.5	by 2050s	Bogra	−6.81	−13.67	−41.55	22.09	−10.21	−0.08
		Rajshahi	−12.79	−15.47	−55.81	9.33	−13.37	−5.33
		Pabna	−10.95	−15.51	−51.55	14.43	−13.34	−0.48
		Dinajpur	−13.09	−16.73	−60.20	60.03	−13.76	−0.51
		Average	**−10.91**	**−15.35**	**−52.28**	**26.47**	**−12.67**	**−1.60**
	by 2080s	Bogra	−14.70	−22.45	−65.56	27.62	−18.18	−5.46
		Rajshahi	−16.67	−21.46	−53.30	2.13	−18.0	−10.35
		Pabna	−18.79	−23.33	−60.54	7.45	−19.97	−8.24
		Dinajpur	−20.25	−26.14	−73.61	63.56	−21.31	−5.64
		Average	**−17.60**	**−23.35**	**−63.25**	**25.19**	**−19.36**	**−7.42**

3.4. Discussion

3.4.1. Future climate change impacts on reference crop evapotranspiration

The analysis of future trends indicates a considerable increase in maximum and minimum temperatures and sunshine hours during the dry winter season. The study by Rajib et al. (2011) indicates that the dry winter months will show steeper increases in temperature than the monsoon and pre-monsoon months in the future. Increase in temperature will lead to an increase in reference crop evapotranspiration during the dry months. Increased potential evapotranspiration could potentially exceed precipitation and resulting in more intense droughts in the Northwestern region (Islam et al., 2017). A study by Faisal and Parveen (2004) indicates an increase in theoretical evapotranspiration requirement for rice and wheat in 2050. According to Kirby et al. (2016), climate change is estimated to have a larger impact on evapotranspiration and runoff in Bangladesh than irrigation development.

The study by Acharjee et al. (2017a) showed a declining recent trend of ET_o over the last three decades in Northwest Bangladesh using historical observed climate data. Increases in humidity, decreasing wind speed and reduced sunshine hours resulted in a decrease in ET_o, despite an increase in maximum and minimum temperatures. This study explored possible future changes in ET_o and water requirements of *Boro* rice using downscaled and bias corrected future climate data. For both RCP 4.5 and 8.5, the changes in minimum and maximum temperatures mainly increased the daily ET_o. The future changes in wind speed, humidity and sunshine hours were not strong enough to reduce the ET_o as observed over the recent decades in the study of Acharjee et al. (2017a). Since, we did not obtain humidity data from the GCMs, we estimated relative humidity based on future temperature data. This method of humidity estimation assumes that the dew temperatures are equal to minimum temperatures. However, if wind speed, humidity and/or sunshine hours follow similar trends as those observed in recent decades, the decrease in water requirement in the future would be somewhat more than the estimated values in this study.

3.4.2. Future climate change impacts on potential crop water requirement

Our results show that, for an average over five climate models and four Northwest districts, potential crop water requirements will reduce by 6.5% and 10.9% for RCP 4.5 and 8.5, respectively for the 2050s; and by 8.3% and 17.6% for RCP 4.5 and 8.5, respectively for the 2080s (Table 3.2). A study by Shahid (2010) indicates an increase in daily water use, but not any appreciable change in total irrigation requirements of *Boro* rice due to a reduction of the irrigation period by approximately 13 days. Our results indicate that the shortening of growth stages could be sufficient to counteract and ultimately decrease the crop water requirement despite an increase of daily ET_o. The shorter duration of growing days of crops will provide scope to increase the cropping intensity by growing more crops each year on a single piece of land. As the daily ET_o will increase in the future, the agricultural water demand during the dry season still may increase if farmers take advantage of the shorter *Boro* season to cultivate an increased number of crops. This can cause an increase in the yearly water demand for crop agriculture. Such an increase in water requirement is mainly caused by crop phenological responses to climate change and related cultivation changes in the farming systems. However, if farmers keep cultivating the same number of crops in a year, the total water requirement for crop cultivation will reduce in the future, because the potential crop water requirements of *Boro* rice will decrease. Therefore, the future agricultural management decisions regarding the number of crops, i.e. the cropping intensity, are very important for the water resources management of the region.

3.4.3. Future climate change impacts on irrigation requirement

This study clearly reveals an increase in reference crop evapotranspiration and a decrease in potential crop water requirement due to future climate change. The exact amount by which potential irrigation requirements for crop evapotranspiration and net irrigation requirement will change, is still uncertain due to a large variability in projected rainfall amounts and distribution. However, all model outputs indicate changes of irrigation requirements in the same direction supporting the reliability of our findings in terms of direction of future changes. Our results indicate an increase in the amount of irrigation water required to satisfy crop evapotranspiration because of reduced rainfall availability, but a decrease of net irrigation requirement (except for RCP 4.5 in 2050s) because of lower percolation due to shorter growing period. A study by Karim et al. (2012a) also indicated a lower demand of irrigation water in the Northern region of Bangladesh in the future with a 13% increase in projected soil moisture. According to Faisal and Parveen (2004), if the water availability for crop production remains unchanged in the dry season, then there should be enough water to meet the irrigation requirements in 2030 and 2050.

A non-significant increasing trend of pre-monsoon rainfall and a reducing trend in winter rainfall were found in Bangladesh during 1969–2003 (Shahid, 2009). The increase in pre-monsoon rainfall will reduce irrigation requirement during flowering and maturing stages of *Boro* rice, while the decrease in winter rainfall will increase the irrigation requirements during initial and development stages of *Boro* rice. The estimation of irrigation requirement using CropWat by Shrestha et al. (2013) for Nepal also indicated variations in irrigation requirement in the projected time windows, with peaking values at the early stages and decreasing in the mid or later stages. Using the CropWat model for tropical paddy in Malaysia, Tukimat et al. (2017) showed that climate change will reduce irrigation demand by 0.9% per decade. The main challenge of climate change however will be to manage the increased variability in future irrigation water demand. Tukimat et al. (2017) also indicated that an increased rainfall will exceed the evapotranspiration loss and lead to reduced irrigation demand. Our study, however, shows that, a reduction in growing stage days will mainly lead to a reduction of total crop water demand and, depending on changes in rainfall, the net irrigation demand can reduce or increase. Both studies indicate that the major challenge in water resources management will be to manage the uncertainty. Future reductions in net irrigation requirement indicate that, if the groundwater irrigated area or the number of crops do not further increase in the future, *Boro* rice cultivation in the area will not put additional pressures on the groundwater resources. A study by Kirby et al. (2015) indicated that the rate of decline in groundwater tables would reduce and could even attain a new equilibrium assuming no further increase in the groundwater irrigated area. According to Mainuddin et al. (2015), the impact of climate change on the irrigation requirements of dry season *Boro* rice is small, and projected to increase by a maximum of 3% for 2050. Our study also confirms a small impact (an increase of 1.59% for RCP 4.5 and a decrease of 1.6% for RCP 8.5 scenario by 2050s) on net irrigation requirement but larger impacts or changes on individual components such as ET_o, $\sum ET_C$, effective rainfall and $\sum ET_C$–ER. However, as those higher individual component changes or impacts compensate for each other (Fig. 3.8) the overall combined effect is a relatively small change in net irrigation requirements.

3.4.4. Implications, limitations and scope for future research

Some future agricultural water management measures, e.g. the preparation of a suitable crop calendar, identification of optimum planting date, etc. can be planned based on the estimates of reference crop evapotranspiration and potential crop water requirement. Anticipatory planning of local and national level water management to adapt to climate change should include flexible measures related to irrigation demand management to deal with future uncertainties. Therefore, for long-term future water management planning, development of adaptation strategies or pathways in relation to various possible rainfall conditions and related changes in net irrigation requirement could be effective to cope with future climate change. In particular the effect of potential shifts in growing season, and intensification of cropping patterns, as facilitated by projected reductions in crop growth periods, needs further attention. Estimates of different water requirement components (i.e. ET_O, $\sum ET_C$, $\sum ET_C$–ER and Net irrigation) can better reflect on future possible consequences of climate change compared to an overall estimate (i.e. Net or Gross irrigation requirement) and therefore, could be more suitable for adaptation planning to deal with an uncertain future.

Although climate change could reduce the water requirements of rice, it may negatively affect yields. According to Karim et al. (2012), the yield of their studied rice cultivar will be hampered by 33% later this century in Bangladesh. Development of suitable rice varieties could be helpful in this regard. If farmers identify and use any late-maturing cultivars of rice that ensure higher production under the future climate change, the net irrigation requirement may increase as the duration of growth period will increase.

The water requirements at actual field condition may differ from our estimated values because of high diversity and complexity of soils in Bangladesh, including differences between the physiographic regions, within the soil topo-sequences, between and within the neighbouring fields, and in areas of shifting cultivation (Brammer and Nachtergaele, 2015). Also, the actual field level estimation may vary because of changes in crop variety, water application methods, soil management, and crop density. As the physical geography of Bangladesh is very diverse (Brammer, 2016a) impacts of climate change are not uniform throughout the country and distribution of rainfall could differently affect different regions, some finer scale studies to understand the changes in future water requirements can be helpful for better agricultural diversification and water management planning.

In addition to the climatic variables, the physiological response of the crop to the increased concentration of CO_2 also plays an important role in the evapotranspiration estimation. However, this has not been considered in this study and needs further research. Elevated CO_2 concentration decreases evapotranspiration and increases water use efficiency (Baker and Allen Jr, 1993; Morison, 1985). Therefore, consideration of elevated CO_2 concentration in the atmosphere is probably not contradictory, but will strengthen the final conclusion of this study.

As both the rainfall amount and distribution are important for irrigation management, and it is very difficult to exactly predict the future rainfall amounts and distribution, a close monitoring and evaluation are needed to identify the direction of changes in rainfall. Based on that, it would be possible to take anticipatory decision related to agricultural water management to cope with climate change. Therefore, this study further recommends to set up some good quality meteorological stations in Bangladesh (if possible, near crop fields) for close monitoring and regular evaluation of changes in climatic parameters. Brammer (2016b) also recommended to install more meteorological stations, especially in rural areas to recognize climate change with greater certainty. The study by Hossain et al. (2016) recommends a proper drought early warning system in the Northwest Bangladesh, which would also be possible by a close monitoring and evaluation of changes in climatic parameters.

3.5. Conclusion

Climate change will lead to an increase in reference crop evapotranspiration, but will not increase the overall water requirement of *Boro* rice, because of crop phenological response to increased temperature that reduces the number of growing days. All model estimates showed a decreased future potential crop water requirement ($\sum ET_C$) of *Boro* rice for all study districts. For RCP 8.5 scenario by 2050s, the potential crop water requirements will reduce by 10.9% and net irrigation requirement will reduce by 1.6% compared to the base period (1980–2013). The variations in the amount of decrease in $\sum ET_C$ for different models are low, compared to the variations in estimated net irrigation requirements. Large differences between climate models in estimates of future rainfall result in high variations in estimated future water requirements. High variations in projected rainfall potentially limits the anticipatory irrigation and water management planning. Therefore, close monitoring and evaluation to detect the direction of future change and, thereafter, development of flexible adaptation strategies are essential to deal with climate change; so that prompt decisions can be taken when the future becomes more visible.

CHAPTER 4

Shifting planting date of *Boro* rice as a climate change adaptation strategy to reduce water use

ABSTRACT

Suitable adaptation strategies for dry season *Boro* rice cultivation under future climate change scenarios are important for future food security in Bangladesh. This study assessed the effect of shifting trans-/planting date of dry season *Boro* rice as an adaptation strategy, with focus on water requirements under future climate scenarios. Potential crop water requirement, effective rainfall and irrigation requirement to satisfy crop evapotranspiration of *Boro* rice were estimated using CropWat 8.0 for early, normal and late planting dates for 2050s and 2080s. Future climate scenarios were constructed using five global circulation model (GCM) outputs for RCP 4.5 and 8.5 by statistical downscaling and bias correction. Number of days exceeding the threshold temperatures (maximum of 35 °C and minimum of 25 °C) was counted for critical period of *Boro* rice to understand compatibility of the changed planting dates. Results indicate that late planting can substantially reduce irrigation demand by increasing rainfall availability during *Boro* growth duration, but the option is very limited due to both day- and night-time heat stress. An early planting, on the other hand, accounts for high water demand but ensures suitable temperature during the critical growth stages of the crop. The normal planting dates show the possibility of day-time heat stress. So, late planting of temperature-tolerant cultivars or early planting of high-yielding varieties would be recommended based on local water availability. However, adjustment of the planting date is currently limited because high temperature-tolerant cultivars are not available in the study region.

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4.1. Introduction

Climate change affects the water requirement of crops. Irrigation demand will increase in Europe, USA and some parts of Asia, while the irrigated regions in India, Pakistan, and South-Eastern China might experience a slight decrease in irrigation demand (Biemans et al., 2013). Future irrigation demand is projected to exceed local water availability in many places (Wada et al., 2013). According to Hijioka et al. (2014), water scarcity due to increased water demand for population growth and higher standard of living will be a major challenge for most parts of Asia. Development of water saving technologies, increased water productivity, and water reuse could be effective in this regard (Hijioka et al., 2014). However, irrigation for crop agriculture, which is the largest water demand sector in Bangladesh, requires special attention to deal with future water demand management. Improved agricultural practices and irrigation management can play a vital role to cope with the risk of water shortage.

Climate change induced changes in water demand, availability and quality will impact water management decisions. Adaptation measures to ensure proper water balance requires strategies for supply-side as well as demand-side (Bates et al., 2008). One possible solution to reduce water demand for irrigation could be changing the cropping calendar. The changes in climatic parameters during recent decades contributed to reduce irrigation requirements in Northwest Bangladesh (Acharjee et al., 2017a; Mojid et al., 2015). However, the water demand for crop agriculture has increased due to expansion of irrigated agriculture. Water demand for *Boro* rice will reduce in the future (Acharjee et al., 2017b). The total annual water demand for crop cultivation, however, may still increase due to increasing cropping intensity as rice growth duration will become shorter. A shorter growing season of *Boro* rice due to the crop's phenological responses to climate change provides more flexibility to shift planting times.

Climate change will not only result in an increase or decrease in different climatic parameters, but will also cause changes in seasonality and variability of different parameters. There will be large seasonal and regional variations in climatic parameters in South Asia (Wassmann and Dobermann, 2007). The contrast in precipitation between wet and dry seasons will increase in the future (IPCC, 2013). Change of planting date of crops could be a simple and effective way to deal with changes in seasonal variability in climatic parameters. Following the climate change, a shift in planting date may allow plants to be exposed to more favourable conditions (Chun et al., 2016). For under developed countries, more emphasis on low-cost strategies is likely to be more effective for large-scale implementation. Farmers can adapt to changed climatic conditions to some degree by changing planting dates, choosing cultivars of different growth duration, or changing crop rotations (Wassmann and Dobermann, 2007). Several researchers have indicated that shifting the rice planting date could be an effective solution to improve rice yields in a changing climate. Simple adaptation options, such as shifting planting dates, can be applied to significantly increase net water productivity (Mainuddin et al., 2011). High-temperature and drought stresses can also be avoided by changing the transplanting date or growth period (Shelley et al., 2016).

Agricultural production in South Asia may reduce by 30% by 2050s if no action is taken to reduce the effects of increasing temperature and hydrologic disruption (Parry et al., 2007). As rice cultivation requires a large quantity of water, both the yield and water requirements are important aspects for optimizing the planting date. Previous studies which assessed the impacts of changing planting date of *Boro* rice in Bangladesh focusing only on yield (Basak et al., 2010; Karim et al., 2012) and disregarded the impact on water use and/or requirements. However, it is also important to understand the impacts of changing planting date on the water requirements of the crop.

Extreme temperature events affect growth and productivity of crops because high temperatures are destructive for plant growth and development. Critical temperatures vary with genotype, duration of critical temperature period, diurnal changes and physiological status of the plant (Yoshida, 1981). Due to climate changes, the number of days with extremely high temperatures will increase potentially reducing crop yield. Changing planting dates can both increase and reduce the risk of yield loss due to extreme temperatures. This study focused on identification of suitable planting date of *Boro* rice that can minimize irrigation requirement without damaging the crop during the critical period by extreme temperatures.

The objectives of the study were to assess the capacity and suitability of shifting planting date of rice as a climate change adaptation option. Several other studies have focused on yield estimation under different planting dates of *Boro* rice. Therefore, we mainly focused on the water demand side of the crop for our analysis. We have estimated water requirements for early, normal and late planting dates, and reflected on high temperature duration to understand the suitability of changing planting date. This study can help with developing strategies to adapt *Boro* rice to climate change and managing water demand for crop agriculture. It will enrich our existing knowledge of optimizing planting dates for future climate conditions and be useful for agricultural specialists and water managers of Bangladesh.

4.2. Methodology

4.2.1 Crop, study area and data collection

Three-season rice, namely *Aus*, *Aman* and *Boro* are generally cultivated in Bangladesh. *Boro* is the dry season rice, grown under a constant stagnant-water condition in the field. It is planted from December to early February, and harvested during April to June (Shelley et al., 2016). The most common cropping pattern that includes *Boro* rice is either *Boro−T.Aman−Potato* or *Boro−T.Aman−Fallow*. Bangladesh receives plenty of rainfall, which varies from 1,527 to 4,197 mm/year, but it is not well distributed both spatially and temporally (Shahid, 2011). Consequently, starting from 1970s, the development of groundwater irrigation has dramatically boosted *Boro* rice cropping area (Fujita, 2010). Rice plants encounter both low and high temperature stress during different growing seasons in Bangladesh (Shelley et al., 2016).

The Northwest part of Bangladesh extends from 23°47′ N to 25°50′ N latitude and from 88°01′ E to 89°48′ E longitude. Four Northwest districts − Bogra, Rajshahi, Pabna and Dinajpur – were selected for this study. Crop data related to dry season *Boro* rice were collected from Bangladesh Agricultural Research Institute (BARI). Soil data were standardized for a medium average soil for the selected districts from FAO standard soil parameter values.

4.2.2 Development of climate scenarios

Five General Circulation Models (GCMs) and two emission scenarios (RCP 4.5 and 8.5) were used to construct the future climate scenarios. Maximum and minimum temperatures, rainfall, solar radiation and wind speed for 2050s and 2080s, i.e. the time series of 2035–2065 and 2065–2095 were prepared. The employed GCMs were the **CNRM-CM5** model: developed by CNRM-GAME (Centre National de Recherches Météorologiques—Groupe d'études de l'Atmosphère Météorologique) and Cerfacs (Centre Européen de Recherche et de Formation Avancée) to contribute to 5th phase of the Coupled Model Inter-comparison Project (CMIP5) that includes atmospheric, land surface, ocean scheme, and sea ice models (Voldoire et al., 2013); the **EC-Earth** model: is a seamless Earth System Model that includes forecasting and climate change studies into a single framework (Hazeleger et al., 2010); the **HadGEM2-ES** model: is a coupled Earth System Model used by the Met Office Hadley Centre for the CMIP5 centennial simulations; the **IPSL-CM5A-LR** model: includes 5 model components: LMDz (atmosphere), NEMO (ocean, oceanic biogeochemistry and sea-ice), ORCHIDEE (continental surfaces and vegetation), and INCA (atmospheric chemistry), coupled through OASIS; the **MPI-ESM-LR** model: is a comprehensive Earth-System Model that consists of ocean, atmosphere and land surface component models. These models were selected for our study because of their important criteria in evaluating the impacts of climate change, such as ocean-atmosphere couple, multi-century simulation capability, well documentation in literature, and participation in the Coupled Model Inter-comparison Project (CMIP) (Barrow et al., 2004). Two different emission scenarios, RCP 4.5 and 8.5 were selected for this study since they represent realistically low and high future climate change scenarios. RCP 4.5 characterises stabilization without overshoot pathway to 4.5 W/m^2 (~650 ppm CO_2 eq.) at stabilization after 2100 and RCP 8.5 characterises rising radiative forcing pathway leading to 8.5 W/m^2 (~1370 ppm CO_2 eq.) by 2100 (Van Vuuren et al., 2011).

The future climate data for daily maximum and minimum temperatures, rainfall, solar radiation and wind speed were generated by statistical downscaling. For bias correction, the WATCH Forcing data (Weedon et al., 2011) of monthly average maximum and minimum temperatures, sunshine hours and wind speed, and monthly total rainfall were compared to the observed historical data. Since, the GCM outputs do not provide relative humidity; this was estimated following the ratio between actual and saturation vapour pressures, which are pure functions of temperature and can be calculated by a common empirical interpolation function (Holbo, 1981; WMO, 1979). For humid temperate climates, when temperature is at its daily minimum, air becomes saturated with water vapour. Hence, the general assumption to estimate relative humidity from temperature data is to consider dew point temperature as equal to the minimum temperature of the day (Eccel, 2012).

4.2.3 Selection of Planting dates and estimation of growth duration

Two normal planting (1 and 11 December), two early planting (1 and 11 November) and two late planting (31 December and 10 January) dates were selected for analysis. Following a 35-day nursery stage, the corresponding transplanting date for normal, early and late planting is: 05-Jan & 15-Jan; 06-Dec & 16-Dec; and 04-Feb & 14-Feb. The lengths of four distinguished growth stages of *Boro* rice were estimated for each transplanting date and for different climate scenarios following the growing degree-days (*GDD*) method as:

$$\boldsymbol{GDD = [(T_{max} + T_{min})/2] - T_{base}} \quad (4.1)$$

where T_{max}, T_{min}, and T_{base} are the maximum, minimum and base temperature, respectively.

First, the GDD was estimated for four study districts using five climate models and two emission scenarios for each of the transplanting dates. Later, the growth stage duration was estimated from GDDs and accumulated heat values at the end of each stage as:

$$\boldsymbol{Growth\ stage\ duration\ (days) = \frac{Accumulated\ heat\ value\ at\ the\ end\ of\ the\ stage\ (°C)}{GDD\ for\ the\ corrosponding\ period\ (°C)}} \quad (4.2)$$

The accumulated heat values (for the base temperature of 15 °C) at the end of the growth stages for *Boro* rice in the Northwest zone of Bangladesh were taken from Mahmood (1997). The accumulated heat values at the end of initial, vegetative, flowering and maturing stages were 80, 528, 1052 and 1291 °C, respectively for Bogra, Rajshahi and Pabna; and 80, 515, 1032 and 1273 °C, respectively for Dinajpur. The growing degree-days method can consistently predict the growth duration of crops (Miller et al., 2001).

The accumulated heat values for currently used long duration varieties (e.g. BRRI dhan29) are about 16% higher compared to short duration varieties (e.g. BRRI dhan28). Growth stage days for the possible future long-duration cultivars were estimated for Bogra. A 16% increased accumulated heat values for each stage with an imposed minimum duration for each stage was used. For the long-duration cultivar, the accumulated heat values at the end of initial, vegetative, flowering and maturing stages were 93, 613, 1221 and 1498 °C, respectively for Bogra. The imposed minimum number of days for initial, development, mid-season and late-season were 22, 45, 36 and 18 days, respectively.

4.2.4 Estimation of water requirements for different planting times

CropWat model was used to estimate potential crop water requirement and potential irrigation requirement for crop evapotranspiration based on climate, crop and soil data. It has been used extensively as a decision-support tool in an international context to estimate regional irrigation requirements (Clarke et al., 2001). This model was also successfully applied to evaluate impacts of climate change on water requirements in several previous researches (Chowdhury et al., 2013; Doria et al., 2006; Doria, 2010; Shrestha et al., 2013).

Water requirements of *Boro* rice were estimated using statistically downscaled bias-corrected daily climate data from GCMs outputs for four districts, five models and two RCPs for 2050s (average of 2035–65) and 2080s (average of 2065–95). *Potential crop water requirement* is calculated as total crop evapotranspiration ($\sum ET_C$) during the crop growing period by considering changes in the length of growing season. The *Potential irrigation requirement for crop evapotranspiration* is the total amount of crop evapotranspiration in excess of effective rainfall, ER, i.e. $\sum ET_C - ER$. The effective rainfall is the amount of rainfall that is effectively added and stored in the soil for later use by the crop and is derived as a simulation output from CropWat.

To assess the impacts of climate change on water requirements under different trans-/planting dates of *Boro* rice, the influence of management practices was excluded by modelling the rice growth in CropWat under a standardized schedule that provides irrigation water as required. The crop co-efficient values were 0.7, 0.3, 0.5, 1.05 and 0.65 under dry condition, and 1.2, 1.05, 1.1, 1.2 and 0.95 under wet condition for nursery, land preparation, initial, mid-season and late-season, respectively. The scheduling criteria to estimate the net irrigation requirement was to provide irrigation at 5 mm water depth above ground surface and refill to 100 mm standing water.

4.2.5 Assessment of heat stress during critical periods

Spikelet sterility may occur at different temperature thresholds (Matthews et al., 1995; Nakagawa et al., 2003) since there is genotypic variation in spikelet sterility at high temperature (Matsui et al., 2001; Prasad et al., 2006; Satake and Yoshida, 1978). Also, shorter durations at very higher temperatures may have the same effect as longer durations at relatively less higher temperatures (Satake and Matsuo, 1995). According to Laborte et al. (2012), the maximum temperature above 35 °C for 10 days can cause day time heat stress, and the minimum temperature above 25 °C for 15 days can cause night time heat stress to rice plant during the critical stages. First, we have identified the critical period to high temperature stress for early, normal and late planting for all studied districts, scenarios and climate models. For Bogra, Rajshahi and Pabna, the identified critical stress periods were the days with accumulated heat values from 659 to 1052 °C. For Dinajpur, the identified critical stress periods were the days with accumulated heat values from 644 to 1032 °C. After identification of the critical days, we identified the days with maximum temperature above 35 °C and minimum temperature above 25 °C within those critical days. The number of days with maximum temperature above 35 °C and minimum temperature above 25 °C within critical periods were counted and their percentage to total number of critical days were estimated for early, normal and late planting under all studied districts, scenarios and models to understand suitability of changing the planting date of existing (i.e. temperature intolerant) cultivars of *Boro* rice.

4.3. Results

4.3.1 Future rainfall in excess of evapotranspiration

The estimated future monthly rainfall in excess of evapotranspiration (Appendix Fig. A1) indicates a 'wet-get-wetter' and 'dry-get-drier' situation in the Northwest Bangladesh. However, the annual distribution of future rainfall in excess of evapotranspiration is almost similar to recent years in all study districts. There will be more dry conditions from November to April, which is the *Boro* growing season. The soil-water deficit or drought could be maximum during March-April. The dry months will be drier in 2080s compared to 2050s. Also, the dry months will be drier for a pronounced climate change (RCP 8.5) than a moderate climate change scenario (RCP 4.5).

The 'dry-get-drier' situation during the dry winter months could be because of less rainfall and/or increased evapotranspiration during this period. The Mann-Kendall trends of estimated reference crop evapotranspiration during the dry months of the 2035–2065 and 2065–2095 time series by Acharjee et al. (2017b) indicate a possible future increase in daily evapotranspiration. The possible future monthly rainfall reveals some increasing trends (Appendix Fig. A2). The study by Shahid (2011) also indicates a significant increase (6.05 mm/year) in annual precipitation in Bogra in the long-term trends during 1958–2007. Therefore, the 'dry-get-drier' condition will be mainly because of increased evapotranspiration despite some expected increase of rainfall amount in the Northwest Bangladesh.

4.3.2 Future Boro growth duration under different planting dates

A shorter growth duration under late planting and a longer growth duration under early planting compared to normal time planting were observed (Fig. 4.1). The results are consistent for all study districts, employed models and scenarios. For the early planting, the rice plant receives a long winter period and the crop matures slowly during the low temperature period, resulting in longer growth duration. For the late panting, the rice plant receives an initial short winter period and thereafter a pre-monsoon high temperature period. Hence, the rice plant receives more number of high temperature days under the late planting compared to early planting and, therefore, matures rapidly.

Fig. 4.1 Growth duration (for the average of five models) of *Boro* rice under different transplanting dates for four different climate change scenarios.

4.3.3 Potential crop water requirements as affected by planting dates

The potential crop water requirement, $\sum ET_C$, will increase in case of early planting and decrease in case of late planting compared to normal time planting (Fig. 4.2). The estimated $\sum ET_C$ are consistent for all districts, models and scenarios under consideration except in 2080s for RCP 8.5. The $\sum ET_C$ for both the early and late planting exhibit an increase compare to the normal time planting in 2080s for RCP 8.5. The difference between potential crop water requirements for early and normal planting is relatively smaller in Dinajpur compared to other districts. The potential crop water requirement is consequently higher in Pabna for all scenarios compared to other districts; this is not because of longer growth duration, but due to higher daily evapotranspiration. The potential crop water requirement is higher in Pabna compared to other districts which is because of higher rate of daily evapotranspiration in Pabna.

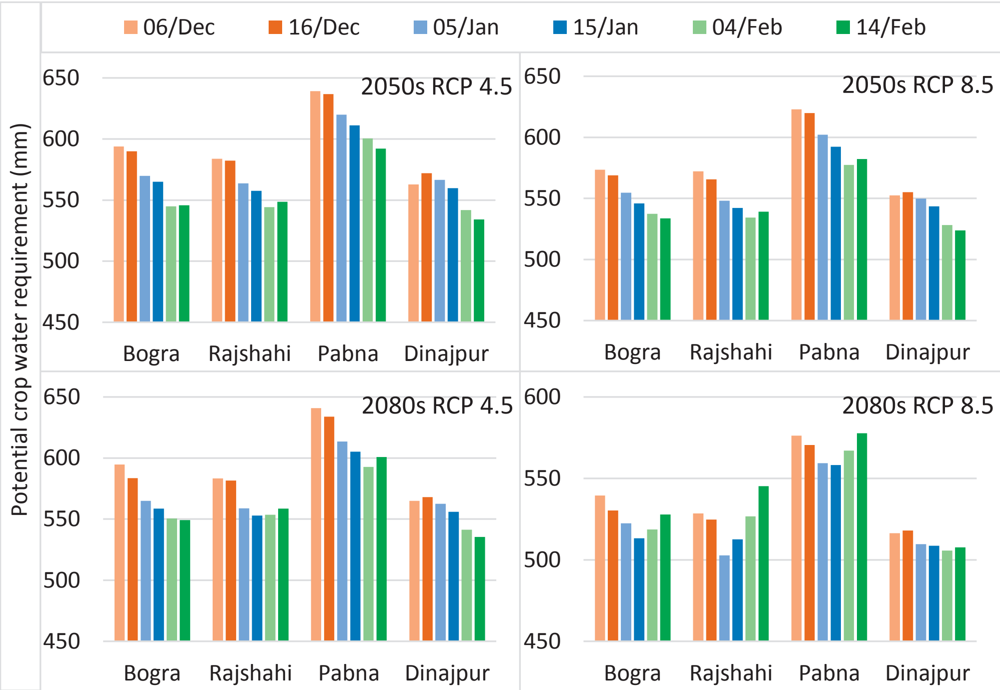

Fig. 4.2 Potential crop water requirement (for the average of five models) of *Boro* rice using six different transplanting dates for RCPs 4.5 and 8.5 and two future periods 2035–65 (2050s) and 2065–95 (2080s).

The estimated potential crop water requirement exhibits a clear link with estimated growth duration of *Boro* rice under different planting dates. For early planting date, the longer growth duration resulted in increased potential crop water requirement; while for late planting, shorter growth duration resulted in reduced potential crop water requirement. However, the potential crop water requirements will increase for both early and late plantings in 2080s because of a rapid climate change. Therefore, for a rapid climate change (RCP 8.5) in the long term both early and late planting options would be ineffective in terms of crop water requirements.

4.3.4 Potential irrigation requirements as affected by planting dates

The potential irrigation requirement for crop evapotranspiration ($\sum ET_C - ER$) showed an increase for early planting and a reduction for late planting (Fig. 4.3). These results are consistent for all study districts, models and scenarios, including 2080s for RCP 8.5. However, the amount of reduction for the late planting is more than the amount of increase for the early planting in comparison to normal planting date.

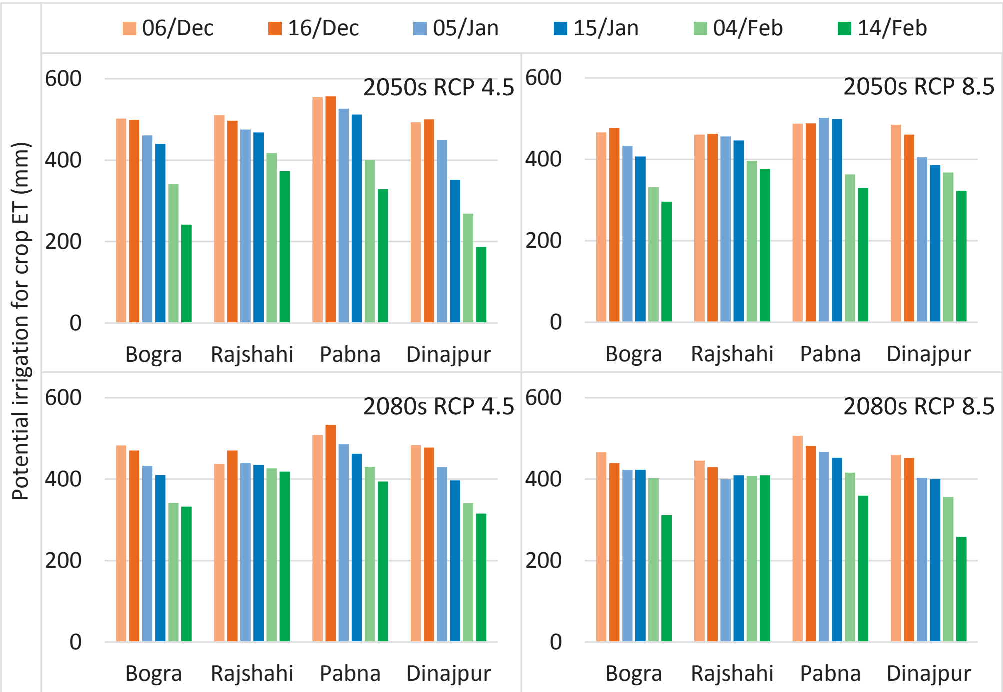

Fig. 4.3 Potential irrigation requirement for crop evapotranspiration (for the average of five models), $\sum ET_C - ER$ (mm) of *Boro* rice using six different transplanting dates for RCPs 4.5 and 8.5 and two future periods 2035–65 (2050s) and 2065–95 (2080s).

The estimated effective rainfall during the *Boro* growth duration reveals increased rainfall availability for late planting compared to the early or normal planting (Appendix, Fig. A3). The difference between rainfall availabilities for the early and normal planting dates is less than the difference between rainfall availabilities for the late and normal planting dates. Therefore, a shift from normal to early plating dates will allow a less change of rainfall availability than a shift from normal to late planting. In other words, a shift of planting date from normal to late planting can substantially increase the rainfall availability for *Boro* rice cultivation.

4.3.5 Temperature stress as affected by planting dates

High temperature stress reduces grain yield of rice by reducing the percentage of ripened grains as a result of spikelet sterility (Oh-e et al., 2007). The flowering and booting are the most sensitive/critical stages of rice to high temperature stress (Farrell et al., 2006; Satake and Yoshida, 1978), which may sometimes lead to complete spikelet sterility (Shah et al., 2011). For early planting, the critical period will begin during 11/Feb – 20/Mar and continue till 11/Mar – 17/Apr depending on different years, scenarios and model estimates in Bogra. For normal planting, the critical period will begin during 05/Mar – 01/Apr and continue till 28/Mar – 26/Apr. For late planting, the critical period will begin during 22/Mar – 12/Apr and continue till 12/Apr – 06/May. The detail results on estimated dates of beginning and end date of critical period of *Boro* rice in Bogra has been presented in Appendix (Fig. A4). For a late planting critical period also begins lately. Other districts also show similar kind of results on estimated critical period dates (were estimated but has not been presented in this paper). According to Laborte et al. (2012), maximum temperature above 35 °C for 10 days during the critical period can cause a day-time heat stress and minimum temperature exceeding 25 °C for 15 days during critical period can cause a night-time heat stress. Our results indicate that for the late planting, with critical period during late-March to early-May, there will be more chance of day-time heat stress compared to early planting having critical period during early-February to mid-April (Fig. 4.4). There will be also high risk of day time heat stress for normal time planting. Krishnan et al. (2011) also commented that, most agronomic interventions for dealing with high-temperature stress aim at early sowing of rice or selection of early maturing cultivars to avoid high temperatures during the grain filling stage. There will be low risk of day time heat stress in Dinajpur compared to other study districts because of less number of days with maximum temperature above 35 °C in Dinajpur.

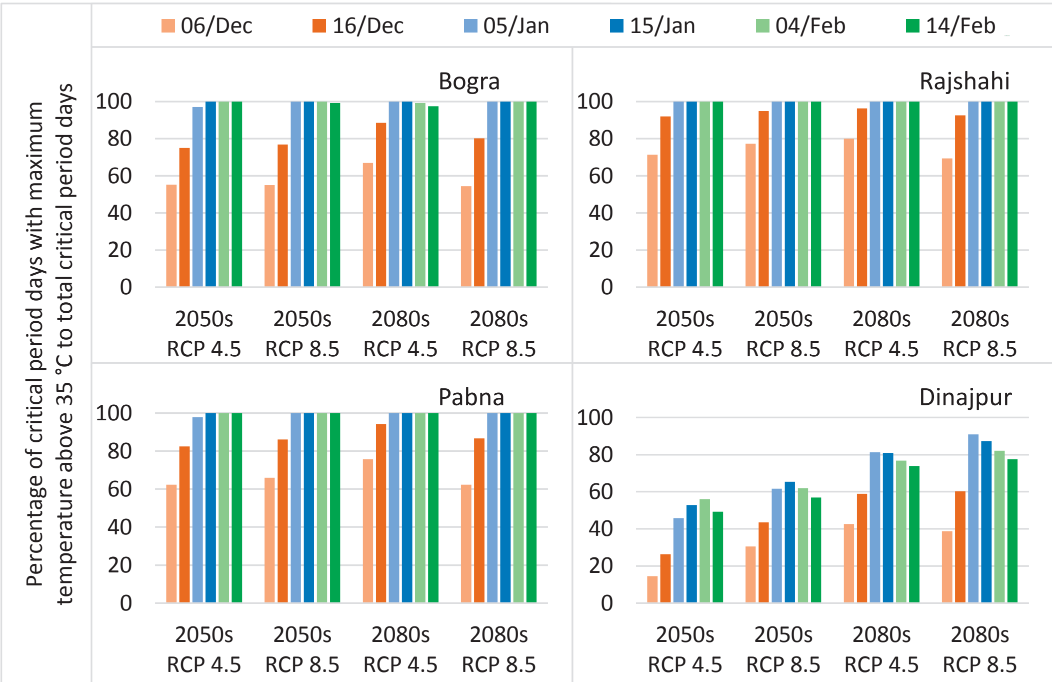

Fig. 4.4 Percentage of critical period days with maximum temperature above 35 °C to total critical period days (for the average of five models) for early, normal and late (trans)planting in 2050s and 2080s under RCP 4.5 and 8.5 in four study districts.

For the late planting, there will be more chance of night-time heat stress compared to the early and normal time planting (Fig. 4.5). For most of the scenarios, there is no chance of night-time heat stress for the early planting. There will also be low risk of night time heat stress in Dinajpur compared to other study districts because of less number of days with minimum temperature above 25 °C in Dinajpur.

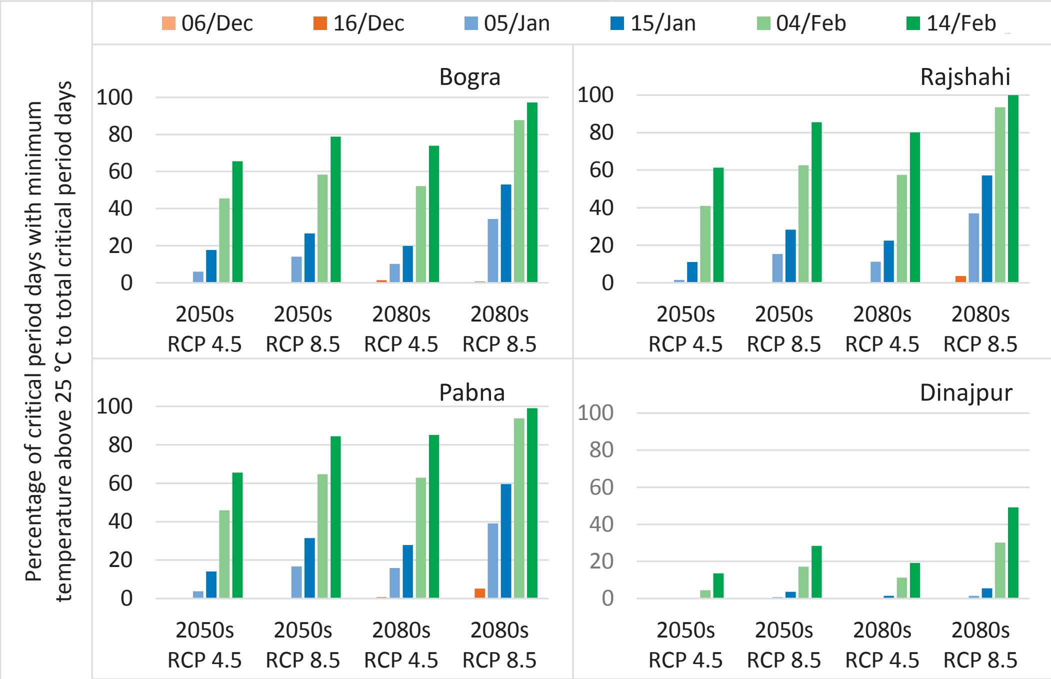

Fig. 4.5 Percentage of critical period days with minimum temperature above 25 °C to total critical period days (for the average of five models) for early, normal and late (trans)planting in 2050s and 2080s under RCP 4.5 and 8.5 in four study districts.

4.3.6 Long-duration cultivars of Boro rice as affected by planting dates

The results discussed so far is a long-duration cultivar (e.g., BR29) in the prevailing climate that will become a short-duration cultivar due to accelerated growth under increased temperature in the future; this cultivar is hereafter stated as usual cultivar. A longer growth duration, usually, allows the tillers to become more mature and produce large number of panicles in winter season (Gomosta et al., 2001). Therefore, farmers may choose a possible more longer duration variety in the future that has been stated as long-duration cultivar in this study. Growth duration is an important aspect for selecting the optimum planting date. Therefore, we also presented the results for possible future long-duration cultivar of *Boro* rice (Fig. 6) and compared with the existing cultivar (Fig. 7).

Similar kind of changes in growth duration of long-duration cultivars of *Boro* rice were obtained for different planting dates like usual/short duration cultivars (Appendix, Fig. A5). However, the percentages of increase in estimated growth duration of long duration cultivars are different for all planting dates. The percentage increase in growth duration for the late planting is higher than the percentage increase for the early planting. Therefore, the difference in growth duration between the early planting and late planting for long-duration cultivars is lower than that for usual cultivars.

Similar kind of changes in potential crop water requirements, effective rainfall and potential irrigation requirements for crop evapotranspiration of long-duration cultivars of *Boro* rice were obtained for different planting dates under investigation for the usual cultivars (Fig. 4.6). However, the differences between potential crop water requirements of different planting dates are smaller for the long-duration variety compared to the usual duration variety. The differences in effective rainfall and irrigation requirement between the planting dates seem larger for the long-duration variety compared to the usual duration variety. Longer growth duration, possibly, may bring more fluctuations in available rainfall because of changing trans-/planting dates.

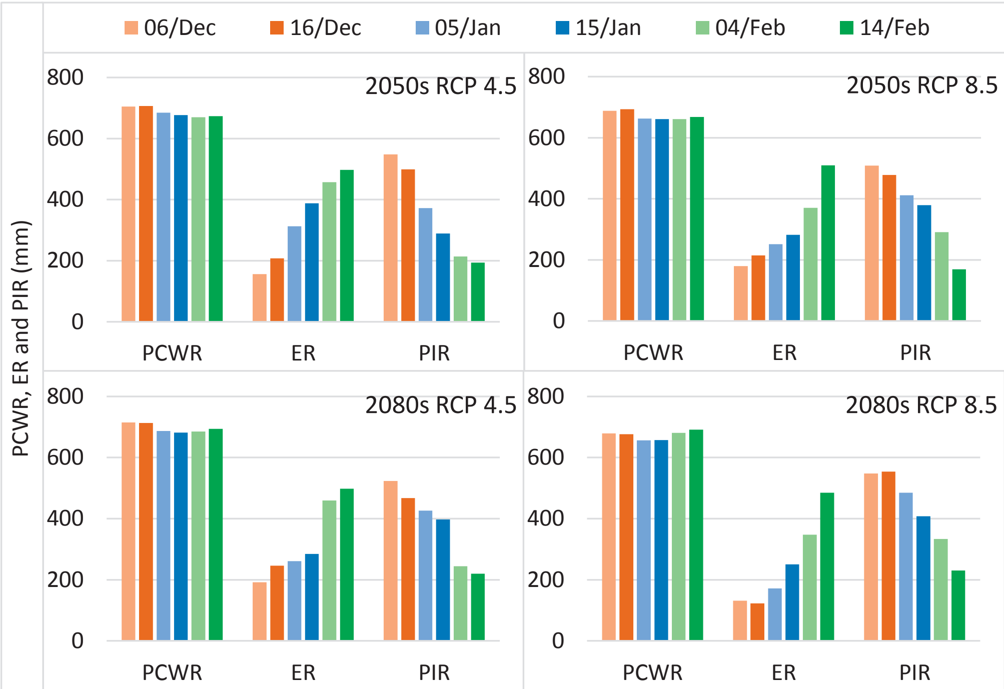

Fig. 4.6 Potential crop water requirement (PCWR), effective rainfall during crop growing period (ER) and potential irrigation requirement for crop evapotranspiration (PIR) for long-duration cultivar of *Boro* rice using six different transplanting dates for RCPs 4.5 and 8.5 and two future periods 2035–65 (2050s) and 2065–95 (2080s) in Bogra district.

The difference in potential crop water requirements between the long and short duration cultivars is similar for all planting dates (Fig. 4.7). However, the difference in effective rainfalls and potential irrigation requirements between the long and short duration cultivars is different for all planting dates. In 2080s for RCP 4.5 and in 2050s for RCP 8.5, the variation in potential irrigation requirement differences is much more between normal and late planting compared to normal and early planting.

This indicates that irrigation requirements may change drastically from long to short duration cultivars between normal and late planting dates for moderate climate change in 2080s or rapid climate change in 2050s. The decrease in potential irrigation requirements for long-duration cultivar compared to usual duration cultivar is because of more rainfall availability during the later stages of the growing season.

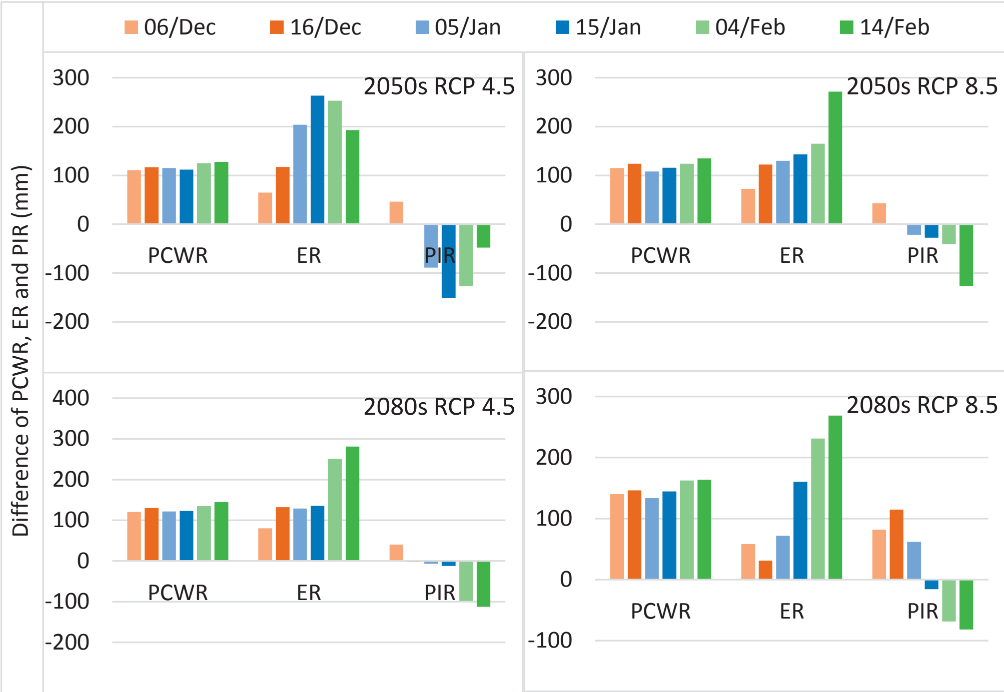

Fig. 4.7 Difference in potential crop water requirement (PCWR), effective rainfall during crop growing period (ER) and potential irrigation requirement for crop evapotranspiration (PIR) of long-duration cultivar compared to usual duration cultivar of *Boro* rice using six different transplanting dates for RCPs 4.5 and 8.5 and two future periods 2035–65 (2050s) and 2065–95 (2080s) in Bogra district.

4.4. Discussion

Several factors may affect the choice of the best or optimum planting date. One of the main concerns for this choice is the amount of water needed for cultivation of the crop, especially in water-limited areas or drought-prone regions. Since, lack of water during dry season is the major concern in the Northwest Bangladesh, we have analysed water requirements for different planting dates of *Boro* rice.

4.4.1 Future Boro growth duration: estimates and possibilities

The study by Kabir et al. (2016) indicates that, the growth duration of two transplanted *Boro* varieties (45-days old seedling) in the recent climate (2001) varied about 5 and 10 days for one month shifting of transplanting date from 15 December to 13 January. In our study, for one month shifting of transplanting date from 16 December to 15 January of 35-days old seedling, the growth duration reduced 19 days in the future. The increased variation in growth duration for one month shifting of transplanting in our study is because of an accelerated accumulation of GDD due to more rapid future climate change compared to recent climate change.

There are two main aspects of future growth duration of *Boro* rice: firstly, the changes in growth duration of current cultivars because of increased temperature in the future, and, secondly, the growth duration of possible new cultivars. Our estimates clearly indicate a considerable influence of temperature difference, due to shifts in planting date, on the growth duration of existing *Boro* cultivar under future climate scenarios (Fig. 1). Rice matures rapidly during the warmer late period compared to the cooler earlier period. However, the exact reduced number of days for a late planting or increased number of days for an early planting may be different for different *Boro* cultivars. As the future shortening of growth duration can substantially reduce the rice yield, farmers may need to change to a long-duration cultivar in the future to maintain their yields. However, the influence of shifting planting date is similar for both short and long-duration cultivars.

4.4.2 Potential crop water and irrigation requirements as influenced by planting date

A delay in planting time of *Boro* rice reduces potential crop water and irrigation requirements by enhancing the crop maturity compared to early planting. Compared to the early planting, the potential crop water requirements (averaged over all districts and models) reduced by 6.5 and 5.9% in 2050s for RCP 4.5 and 8.5, respectively, and by 5.7 and 0.6% in 2080s for RCP 4.5 and 8.5, respectively in case of late planting. The potential irrigation requirement for crop evapotranspiration (averaged over all districts and models) for late planting was reduced by 31 and 21% in 2050s for RCP 4.5 and 8.5, respectively, and by 14% in 2080s for both RCP 4.5 and 8.5 compared to normal planting dates. The potential irrigation requirement for crop evapotranspiration for late planting was reduced by 38 and 27% in 2050s for RCP 4.5 and 8.5, respectively, and by 22 and 21% in 2080s for both RCP 4.5 and 8.5, respectively compared to early planting. The reduction in irrigation requirements for late planting is caused by high rainfall availability during the later parts of the growing season. Late planting in winter, generally, ensures a higher rainfall during the vegetative growth and brings some beneficial effects by reducing the possibility of water stress (Karim et al., 2012). The reduced crop growth duration and better rainfall accessibility for the late planting dates ensure a much lower irrigation requirement for *Boro* rice. Therefore, the late planting is a good choice for the future from a water demand perspective.

A later planting date can substantially reduce the amount of irrigation required for *Boro* cultivation, but may reduce yield due to heavy rainfall events before harvesting. Perez and Hosen (1987) reported that rain can cause delay in harvest and increase proportion of broken grains during milling. The number of heavy rainfall events will increase in the future against a decrease in total rainy days in a year (Wassmann and Dobermann, 2007); this can potentially reduce water availability for crop growth because during heavy rainfall events runoff is relatively high and there is only limited water infiltration into the soil (Challinor et al., 2004). Another major concern for late planting is the reduced growth duration. Higher temperatures, by accelerating plant growth rate, reduce growth duration leading to shorter grain filling period, varying from 25 days in tropics to 35 days in temperate zones (Swaminithan, 1984). However, selection of a suitable crop variety can mitigate the impact of higher temperatures (Challinor et al., 2005). Therefore, a suitable crop variety that can withstand higher temperatures and heavy rainfall events is required for late planting strategies.

4.4.3 Planting date related temperature stress on Boro rice

The panicle initiation stage is sensitive to low-temperature damage, whereas the flowering stage is more sensitive to high-temperatures; both cases can cause spikelet sterility (Shelley et al., 2016). At present, early planted *Boro* rice in Bangladesh often faces low-temperature stress at both vegetative and reproductive stages (Nahar et al., 2009). In contrast, the late *Boro* rice often encounters high temperature stress at the reproductive stage (Shelley et al., 2016). Our study indicate a high chance of temperature stress for normal and late planting. The yield of *Boro* rice may decline with late sowing due to greater exposure to high temperature during anthesis (Ahmed et al., 2016). A study in Sri Lanka by Dharmarathna et al. (2014) indicates that dry season rice yield would increase when the planting date is advanced by one month. Both daily maximum and minimum temperatures will increase in the future due to global warming, which will reduce the chance of low-temperature damage during panicle initiation but increase the risk of high-temperature damage during booting and flowering. Both day- and night-time high-temperatures are likely to become more crucial in the future. Our results indicate that, day time heat stress can be more crucial than the night time heat stress for *Boro* rice in the Northwest Bangladesh. The night time heat stress can be avoided by selecting an early planting date. However, *Boro* rice may be affected by day time heat stress even in case of early planting. More studies on *Boro* rice cultivars are required to minimize the heat stress induced spikelet sterility. Studies on heat escape mechanism by early-morning flowering (Bheemanahalli et al., 2017; Hirabayashi et al., 2014; Ishimaru et al., 2010), heat avoidance through transpiration cooling (Julia and Dingkuhn, 2013), and heat tolerance to increase resilience by altering cellular metabolites (Jagadish et al., 2009) need more attention. A high-temperature tolerant rice variety is, therefore, highly recommended for this region and, thereafter, a date between normal and late planting may be chosen based on temperature-tolerance capacity of the selected cultivar. Otherwise, an early planting would be more suitable to avoid the risk of high temperature stress and, in such a case, other options of water demand management need to be explored instead of the delayed planting option for the reduction of water use.

4.4.4 Planting date change: an adaptation strategy

For wet season crops like *Aman* rice, farmers can adjust planting date following the availability of rainfall. The erratic intensity and distribution of pre-monsoon rainfall contributes to considerable variations in sowing dates between different areas, sometimes within short distances (Brammer, 1987). However, for dry season crops like *Boro* rice, it is more difficult to choose a suitable trans-/planting date, because the rainfall availability varies during the time period when the rice plant requires it most.

Changing planting date may provide some adaptation options, but that will be limited in the Indo-Gangetic plain by low winter temperatures (Wassmann and Dobermann, 2007). Our results indicate, the option of changing planting date, as an adaptation strategy, will be limited by high temperature stress, especially in the case of late planting choices. In the Indo-Gangetic plain, delayed planting is a well-recognized cause of yield reduction in rice and wheat (Wassmann and Dobermann, 2007). Therefore, identification of the best or optimum planting date may be a great challenge for the future, especially in case of non-availability of temperature-tolerant varieties.

The risk of yield reduction of *Boro* rice due to both heat stress and heavy rainfall/storm during harvesting period is high for the late planting. Since, the heat-stress induced risk may not vary much throughout the study region, it can be eliminated by choosing a temperature-tolerant variety. But, the heavy shower/storm-related risk can considerably vary depending on local geographic conditions, drainage capacity, etc. in the region. Estimation of return period and better forecast of extreme rainfall events/storms can help to reduce this risk.

Since irrigation demand is much less for late planting, farmers under water-limited situation can be recommended to choose a late-planting date taking into account of the impacts of high temperature stress. Karim et al. (2012) reported significant reduction in rice yield due to lack of available water for early planting, especially before 28^{th} January. The main limitation of late planting is the increased chance of temperature stress during the critical stage of *Boro* rice. Climate change may expose rice yield more vulnerable to transplanting date, predicting significant yield reduction as transplanting date is delayed, especially after 15 January (Basak et al., 2009). Another concern for late planting is the increased possibility of heavy rainfall during rice harvesting that cause crop failure. Late planting may also prevent the next crop from being obtained the suitable condition later in the season (Matthews et al., 1997). However, the late planting of temperature-tolerant cultivars would be the best choice for water-limited regions. For regions with high water availability, the early planting of a long-duration high-yielding cultivar would be the optimal choice in the future. Any long-duration variety is not recommended for the low-lying *Haor* areas where flash floods may cause damage to *Boro* rice before harvesting.

Many investigators at several agricultural research institutes are working to improve rice cultivars by incorporating tolerance to drought, flood and salinity. Most rice varieties, so far developed in

Bangladesh, cannot withstand high-temperature stresses (Shelley et al., 2016). Development of heat-tolerant rice cultivars is, therefore, highly recommended. This will not only increase crop yield but may also reduce irrigation requirement by adjusting planting date.

4.5. Conclusions

A delay in trans-/planting date enhances maturity of *Boro* rice and, consequently, reduces potential crop water requirement compared to early planting. Further reduction in irrigation requirement under late planting occurs because of increased rainfall availability during the later periods of crop growth. Hence, the late planting is a good choice for the future from a water demand perspective. However, there will be more chances of both day- and night-time heat stress for late compared to early planting strategies of *Boro* rice. Shift of trans-/planting dates may bring more fluctuations in available rainfall and irrigation requirements for long duration cultivars than short duration cultivars. Although, shifting the planting date of the crop has the potential to substantially reduce irrigation requirement, the option is, however, highly limited by the possible high temperature stress. Therefore, development of temperature-tolerant rice variety is a pre-requisite to reduce irrigation requirement by choosing late trans-/planting date.

CHAPTER 5

Prioritization of adaptation measures for improved agricultural water management

ABSTRACT

Adaptation strategies are essential to manage water demand and ensure optimal use of available water resources in drought-prone and water-scarce Northwest Bangladesh. Identification and prioritization of adaptation measures would greatly support decision-making for sustainable utilization of water resources for agriculture. First, the recent progress in adaptation plans was reviewed to identify options for improved agricultural water management. Then, the adaptation options were evaluated and ranked based on experts'/stakeholders' judgment following a multi-criteria analysis. Further, the social, institutional and technological dimensions of adaptive capacity were reviewed in the context of Northwest Bangladesh. A broad set of 72 measures was identified and structured in six broad categories. Transboundary co-operation was ranked as the top-priority, but this is a very complex and *out-system dependent* option. Integrated water resources management and integrated crop management were the top-ranked options from the water and crop production management categories. Different levels of social, institutional and technological complexities were found for different categories. Increasing crop land by clustering scattered households and training programs for on-farm water management were the most and least complex measures, respectively. There is a clear preference among stakeholders to opt for higher scale *out-system dependent* strategies that aim to minimise the impacts of climate change on agricultural systems, rather than *in-system dependent* options that focus on changing the agricultural system itself to cope with the impacts. Short- or medium-term planning should invest on local agricultural system to ensure gradual but obvious development and success. However, investment in complex and dependent strategies is also important for long-term planning. Capacity building and mainstreaming climate change adaptation may transform complex options into reliable feasible measures in course of time.

The manuscript corresponding to this chapter is currently under preparation for journal submission.

5.1. Introduction

Now-a-days it is a national priority in Bangladesh to address climate change. *Bangladesh Climate Change Strategy and Action Plan* (BCCSAP) identified three main climate hazards: tropical cyclones/storm surges, inland flooding, and droughts. Though the Northwest part of Bangladesh is vulnerable to drought, this region has contributed much for the food security of the country during recent decades. The country is already facing the challenges of reduction in cultivable areas due to urbanization and industrial growth, declined ground water table due to rapid expansion of irrigated rice areas, lower dry season surface water availability and higher food demand for increased population. In future, the major challenge for the agriculture of Northwest Bangladesh will be to ensure food security and manage water demand in the face of climate change, specifically under drought and high temperature stress. Adaptation planning related to sustainable agricultural water management is vital for the future food security of Bangladesh.

Adaptation planning is essential to cope with future climate change. Planned climate change adaptation refers to the actions, which are to be undertaken to minimize the risks of climate change and maximize the associated opportunities by reducing vulnerability (Smit and Pilifosova, 2003). Adaptation planning addresses what needs to be done more, less or differently by whom, and with what resources (Füssel, 2007). Anticipatory adaptation planning includes different steps such as the assessment of recent and future vulnerability, identification of adaptation options, prioritization of potential options, implementation of prioritized options, and monitoring and evaluation of the effectiveness of implementation (Champalle et al., 2015). The prioritization of adaptation options indicates which measure(s) is/are to be considered first for implementation in order to properly deal with the impacts of climate change. However, identification and assessment of adaptation measures is one of the pre-requisites for effective planned adaptation (Füssel, 2004).

Two approaches, which are usually applied in adaptation assessment, are hazard-based and vulnerability-based approaches (Lim et al., 2005). The first approach starts from model-based climate change projections, and hence, consideration of non-climatic factors is limited in this approach. The second approach starts from the experience with managing recent climate risks by directly involving the stakeholders in the adaptation assessment (Füssel, 2007). The hazard-based approach is most useful for raising awareness regarding the problem or identifying research priorities. Whereas, the vulnerability-based approach is most useful for assessing the effectiveness of specific interventions, especially if the resources, in terms of data, expertise, time, and money are limited (Füssel, 2007).

Adaptation planning must be context specific since it depends on the local environmental, climatic, social and political conditions. The contextual aspects of adaptation planning can be addressed well in adaptation assessments by involving local experts and stakeholders. This process, by specifying policy priorities, would ensure a successful implementation of an adaptation program. Moreover, involvement of local stakeholders can remove or minimize the gap between top-down and bottom-up approaches. According to Lobell et al. (2008), the priorities will depend on the risk attitudes of investment institutions since uncertainties vary considerably with crop types in South Asia. Therefore, involvement of stakeholders from local level investing institutes could be effective in prioritizing operational adaptation measures.

Identification of measures applicable for a region is the first step in adaptation planning that needs to consider the local context. Identification of possible effective options for the local context sets the basis of an adaptation assessment. For example, development of a salt-tolerant crop variety would be an effective adaptation measure for the saline Southern part, but not for the non-saline Northern part of Bangladesh, for which selection of drought-tolerant crop varieties would be a more effective measure. Therefore, if the government of Bangladesh plans to reduce rice cultivation in the Northern part but promotes it in the Southern part, first, they must ensure the development of high yielding salt-tolerant rice varieties.

The evaluation of specific adaptation options/alternatives aims to identify the preferred measures (Smit and Wandel, 2006). For anticipatory adaptation, prioritization of measures is required after identification of suitable adaptation measures. Ranking or prioritization of the measures ensures that (i) the best option has been considered first for the evaluation, test or implementation, (ii) the best option has not been skipped to implement a contradictory less beneficial option, (iii) the best possible actions have been taken in a resource-limited situation.

Adaptation actions are closely linked to development activities, which need to be considered in evaluating the adaptation measures (Smit and Pilifosova, 2003). Different social and individual factors limit the adaptation actions (Adger et al., 2009). For developing countries, the primary challenge on adaptation to climate change is to promote adaptive capacity in the context of competing development objectives (Adger et al., 2003). Therefore, ranking of options could help moving forward and taking actions to implement effective measures to cope with climate change.

Agriculture, water availability and water demand are all sensitive to climate conditions. Agricultural systems have varying degrees of capacity to cope with climate change and adapt to changing conditions (Feenstra, 1998; Reilly, 1995). However, agricultural water management under water-limited situation in a developing country with poor economic condition and high population growth, such as Bangladesh, is an enormous challenge. Based on local conditions, farmers usually take steps to adapt to the changed situations. Although, most of the recent adaptation works in Bangladesh focus on the coastal zone, adaptation planning is also needed for other parts of the country where agriculture plays a major role in contributing to the food security of the country. Farmers in the Northwest Bangladesh have been adapting various practices to cope with drought, mainly through agronomic management, water resource exploitation, and crop intensification (Habiba et al., 2012a). Some of the practices used by the local farmers (e.g., withdrawal of large quantity groundwater with deep tubewells for rice irrigation) to cope with drought can become ineffective or detrimental from the view of sustainability of the system. Therefore, it is very important to identify which options should be prioritized for Northwest Bangladesh for better agricultural water management by ensuring sustainable water use under climate change.

Different methods are available to rank adaptation options; ranking can be done through Cost-Benefit Analysis (CBA), Cost-Effectiveness Analysis (CEA), and Multi-Criteria Analysis (MCA). The evaluation of costs and benefits is difficult due to the inherent uncertainty in climate change adaptation studies. Also, for a low developed country like Bangladesh, prioritization of adaptation options based on social cost-benefit analysis is not feasible due to insufficient data. Füssel (2009) commented that, prioritization of national level adaptation measures based on social cost-benefit analysis is not even feasible for a country with high economic, institutional and technical capacity. Prioritization of adaptation options based on cost-effectiveness analysis is also infeasible in case of insufficient data. UN advocates MCA as the preferred method for least developed countries to prioritize and select adaptation measures (Brooks et al., 2009). MCA is a widely used method to prioritize adaptation options related to climate change. This method can be used as an effective decision-support system involving several decision makers. Multi-criteria decision analysis being coherent with the real decisions is able to support real decision processes (Boettle et al., 2013). Different stakeholders' interests can be incorporated into decision processes by MCA.

The main objective of this study is to identify and prioritize adaptation measures in Northwest Bangladesh to cope with climate change. The approach used for the identification of adaptation measures was the review of recent adaptation plans and stakeholder consultation. Prioritization and complexity assessment of the identified measures were done by following multi-criteria analysis based on opinions of local experts/stakeholders. Further, we reviewed the social, institutional and technological dimensions of adaptive capacity in the context of Northwest Bangladesh to better understand the associated complexities for implementing adaptation measures.

5.2. Methodology

5.2.1. Identification of adaptation options

A detail review of the literature was done to gather information on recent development plans for adaptive agricultural water management in Bangladesh. The selection of literature focussed on recently published reports by government authorities that work on climate change impact and adaptation in relation to planning. Suitable adaptation options for sustainable agricultural water management in the Northwest part of Bangladesh were identified based on literature review and stakeholder consultation. The listed options were checked to prepare a short list and avoid repetition. However, some of the options, although different from management point of view or inherent objectives, are very closely linked. The identified adaptation options were divided into six categories based on sector and management objective. The categories are: crop production management (CPM), land use management (LUM), water management (WM), environmental management (EM), social and institutional management (S&IM), and education and research (E&R). The identified adaptation options were also classified based on their type of dependency and level of strategy (Table 5.1). Note that, as Noble et al. (2014) mentioned, any categorization of adaptation options is unlikely to be universally agreed upon, but the categorization takes into account the diversity of adaptation measures for different sectors and stakeholders.

Table 5.1

Classification of adaptation to climate change.

Concept	Types	Explanation
Type of dependency	*In-system dependent*	Measures that are implementable by local water managers or farmers without any dependency on other systems or bodies. For example, local agricultural or water management authorities can adjust their irrigation method (e.g. shifting from basin/furrow irrigation to drip/sprinkler irrigation method for vegetables and some other crops) by themselves; hence, adjustment of irrigation method is an *in-system dependent strategy*.
	Out-system dependent	Strategies that rely on systems or bodies other than local agricultural or water management authorities for successful implementation. For example, development and dissemination of updated irrigation technologies is dependent on policy makers to support exploration and extension of new irrigation technologies (e.g. promoting solar irrigation in areas with no electricity, etc.) by research and extension institutes; hence, development and dissemination of updated irrigation technologies is an *out-system dependent*.
Level of strategy	*On-farm*	Measures that are implemented at farm/community level.
	Off-farm	Measures that are implemented beyond farm/community level.

5.2.2. Prioritization of adaptation options

Following the evaluation criteria used by de Bruin et al. (2009) for ranking adaptation options in the Netherlands, we used four criteria – importance, urgency, no-regret, and co-benefits – to prioritize adaptation options. The importance of an option indicates the level of its necessity to implement the option in order to avoid negative impacts and/or utilize positive impacts of climate change by taking into account the local perspectives. A highly important option is one that can greatly reduce the detrimental impacts of climate change. The importance, thus, concerns about the capacity or skill of an option. The urgency of an option implies how quickly the option needs to be implemented to deal with an on-going or near possible detrimental or problematic situation. A highly urgent option indicates that the option should be implemented immediately to reduce or stop negative effects of climate change. The urgency concerns about the timing of implementation of an option. A high score on urgency, however, does not necessarily indicate an overall high-ranked option since an option can be very urgent only because of its delayed implementation can cause higher costs or irreversible damages (de Bruin et al., 2009). The no-regret characteristics of an option indicate how good an option can still be under a minor climate change situation or when the impacts of climate change are not noticeably considerable. So, a high-scored no-regret option is one that needs to be implemented irrespective of climate change. In another words, no-regret options are the options that would be justified under all plausible future scenarios considering the absence of human-induced climate change (Willows et al., 2003). Therefore, the no-regret characteristics concern about the flexibility to implement an option under variable situations. The co-benefits of an option indicate how good an option is in contributing to other related sectors or objectives (e.g., to reduce poverty). Hence, the co-benefits concern about the independent additional benefits of implementing an option.

Assessment of different adaptation options was done in consultation with experts having detailed knowledge on the specific problems and with other stakeholders of the Northwest Bangladesh. Research institutes and universities from which experts/stakeholders participated for providing information on MCA included BADC, BARI, BRRI, BSRI, BINA, DAE, RDA, BAU, SAU and BSMRAU (see Appendix D for full names of the organizations). The adaptation measures were prioritized through multi-criteria analysis. Several other studies (e.g., Agrell et al., 1998; Almasri and Kaluarachchi, 2005; Joubert et al., 2003; Raju and Kumar, 1999) have also employed the MCA method to prioritize adaptation measures for national-level ranking of adaptation alternatives. de Bruin et al. (2009) used MCA based on stakeholder analysis and expert judgement for qualitative assessment of adaptation options to cope with climate change in the Netherlands. MCA is a well-established methodology (Greco et al., 2016).
A numerical score of 1 to 5 was assigned by experts/stakeholders to each of the adaptation options. The scores, therefore, represent the experts'/stakeholders' judgements about each option. This step was subject to various biases, for example, the experts' distinguished concept about possible future condition, job type and/or posting, etc. However, in this study, we have not distinguished between the types of experts/stakeholders. Also, the experts/stakeholders were asked to set weights to the criteria. The adaptation options were prioritized based on the final weighted-score per option.

The weighted score was calculated by

$$WS_{xi} = W_i \times S_{xi} \tag{5.1}$$

where, WS_{xi} is the weighted score of option x under criterion i, W_i is the weight of criterion i assigned by an individual expert/stakeholder, and S_{xi} is the score for option x under criterion i assigned by an individual expert/stakeholder.

The final score under each criterion was calculated by

$$FS_{xi} = \frac{\sum WS_{xi}}{\sum W_i} \tag{5.2}$$

where FS_{xi} is the final score of option x under criterion i.

The overall final score used for ranking and identifying complexity of an adaptation measure was the average final score of selected criteria.

5.2.3. Assessment of complexity and adaptation capacity

The complexity to implement an option reflects how difficult it is to implement the option under prevailing local perspectives. The complexities of adaptation measures were assessed through Multi-Criteria Analysis following the same procedure as discussed in previous section. Following the feasibility criteria used by de Bruin et al. (2009), we used three criteria – technical, social and institutional complexities – to assess the overall complexity of the identified adaptation options. A high score in complexity indicates that an adaptation measure is difficult to implement under current technical capacity, social acceptance and institutional setup. The technical complexity entails the level of difficulty to implement an option due to lack of technical expertise, instruments, etc. related to that specific adaptation measure. The social complexity, on the other hand, indicates the level of difficulty of an option to get accepted by the farmers or local level practitioners. The institutional complexity indicates the level of institutional weakness or lack of institutional setup to implement an option at a large scale in the study region. Moreover, recently published scientific articles and grey literature were reviewed to explore the social, institutional and technological dimensions of adaptive capacity in the context of Northwest Bangladesh.

5.3. Results

5.3.1. Recent adaptation plans and identified measures

Adaptation to climate change has been mainstreamed in Bangladesh in a number of policies, such as *National Adaptation Program of Action*, *Bangladesh Climate Change Strategy and Action Plan*, *National Adaptation Plan*, *Vision 2021, Bangladesh Delta Plan 2100*, and *National Perspective Plan* (MoA, 2015; Planning Commission of Bangladesh, 2015). Climate change was a key concern in re-drafting the National Water Management Plan (NWMP). The key adaptation needs, applicable for the drought-prone Northwest Bangladesh, are listed in Appendix (Table D.1) based on recent policy decisions (BDP2100, 2017; MoEF, 2009, 2012; NAPA, 2005). Bangladesh identified 15 priority activities in the National Adaptation Program of Action (NAPA) in 2005 and updated these activities to 45 programs in 2009 (World Bank, 2010). NAPA was a pioneer step in the identification and prioritization of adaptation measures in Bangladesh (Rahman et al., 2007). Some of the prioritized actions are applicable for all sectors, e.g. capacity building for integrating Climate Change in planning and development, mainstreaming adaptation into policies and programmes in different sectors, development of eco-specific adaptive knowledge, etc. However, some options are applicable for the adaptive agricultural water management in the drought-prone Northwest part of Bangladesh, such as promotion of research on drought-tolerant crop varieties, exploring options for insurance, etc. The prioritized measures of NAPA (2005) are very broad and useful for policy planning level. For local practice, learning by doing and field-level implementation of specific measures are required. The actions of developing and testing adaptive measures in drought-prone areas by appropriate cultivars, cropping patterns, land and water management practices, and effective dissemination of farmers have been recommended by BCCSAP under the programme of adaptation against drought, salinity submergence and heat (MoEF, 2009). To ensure adequate water supply, BCCSAP suggested to monitor changes in water quality and quantity, and to forecast future changes due to climate change under water and sanitation programme for climate vulnerable areas (MoEF, 2009). Bangladesh Delta Plan 2100 has recently prepared adaptation pathways for *Barind* and drought-prone areas of Bangladesh. The inventory of identified measures in this study include crop production management (18 options), land use management (7 options), water management (19 options), environmental management (9 options), social and institutional approaches (13 options), and education and research activities (6 options). The full inventory of adaptation measures is provided in Appendix A (Tables D.2–D.7). Some of the options are very specific (e.g., alternate wetting and drying, rain water harvesting, etc.), while some other options are broad (e.g., integrated water resources management, integrated crop management, etc.). The identification of adaptation measures in this study did not focus on any specific scale, type, level or approach. Some of the options can directly reduce the water demand for crop agriculture (e.g., rain-fed agriculture, deficit irrigation, AWD, etc.), or directly increase the water availability (e.g., enhancing capacity of sluice or weir, international co-operation to increase surface water flow, etc.), while some other options are important for long-term sustainable use of water resources (e.g., agro-environmental schemes, water pollution control, etc.) and/or indirectly help water management to cope with climate change impacts. Hence, the identified measures are of mixed type of dependency and level of strategy (Fig. 5.1).

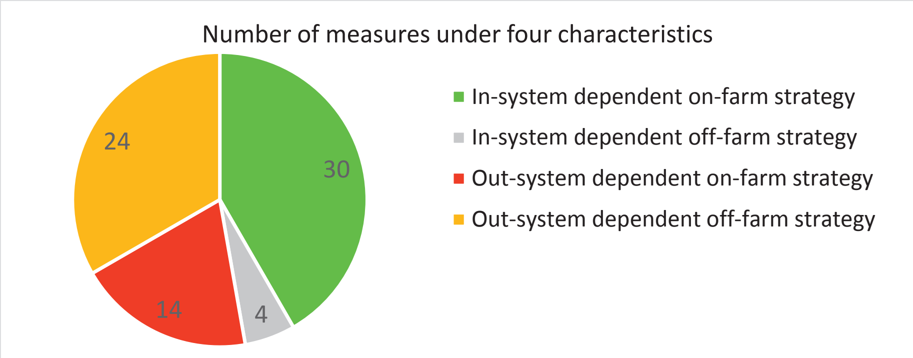

Fig. 5.1 Number of identified measures under different types of dependency and level of strategy.

3.2 Top-priority options

Two crop production management options (option number 16 and 3), one land use management practice (23), four water management measures (29, 27, 31 and 26), one social/institutional approach (58), and two education/extension/research related options (69 and 67) were ranked as the top ten prioritized adaptation options (Table 5.2). The prioritization was based on experts'/stakeholders' judgement, taking into account importance, urgency, no-regret characteristics and co-benefits of the options. International co-operation to increase surface water flow received the highest score for all criteria. No environmental management measure obtained high enough score to rank it among the top ten options. The top most option from environmental management sector was the waste management to reduce water pollution. Sector-wise average weighted score, as compared in Fig. 5.2, indicates the highest priority for education and research related activities (score 3.61). The average weighted score of social & institutional approaches, water management measures, environmental management, crop production management and land use management was 3.33, 3.32, 3.13, 3.01 and 2.87, respectively. Most of the top-priority options are of out-system dependent and on-farm strategy (Table 5.2). Only three in-system dependent measures, i.e. fully implementable measures by local agricultural water managers or farmers were found within the top-ranked ten options. The average weighted score under different adaptation characteristics also indicates stakeholders' preference for out-system dependent on-farm strategy (Fig. 5.3). In-system dependent on-farm strategy was the least preferred option by stakeholders.

Table 5.2

List of average scores under different criteria and weighted score of ten top-priority measures.

SL No.	Adaptation measures	Type of dependency	Level of strategy	Importance (32.33)*	Urgency (29.67)	No regret (18.5)	Co-benefits (19.5)	Weighted score**
58	International co-operation to increase surface water flow	out-system	off-farm	4.73	4.67	4.32	3.84	4.39
29	Integrated water resources management	out-system	on-farm	4.61	4.32	3.86	3.47	4.07
27	Adjustment of irrigation method (e.g., drip, sprinkler or buried pipe irrigation)	in-system	on-farm	4.34	4.07	4.04	3.67	4.03
16	Integrated crop management	out-system	on-farm	4.53	4.17	3.76	3.54	4.00
31	Alternate Wetting and Drying method for rice cultivation	in-system	on-farm	4.28	4.06	3.73	3.66	3.93
23	Conservation of agricultural lands	out-system	off-farm	4.30	3.90	3.82	3.59	3.90
69	Education and research on climate-smart agriculture	out-system	off-farm	4.32	4.03	3.49	3.53	3.84
26	Adjusting irrigation scheme; irrigation system evaluation and adjustment	in-system	on-farm	4.48	3.98	4.05	2.86	3.84
67	Development and dissemination of updated irrigation technologies	out-system	on-farm	4.24	4.16	3.63	3.25	3.82
3	Choice of drought-resistant and high-temperature tolerant crop varieties	out-system	on-farm	4.44	3.84	3.87	2.93	3.77

* The value within parenthesis under each criterion indicates the average weight of that criterion.

** A high score indicates that the measure is of top priority.

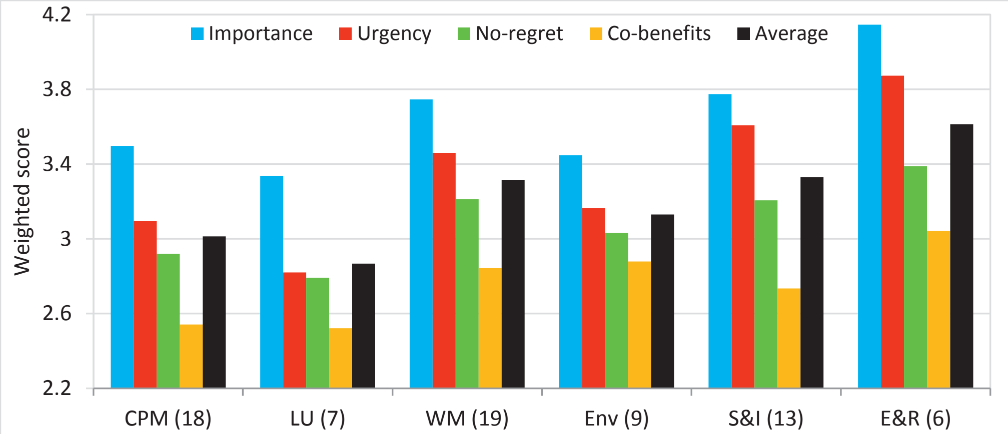

Fig. 5.2 Average weighted score for different prioritization criteria under six adaptation categories, i.e. crop production management (CPM), land use management (LUM), water management (WM), environmental management (Env), social and institutional management (S&I), and education and research (E&R).

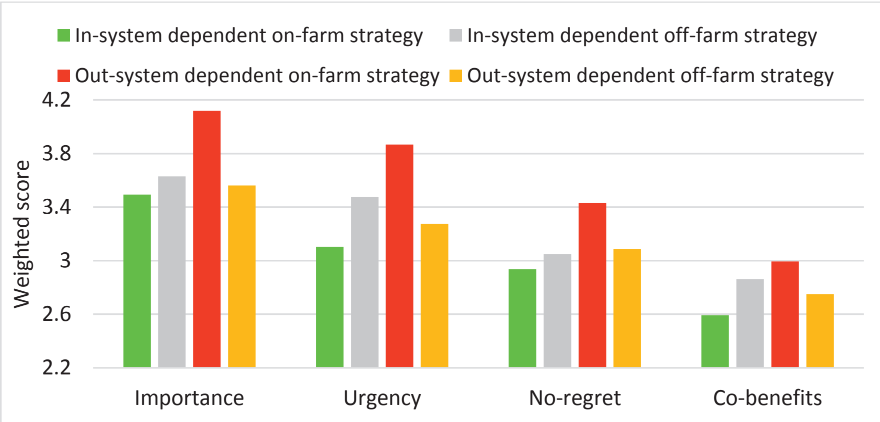

Fig. 5.3 Average weighted score of four adaptation characteristics under four prioritization criteria.

3.3 Most complex options

One crop production management option (option number 15), two land use management practices (21 and 19), two water management measures (41 and 33), three environmental management measures (50, 46 and 48), and two social/institutional approaches (58 and 65) were scored highest by the experts/stakeholders and listed as the ten most complex options (Table 5.3). Increasing crop lands by clustering the scattered households received the highest weighted score (3.86) on complexity and was listed as the most complex adaptation option. However, the *Rural Development Academy* (RDA) has already initiated a pilot rural housing project, called *Pallijanapad*, in three districts to increase crop land by clustering the scattered households. None of the options from the education and research sector was within the top ten complex options. International co-operation to increase surface water flow was the only option that was within both the top prioritized and most complex options; it was also the most complex option under institutional complexity category. Options that are both within the ten least prioritized and most complex options are the relocation or mobilization of farms, fair (re)allocation of water among different regions and construction of greenhouses/crop houses.

Three crop production management options (option number 18, 14 and 5), one land use management practice (22), two water management measures (31 and 38), three social/institutional approaches (61, 63 and 62), and one option from education and research (72) received the lowest scores by experts/stakeholders and are ranked as the top ten least complex options to implement. Training programs for on-farm water management was the least complex measure. None of the options from the environmental management sector was within the least complex ten options. Rain-fed crop cultivation was the least complex measure from technical point of view, while developing meteorological stations to support better forecasting was the least complex measure from social point of view. Alternate wetting and drying method of irrigation for rice cultivation was the least complex measure from institutional point of view. It is the only option that was both within the ten most prioritized and least complex adaptation options.

Sector-wise average weighted score (Fig. 5.4) indicates a high social complexity, but less technical and institutional complexities for crop production management options. There are high technical, social and institutional complexities for land use management and environmental management measures. All three criteria show a medium-level complexity for water management measures. A medium technical complexity, low-level social complexity and high-level institutional complexity were found for social and institutional approaches and educational & research related measures.

Table 5.3

List of average scores under different criteria and weighted score of ten most complex measures.

SL No.	Adaptation measures	Technical (36.5)*	Social (34.33)	Institutional (29.17)	Weighted score**
21	Increasing crop lands by clustering scattered households	3.87	4.12	3.61	3.86
19	Relocation or mobilization of farms	3.61	4.04	3.10	3.58
50	Restoration of ecosystems	3.79	2.88	3.82	3.50
46	Waste management to reduce water pollution	3.60	3.43	3.34	3.46
41	Fair (re)allocation of water among different regions (more to affected areas)	3.26	3.45	3.35	3.35
58	International co-operation to increase surface water flow	3.22	2.47	4.33	3.34
65	Climate risk management measures	3.58	2.96	3.48	3.34
15	Construction of greenhouses/crop houses for fruits and vegetables cultivation	3.44	3.55	3.02	3.34
33	Reconnection of water systems	3.84	2.78	3.34	3.32
48	Implementation of effective agro-environmental schemes	3.37	2.97	3.58	3.31

* The value within parenthesis under each criterion indicates the average weight of that criterion.

** A high score indicates that the measure is more complex to implement.

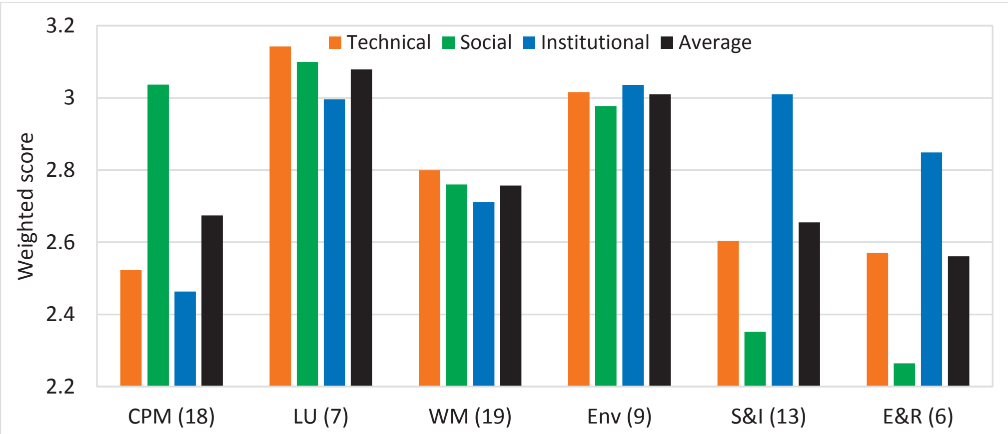

Fig. 5.4 Average weighted scores for different complexities under six adaptation categories, i.e. crop production management (CPM), land use management (LUM), water management (WM), environmental management (Env), social and institutional management (S&I), and education and research (E&R).

The analysis of average weighted score of different adaptation characteristics under different complexities indicate a relatively lower technical and institutional complexities of in-system dependent on-farm strategy compared to other strategies (Fig. 5.5). The technical and institutional complexities are highest for the out-system dependent off-farm strategies. The out-system dependent on-farm and off-farm strategies also entail higher technical and institutional complexities compared to the in-system dependent on-farm strategies.

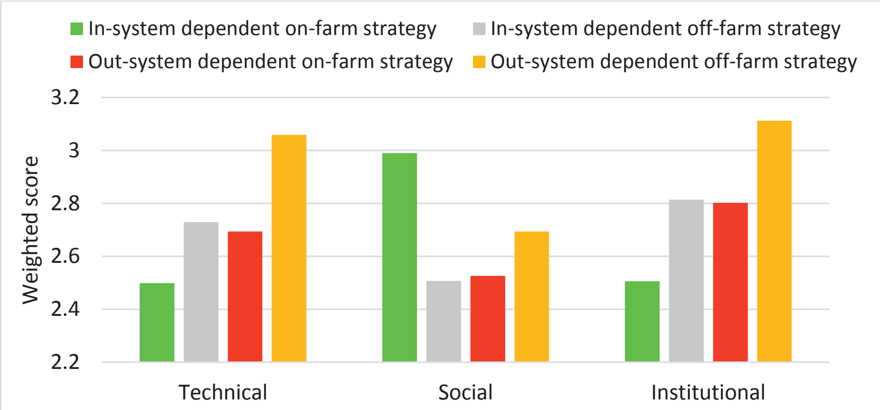

Fig. 5.5 Average weighted score of different adaptation characteristics under different complexities.

The prospects and constraints of the existing social, institutional and technological dimensions of adaptive capacity for water management in Bangladesh are summarised in Table 5.4. The review of prospects and constraints related to social, institutional and technological dimensions of adaptive capacity for water management reflects the possible reasons of high social, institutional or technical complexities in Bangladesh. Increased facilities for farmers, institutional capacity development and technological resource development could be the key actions to eradicate the complexities.

Table 5.4

Prospects and constraints related to social, institutional and technological dimensions of adaptive capacity for water management in Northwest Bangladesh.

Adaptive capacity	Prospects	Constraints	References
Social	• farmers in Northwest Bangladesh can identify recent climatic changes • people are changing livelihood status with changing climate • farmers has capacity to autonomously adjust with some changes	• existing level of adaptation by farmers is limited • large number of vulnerable small holder farmers • poor economic conditions of farmers limit their activities towards expensive but effective adaptive solutions • lack of awareness • lack of secured land tenure rights	Anik and Khan (2012); Habiba et al. (2012b); Islam and Nursey-Bray
Institutional	• responsible institutions have initiated activities towards capacity building • policy level contributions by institutions • responsible institutions have formulated several adaptation programmes • better negotiation capacity of local institutions • responsible institutions have mainstreamed climate change at sectoral level • training courses for government officials	• over-emphasis on technological aspects by local institutions • lack of acknowledgement of cultural factors • failure of practicing institutional communities to mediate and create linkages with informal institutional communities • occurrence of mal-adaptation by formal institutes • lack of mainstreaming climate change in field activities • lack of investment for drought prone areas • low investment for capacity building and institutional strengthening	Faisal (2017); Haq and Rabbani (2011); Islam and Nursey-Bray (2017); Mondal (2010)
Technological	• gradual advancement in crop variety development • rapid extension of mechanized agriculture • beneficial return from the investment in agricultural research • development in ICT sector and improved access to internet	• lack of advanced research equipment • lack of resources for learning, access to global knowledge and databases, and research • fund constraints and donor-driven research • lack of advanced technologies for water and soil management • limited access to existing facilities, information and technologies	Haq (2017); Mondal (2010); Nagy (2000); Ramos (2015); Roy and Singh (2008)

5.4. Discussion

5.4.1. Identified adaptation measures

The inventory of adaptation measures presents a broad range of adaptation options applicable for the Northwest Bangladesh. Most of these options are applicable not only for Bangladesh, but also for any other regions of the world under challenges of water shortage for crop agriculture. However, the capacity, suitability and feasibility of those options to deal with local-level climate change impacts will be different for different regions. For example, the alternate wetting and drying is an important measure for rice cultivating regions only. Although salinity is an important issue for Southern Bangladesh, no salinity management measures were included in this inventory since we focused on Northwest part of Bangladesh only. The purpose of preparing an inventory of adaptation options was not to limit our activity within the identified measures, but to move forward to the planning process and effective decision-making with the existing measures. The identified adaptation options were prioritized to enable and accelerate effective actions for a better agricultural water management.

5.4.2. Top priority measures: recent progress and future prospects

Transboundary cooperation to increase surface water flow during dry months was the top-demanded option according to our study. For a country like Bangladesh having 57 trans-boundary rivers, which originate at outside of its border and most of which are distributaries (Chowdhury, 2010), trans-boundary water cooperation is a vital issue for sustainable development of the country. BDP2100 (2017) developed adaptation pathways for *Barind* and drought-prone areas of Bangladesh and identified the trans-boundary cooperation in the Ganges-Brahmaputra basin as an important measure. Although international cooperation to increase surface water flow was the top option, it was also one of the most complex options. The option is of higher scale strategy and highly out-system dependent due to its political dimension. Dependence on a highly out-system strategy for future development could increase vulnerability and uncertainty and be risky. Since, the option is an off-farm strategy, local agronomic practice and water management cannot fully rely on this.

The top most adaptation measure from water management category was the integrated water resources management practices. The Flood Action Plan (1989-95), Bangladesh Water & Flood Management Strategy (1995), Ganges Water Treaty (1996), National Policy for Safe Water Supply and Sanitation (1998), National Water Policy (1999), Guidelines for Participatory Water Management (2000), National Water Resources Database (2001), National Water Management Plan (2004), Regional Technical Assistance (2009), and Bangladesh Water Act (2013) are the major examples of IWRM development plans in Bangladesh (Alam and Quevauviller, 2014). Therefore, the best practices of IWRM need to be enhanced by systematically identifying the variables and conditions, which create implementation gaps (Mitchell, 2009). The required best practices of IWRM can be identified by research. Hence, education and research on IWRM (option number 71), which ranked 14 in this study, needs special attention for successful implementation of IWRM practices in local regions. IWRM is an on-farm strategy, i.e. for practice by local water managers and farmers. However, IWRM is a cross-sectorial policy approach and a broad concept and, therefore, it is often difficult to define what aspects should be integrated, by whom, how, or even if such integration in a wider sense is possible (Biswas, 2004). The future development and success of IWRM for a region is not 100% obvious because of its out-system dependence. Insufficient local people's participation and stakeholders' involvement, uncoordinated planning and development, poor project conceptualization, lack of post-evaluation of projects, gap between local initiatives and national projects, and high dependency on international donor funds remain the main constraints to IWRM in Bangladesh (Das Gupta et al., 2005; Datta, 1999; WARPO, 1999). However, since several institutes in Bangladesh are working during recent years on IWRM, it may show progress in the coming years.

Several institutes are working to improve irrigation method in Bangladesh. Barind Multi-purpose Development Authority (BMDA) developed low cost channel for improving water distribution system since 1980. Rural Development Academy, RDA, implemented a project, technically assisted by FAO in 1982, to introduce buried pipe method in Bogra. During the recent decade, Bangladesh Agricultural Development Corporation (BADC) has constructed some large-scale buried pipe lines in Northwest Bangladesh. During recent years, successful example of solar irrigation system is also found in Northwest Bangladesh. The country has built 320 solar irrigation pumps benefiting 8,000 farmers (World Bank, 2016). The adjustment of irrigation method is an on-farm strategy, therefore, the local water managers or farmers may adjust differently for different locations based on type of crops grown, soil condition, farm structure, power availability, etc. Since adjustment of irrigation method is an in-system dependent strategy, the future development and success is obvious under a positive attitude of local water managers and farmers.

The top most adaptation measure for the crop production management category was integrated crop management, ICM. The study by Gaunt et al. (2000), based on consultation with farmers, confirmed that there is a need for ICM at the farm level of Bangladesh. Several organizations, such as Department of Agricultural Extension (DAE), Bangladesh Rice Research Institute (BRRI) and *Proshika*, have undertaken activities to implement ICM. During 2001–2004, BRRI in collaboration with *Rangpur Dinajpur Rural Service*, and *Grameen Krishi Foundation* implemented a sub-project in the Northwest Bangladesh on ICM with one of the objectives to increase water use efficiency (Magor et al., 2007). DAE implemented ICM activities in 217 Upazillas of 32 districts in North, Northwest and Southern part of Bangladesh.

ICM is an on-farm strategy with a broad concept. Therefore, ICM has the capacity to combine the local knowledge with on-going research and new technologies. Moreover, it can be considered specifically and differently for different local situations. However, the development and success of ICM is not obvious due to its out-system dependency. Since several institutes are working on ICM and farmers in the Northwest Bangladesh have the capacity to adjust with changes, this option may show reliable progress in the coming years. On the other hand, since ICM is an on-farm strategy, social constraints like poor economic conditions and lack of awareness and facilities to farmers may hinder the progress of ICM. From an institutional perspective of ICM, there is a lack of integration between agricultural and water management sectors (Gaunt et al., 2000).

5.4.3. Complexities in implementing adaptation measures

The prioritization of adaptation options and assessment of associated complexity to implement those options indicate that there is a huge gap between what is required and what is feasible. Therefore, special attention is required to eradicate complexity of top-ranked options. Different categories of adaptation options have different kind and level of complexity. The changes in crop production management reveal relatively high complexity in terms of social acceptance rather than the technical capacity and institutional setup. The water management measures show moderate complexity technically, socially and institutionally compared to the measures under other categories. Social/institutional approaches and educational/research measures reveal high technical and institutional complexity. Land use and environmental management measures show very high technical, social and institutional complexity. The feasibility study by Gain et al. (2012) showed that weakness in local technical capacities for water management and lack of institutional coordination are the current main constraints to climate change adaptation in Bangladesh.

The review of prospects and constraints related to social dimension indicates that increased facilities to farmers, (e.g., economic assistance, access to knowledge, etc.) may increase the social adaptive capacity, which will reduce social complexity. Since there is high social complexity in crop production, land use, water and environmental management measures, facilitation of farmers would be helpful for those sectors. The review of prospects and constraints related to institutional dimension indicates that capacity building and mainstreaming climate change adaptation would contribute much to increase institutional capacity. Since there is high institutional complexity in every sector except crop production management sector (Fig. 4), capacity building and mainstreaming climate change adaptation would contribute much to all those sectors. The review of prospects and constraints related to technological dimension indicates that resources development (e.g., research facilities, data availability, etc.) will contribute much to increase the technological capacity. Therefore, technological resources development will support land, water and environmental management.

5.4.4. Required actions towards effective planning

The findings in this study indicate that there is a clear preference among stakeholders to choose higher scale *out-system dependent* strategies that aimed to minimise the impacts of climate change on agricultural systems in the Northwest, rather than *in-system dependent* options that focus on changing the agricultural or water management system itself to cope with the impacts. This is surprising as there is ample opportunity within the agronomic system to opt for adaptation of the agricultural system to the changes with possible obvious development and success. Whereas, the preferred higher scale *out-system dependent* strategies are all complex to implement and puts dependency of success on '*outsiders*'. However, there is opportunity to invest in adaptation of the agricultural system, which would seem a much saver fall-back option. It is essential to highlight this further among stakeholders and institutions, since, when complex abate options fail, changes will impact local production systems. Therefore, short or medium-term planning should explore the opportunities within the local agricultural system to ensure clear and obvious development and success.

For long-term planning, it is essential to transform the complex options into feasible measures by capacity building at national and local levels, and mainstreaming climate change adaptation into development process. A framework proposed by Huq and Ayers (2008) to build national capacity on climate change adaptation for mainstreaming could be effective in this regard. As different categories of adaptation options have different kinds and levels of complexity, the capacity building requires specific objectives to reduce those complexities. For example, since crop production management has high social complexity, the capacity building by social awareness and farmers training would be helpful in this regard.

5.4.5. Implications, limitations and scope for future research

For a sustainable future under climate change vulnerability and resource-limited condition, prioritization of adaptation options and assessment of associated complexity to implement those options undertaken by this research will support the policy design and decision-making. Studies related to the cost and benefits of adaptation measures during the pilot studies or the initial phase of implementation of those options are required before large-scale implementation. The set of top-priority options does not reflect a conflicting or competitive choice among different alternatives to implement at the local level. Rather, it is possible to combine or integrate those top-priority options under a framework to implement simultaneously or sequentially as required by a specific region. Identification of interconnections of the prioritized options and following a combined approach can help sequential, simultaneous, and timely implementation of those measures. Moreover, the combined approach will ensure flexibility to reach targets. For example, identification of drought-resistant or temperature-tolerant crop varieties has a close link with the selection of suitable cropping pattern. If future research can develop better drought-resistant and temperature-tolerant rice variety then the future cropping pattern should be dominated by rice crops, otherwise it should be planned with crops that are already suitable for high-temperature climate, e.g. date palm.

The experts'/stakeholders' participation was a prerequisite to conduct the multi-criteria analysis. The selection of top-priority measures based on only expert judgement without technical or economic evaluation may not reflect a complete judgement to those options, but it can reflect which options need more attention for future technical or economic studies. Use of selected criteria for the MCA has a limitation of interdependency among them (Brooks et al., 2009). The ranking of adaptation options for the Northwest Bangladesh provides an initial priority measures for an anticipatory planning. For different areas of the Northwest Bangladesh, different options could be more effective based on different degrees of local climate change, and soil and water availability. Therefore, technical studies during pilot projects for top-ranked adaptation measures are highly recommended.

5.5. Conclusion

This study identified and ranked adaptation options for better agricultural water management to cope with climate change in Northwest Bangladesh. Local experts/stakeholders mainly prefer integrated, cooperative and advanced technological strategies that are mostly *out-system dependent* strategies. Most of the top listed option also involve high technical, social or institutional complexity. On the other hand, the *in-system dependent* on-farm strategies are more reliable and may ensure successful implementation and gradual development. Therefore, for short- or medium-term planning, priority of *in-system dependent* strategies over *out-system dependent* strategies is essential. For long-term adaptation planning, actions are required to reduce the associated complexity of the top-ranked measures. Eradication of the associated complexities may support large-scale implementation of complex strategies in the future.

CHAPTER 6

Synthesis

6.1. Introduction

The drought-prone Northwest Bangladesh is vulnerable to the impacts of climate change. A complete understanding of recent and future possible changes in water requirements and exploration of water demand management options are essential for the sustainable development of this region. Despite some on-going scientific research on this topic, uncertainty exists about how the water demand for crop agriculture will change under climate change. Also, the ranking of adaptation measures is rarely developed with focus on water demand management. This study addresses these knowledge gaps through achieving two research objectives:

1. To quantify the recent and future changes in water requirements of dry season rice in Northwest Bangladesh; and
2. To identify and develop strategies to improve water demand management under possible agro-climatic changes.

These research objectives were achieved through a four-step procedure. First, the trends in recent water requirements of dry season *Boro* rice were estimated for the period of 1980–2013 in four Northwest districts of Bangladesh (Chapter 2). The water requirement terms used in this study are presented in Chapter 2. In this chapter, the influence of changes in different climatic parameters on the reference crop evapotranspiration was critically assessed. Second, the future possible changes in water requirements of *Boro* rice were estimated for 2050s and 2080s for a moderate (RCP 4.5) and rapid (RCP 8.5) climate change (Chapter 3). The trend analysis of recent changes is not sufficient for future long-term planning in context of climate change; as an extrapolation of recent trends cannot reflect the actual future situation in climate studies. Therefore, this research further focused on understanding the future consequences of climate change. The future possible changes in different water requirement components were quantified and compared to the base period (1980–2013) in Chapter 3. In this chapter, the influences of changes in different climatic parameters and crop phenology on different water requirement components were critically assessed. Third, the study focused on water demand management of *Boro* rice to cope with climate change. The effectiveness of shifting trans-/planting dates of dry season *Boro* rice was assessed (Chapter 4). The quantification of recent and future changes in water requirements (as presented in Chapters 2 and 3) is very important to fundamentally understand the direction of changes in agricultural water demand, but not sufficient for specific adaptation planning, e.g. shifting planting date, changing crop cultivars etc. Simple, cost-effective and easily-implementable strategies like, shifting trans-/planting dates are essential to assess for effective adaptation planning. The future water requirements of *Boro* rice for early, normal and late planting and possibilities of high temperature stress during critical periods were quantified in Chapter 4. In addition, the future water requirements of long-duration *Boro* cultivar for early, normal and late planting dates were quantified. Finally, the study focused on identifying and ranking suitable management strategies for improved agricultural water management to cope with climate change (Chapter 5). Quantitative studies are important to understand the effectiveness of an option (as presented in Chapter 4), but qualitative studies are appropriate for the assessment of several management options for policy preferences.

The following sections subsequently present the study's main results, synthesis of the main findings, methodological strengths and limitations, scientific contributions, recommendations for agricultural water demand management, and finally, outlook and perspectives for future research.

6.2. Main results

This section presents the study's main results for each research question.

Q1: *What are the impacts of recent climate change on water requirements of dry season Boro rice in Northwest Bangladesh? (Chapter 2)*

Following are the main results of this study that address the first research question.

- Significant decreasing trends of reference crop evapotranspiration were observed during 1980–2013 in the dry months due to increasing relative humidity and decreasing wind-speed and sunshine hours, despite a slight increase in temperatures.
- Decreasing trends of potential crop water requirement ($\sum ET_C$) of *Boro* rice were found due to decreasing reference crop evapotranspiration and shorter crop growing periods.
- High variations in trends of potential irrigation requirement for crop evapotranspiration ($\sum ET_C$– ER) were found among different districts due to variations in effective rainfall trends.
- The net irrigation requirement of *Boro* rice decreased, by 11% during the last three decades at an average rate of 4.4 mm/year, despite a slight decrease in effective rainfall, mainly because of high rate of decrease of crop evapotranspiration (5.9 mm/year).

Q2: *What are the impacts of future possible climate change on water requirements of dry season Boro rice in Northwest Bangladesh? (Chapter 3)*

Following are the main results of this study that address the second research question.

- Reference crop evapotranspiration will increase in the future, mainly due to possible rapid increase in temperatures.
- Potential crop water requirement ($\sum ET_C$) of *Boro* rice will reduce because of a considerable shorter growing season due to the phenological response of rice to higher temperatures.
- The amount of irrigation water required to satisfy crop evapotranspiration demand ($\sum ET_C$– ER) will increase because of reduced rainfall accessibility under a shortened *Boro* season.
- Although daily water requirements will increase, the total net irrigation requirement of *Boro* rice will decrease by 1.6% in 2050s and 7.4% in 2080s for RCP 8.5 scenarios averaged over all climate models and districts.

Q3: *How effective is the shifting of trans-/planting date of Boro rice to adapt to future climate change? (Chapter 4)*

Following are the main results of this study that address the third research question.

- Shorter growth duration under late planting and longer growth duration under early planting compared to normal time planting were observed.
- A shift of planting date from normal to late planting can substantially increase the rainfall availability for *Boro* rice cultivation. Hence, late planting can substantially reduce irrigation demand. However, the option is very limited due to both day- and night-time heat stress.
- Early planting accounts for high water demand but ensure suitable temperature during the critical growth stages of the crop.
- Normal planting dates show high possibility of day-time heat stress.
- The differences in effective rainfall and irrigation requirements between the planting dates seem larger for the long-duration variety compared to the usual duration variety.

Q4: *What are the suitable measures for the drought prone Northwest Bangladesh to cope with climate change? (Chapter 5)*

Following are the main results of this study that address the fourth research question.

- Transboundary co-operation, integrated water resources management and adjustment of irrigation methods are ranked as the top three measures by the stakeholders.
- Increasing crop lands by clustering scattered households, relocation/mobilization of farms, and restoration of ecosystems are the three most complex options.
- Experts/Stakeholders prefer higher scale 'out-system' dependent strategies that are aimed at minimising the impacts of climate change on agricultural systems.

6.3. Synthesis

Climate change will not increase the water requirements of rice but annual agricultural water demand may increase due to increase in cropping intensity.

The daily reference crop evapotranspiration (ET_o) has reduced over the last three decades due to climate change. The results of this study are consistent with the study of Chattopadhyay and Hulme (1997) who reported a reduced ET_o in recent decades over the Indian region despite a general increase in temperature. Mojid et al. (2015) also found decreasing trends of ET_o during 1990–2010 for Bogra and Dinajpur district of Bangladesh. Generally, it is considered that there will be an increase in ET_O as a consequence of global warming (Roderick and Farquhar, 2002). However, the estimated ET_O or the observed pan evaporation has been surprisingly shown to decrease in many regions over the past several decades including India (Bandyopadhyay et al., 2009; Chattopadhyay and Hulme, 1997; Jhajharia et al., 2009), China (Gao et al., 2012; Shen et al., 2010; Shenbin et al., 2006; Tang et al., 2011; Thomas, 2000; Wang et al., 2007), Thailand (Tebakari et al., 2005), USA (Hobbins et al., 2004), Australia

(Roderick and Farquhar, 2004) and New Zealand (Roderick and Farquhar, 2005). Many previously conducted research attempted to understand the relationship between ET_O and climatic variables. The decrease in solar radiation usually called global dimming due to increase in cloudiness caused by the decrease of global solar irradiance, urbanization and the increased air pollution and aerosols concentration lead to decrease in ET_O (Peterson et al., 1995; Roderick and Farquhar, 2002, 2004; Stanhill and Cohen, 2001; Wild et al., 2005; Zhang et al., 2011a; Zhang et al., 2011b). Changes in near-surface wind speed and relative humidity have also been pointed out for the last half century at different locations, and therefore, affecting ET_O (Cohen et al., 2002; McVicar et al., 2012; Roderick et al., 2007; Todisco and Vergni, 2008; Vautard et al., 2010; Wang et al., 2007). However, the radiation decrease caused by the increase of cloudiness or aerosol is the main cause of the decrease of ET_O from a global perspective (McVicar et al., 2012). This study indicates a significant decreasing trends of sunshine hour during dry months which could be caused by an increase in cloudiness. However, the combined effect of changes in different climatic parameters on ET_O could vary widely in different location and time scale.

Our model results show comparatively high reduction rates of reference crop evapotranspiration during the *Boro* growing season. Due to increasing temperatures rice plants mature faster, resulting in shorter growing seasons. As a result of the combined impacts of reduction in daily ET_o and a shorter growing season, the potential crop water requirements ($\sum ET_C$) in the Northwest districts significantly reduced during recent decades. The potential irrigation requirement for crop evapotranspiration, i.e. $\sum ET_C - ER$, showed a decreasing trend (except in Bogra) and the net irrigation requirement showed a decreasing trend. In the future, the daily reference crop evapotranspiration is likely to increase due to a strong increase in temperatures. The potential irrigation requirement for crop evapotranspiration, i.e. $\sum ET_C - ER$, showed an increase due to less accessibility of rainfall, the net irrigation requirement showed a decrease (except in 2050s for RCP 4.5) due to decreasing percolation loss during crop growth duration. However, all model estimates indicate a decrease in potential crop water requirement in the future. Hence, both the analysis of recent trends of and future changes in water requirements yielded robust signal of possible decrease in water requirements of dry season *Boro* rice (Table 6.1). In actual field conditions the amount of changes in water requirements could be different from the model estimates but the direction of changes predicted in this study is reliable due to the robust signal of possible changes.

Although we found decreasing trends of net irrigation requirements for both historical and future time periods, there is an important difference between recent and future changes with regard to the direction of change in reference crop evapotranspiration. During recent decades, the net irrigation reduced due to a reduction in reference crop evapotranspiration. However, for future scenarios, the net irrigation shows a reduction combined with an increase of reference crop evapotranspiration. This signifies two important findings. First, the crop's phenological response to increased temperature is expected to be higher for the future compared to the recent changes. This is a direct result of the rate of increase in temperature, which is likely to be higher in the future compared to recent decades. Second, the daily water requirement for *Boro* rice reduced over the past decades but will increase in the future. Hence, if we would consider no changes in growth duration of crops to occur due to temperature change, the water requirement would show a decrease in the recent decades but an increase in the future. Based on these two findings, another important issue could be reflected for the future, that is the possible change in cropping intensity and associated changes in water requirements. The shorter growing season due to the crop's phenological response to increased temperature will provide scope to increase the cropping intensity by growing more crops each year on a single piece of land. As discussed before, the crop's phenological response to increased temperature will be higher in the future compared to the recent period. There will thus be more scope to increase cropping intensity in the future. In other words, farmers could take advantage of the shorter *Boro* season to cultivate an increased number of crops in the future. Since, daily ET_O will increase in the future, the annual water demand for crop agriculture may increase.

Table 6.1

Summarized recent and future changes in water requirement components at a glance.

Parameters	Recent	Future
Reference crop evapotranspiration, ET_O	↘	↗
Growth duration	↘	↘
Potential crop water requirement, $\sum ET_C$	↘	↘
Effective rainfall (ER)*	↘	↘
Irrigation requirement to satisfy crop evapotranspiration, $\sum ET_C - ER$	↘	↗
Percolation amount	↘	↘
Net Irrigation Requirement	↘	↘

The cropping intensity is gradually increasing in Bangladesh and recently there are areas where even four crops are cultivated in a year (Mainuddin et al., 2014). The single-cropped area is turning into double-cropped area and double-cropped area is turning into triple-cropped area. The gradual increase in cropping intensity in Bangladesh is shown in Fig. 6.1. The cropping intensity is slightly higher in Northwest districts, especially in greater Bogra, Dinajpur and Rangpur than the overall country average. The highest cropping intensity is in the Northwest region (196% in 2009-10) while the lowest is in the Northeast region (153%). Cropping intensity in the greater districts of Bogra, Rajshahi and Dinajpur has increased at a rate of 3.0–6.0% per year and in Pabna at a rate of 1.0–3.0% per year during 2006-07 to 2010-11 (Mainuddin et al., 2014). During 1980s, the most important factor for the increase of cropping intensity was the increasing availability of irrigation facilities. But, in future, climate change by means of accelerated crop growth could be the most influencing factor to increase the cropping intensity.

Bangladesh Agricultural Research Institute experiments conducted in 2011-12 and 2012-13 suggests four-crop rotation to increase farm output (Ahmad, 2013). Bangladesh's cropping intensity has already reached 191 percent. Now, introduction of the four-crop rotation, as planned by the government, would further increase the country's cropping intensity. The accelerated growth of *Boro* rice due to increased temperature may allow mass scale cultivation of pulses, mustard, potato and seasonal vegetables in between rice crops. Since, the daily water requirements may increase in the future due to increased daily reference crop evapotranspiration, the annual water demand for crop cultivation would increase under increased cropping intensity. Such an increase in water requirement is not a direct influence of climate change but a consequence of crop’s phenological responses to climate change and related cultivation changes in the farming systems.

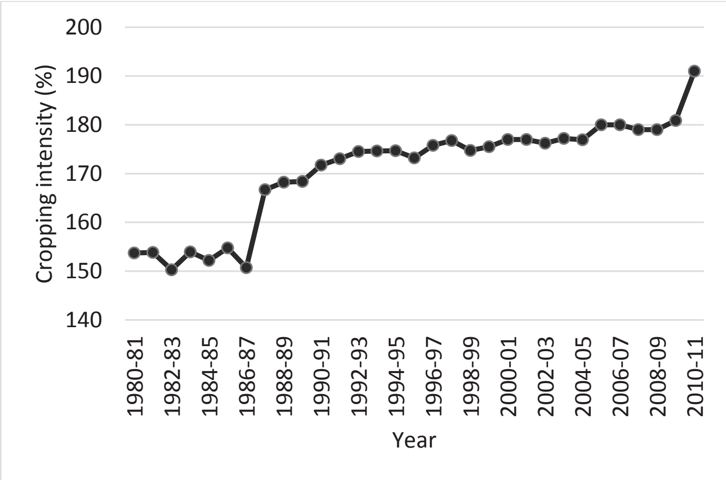

Fig. 6.1. Cropping intensity from 1980-81 to 2010-11 in Bangladesh (data source: Bangladesh Bureau of Statistics).

Boro cultivation area at the country level seems to have reached its peak and there is no growth in area over the last few years. The area of *Aus* rice, cultivated during pre-monsoon hot summer, is declining and the area of *Aman* rice, cultivated during monsoon, is more or less stable. There is significant growth in area of maize, potato and tomato in the Northwest region (Mainuddin et al., 2014). Therefore, the future increase in cropping intensity will probably be dominated by non-rice crops. Hence, yearly water demand for the cultivation of rice crops might not increase but annual water demand for the cultivation of non-rice crops is likely to increase.

Groundwater levels in the Northwest Bangladesh are declining due to increasing groundwater extraction for irrigation in the dry season and recurrent droughts (Shahid and Hazarika, 2010). This study indicates that the increased extraction of groundwater for irrigation during recent decades was probably not because of an increase in climatic water requirements of crops, but as a result of an increasing area used for *Boro* cultivation. Although in quantitative terms total monsoon rainfall should be enough to prevent groundwater depletion, the hydro-morphological conditions in Northwest Bangladesh are such that a large portion of rainfall is drained as surface runoff and does not infiltrate into the soil. A study by Adham et al. (2010) based on GIS and remote sensing techniques showed that about 85 percent of land has a low recharge potential and only 8.6 percent of the average annual precipitation percolates into the subsurface to recharge the groundwater. A possible increase in cropping intensity may further cause more over-exploitation of groundwater resources.

In this study, we have explored only the impacts of climate change on water demand for crop agriculture. For policy formulation, consideration of future socio-economic development is also important. The demand for water in agriculture may also increase over time with increasing population, rising incomes, and changes in dietary preferences (De Fraiture and Wichelns, 2010).

Preference of integrated, co-operative and advanced technological strategies which are complex and out-system dependent involve uncertainties, whereas local in-system dependent adaptations have ample opportunities to cope with climate change

The prioritizations of adaptation options based on stakeholders' opinion indicate that integrated, co-operative and advanced technological strategies are preferred over simple agronomic in-field strategies. The top most option was the transboundary co-operation to increase dry season flow that involves large uncertainty due to political dimension for implementing the option. For example, the uncertainty arises from the political dimensions and high dependency on 'out-siders' in case of transboundary co-operation for dry season surface water flow. Integrated water resources management and integrated crop management also have large complexities. Some local in-system strategies, like adjustment of irrigation method, alternate wetting and drying were listed as top measures, but stakeholders mostly preferred integrated, co-operative or advanced technological strategies.

This study assessed the effectiveness of a simple in-system agronomic strategy, the adjustment of trans-/planting date of *Boro* rice to cope with climate change. Results indicate that shifting trans-/planting date has large potential to manage water demand and crop productivity (Chapter 4). The future changes in different components of water requirements under early, normal and late planting compared to the base period normal planting (Table 6.2) reflect two important findings in this respect. First, we found an increase in future potential irrigation requirement for crop evapotranspiration (Chapter 3), but it showed a reduction for late planting compared to normal planting during base period. Second, we found slight reduction in future net irrigation requirement (Chapter 3), but it may increase under future early planting or may substantially reduce under future late planting compared to base period normal planting. Therefore, the shifting of trans-/planting dates has the capacity to substantially reduce the water requirements. Many researchers have previously reported that changing the planting date of rice could be a very good solution to maintain rice yield under changing climate (Desiraju et al., 2010; Mitin, 2009; Parry et al., 2004; Tripathy et al., 2009). Earlier planting showed possibility of increase yield in India (Krishnan et al., 2007) and Sri Lanka (Dharmarathna et al., 2014). According to Van Oort and Zwart (2018), the future rice yield declines would be caused mainly by two factors: (i) increased heat induced spikelet sterility and (ii) shortening of the growing season. Increased temperature accelerates phonological development of plant and may decrease the length of the grain filling period and thus reduce yield (Amthor, 2000; Bachelet and Gay, 1993; Vaghefi et al., 2013). This study reveals that, if an early planting date is followed in the future for *Boro* rice, there will be less chance of heat-stress and growing season will be less shorter compared to late planting. Therefore, early planting would be the best choice from rice yield perspective. Since net irrigation requirement may increase for early planting, choice of early planting option to maintain or increase rice yield may put additional pressure on water resources.

Table 6.2

The percentage changes in future water requirement components under early, normal and late planting for average of five models compared to normal planting during base period (1980–2013) in Bogra.

		Early planting		Normal planting		Late planting	
Parameters	Scenarios	06-Dec	16-Dec	05-Jan	15-Jan	04-Feb	14-Feb
Potential crop water requirement	2050s RCP4.5	–6.96	–7.58	–10.72	–11.49	–14.64	–14.48
	2080s RCP 4.5	–10.16	–10.85	–13.08	–14.47	–15.80	–16.39
	2050s RCP 8.5	–6.83	–8.57	–11.48	–12.49	–13.76	–13.95
	2080s RCP 8.5	–15.46	–16.91	–18.15	–19.59	–18.74	–17.30
Effective rainfall	2050s RCP4.5	–68.43	–68.60	–62.52	–56.97	–29.57	5.00
	2080s RCP 4.5	–62.99	–68.15	–57.99	–52.11	–28.99	–17.98
	2050s RCP 8.5	–61.48	–60.88	–54.42	–48.69	–28.06	–25.22
	2080s RCP 8.5	–74.65	–68.67	–65.71	–68.98	–59.87	–25.49
Potential irrigation for crop ET	2050s RCP4.5	44.20	43.20	32.40	26.36	–2.21	–30.69
	2080s RCP 4.5	33.80	36.84	24.30	16.86	–4.82	–15.07
	2050s RCP 8.5	38.66	34.98	24.25	17.65	–1.85	–4.56
	2080s RCP 8.5	33.80	26.16	21.43	21.51	15.49	–10.47
Percolation amount	2050s RCP4.5	–0.91	–4.57	–12.26	–15.14	–21.15	–22.82
	2080s RCP 4.5	–1.03	–6.47	–12.49	–16.14	–23.52	–25.64
	2050s RCP 8.5	–3.84	–7.68	–11.56	–14.83	–22.09	–25.09
	2080s RCP 8.5	–7.04	–12.12	–17.11	–22.72	–27.18	–27.98
Net irrigation requirement	2050s RCP4.5	10.59	5.12	0.36	–3.58	–10.59	–13.67
	2080s RCP 4.5	7.47	4.02	–2.33	–5.40	–14.23	–17.09
	2050s RCP 8.5	4.99	4.82	–1.93	–5.37	–11.85	–16.23
	2080s RCP 8.5	2.13	0.71	–5.48	–8.93	–11.92	–13.91

Green colour (■) indicate progress towards less water requirement and yellow colour (■) indicate progress towards more water requirement in the future compared to the base period.

Rice cultivars differ greatly in growth duration which are strongly influenced by planting date (Vergara et al., 1966). A short-duration crop would have several advantages over an unnecessary long-duration crop, even with equal total grain yields such as less water demand, less expose to hazards etc. (Vergara et al., 1966). On the other hand, several studies indicate a yield reduction under a very short growth duration (Van Oort and Zwart, 2018). Therefore, determination of the optimum growth duration of popular cultivars for producing maximum or optimum grain yield is needed. After determination of optimum growth duration required for a rice cultivar, it would be possible to adjust the planting date to attain the optimum growth duration of a rice cultivar.

The scope to shift trans-/planting date of *Boro* rice towards a late planting to minimize water demand is limited due to day- and night-time heat-stress. There is also high chance of heat-stress under a normal time planting of *Boro* rice in the future. Therefore, the scope of local in-system adaptation strategies may become limited due to climate change. Hence, more research on local in-system adaptation strategies are essential to eradicate the constraints arising due to climate change. However, there are limits to the effectiveness of potential adaptation options in the existing agricultural systems under severe climate changes (Howden et al., 2007). Although there is a limit to agronomic in-field adaptation measures, careful agronomic decisions are very important to better adjust current cultivation practices to changed climatic conditions. Careful agronomic decisions related to crop cultivation area, cropping intensity, types and varieties of crops to cultivate (e.g. rice or non-rice, short- or long-duration cultivars etc.), trans-/planting date could contribute to lessen the detrimental impacts of climate change before moving forward for complicated and dependent measures.

6.4. Strengths and limitations of the study’s methodology

Quality of historical climate data

One of the main concerns for a good quality research is the availability of good quality data. Lack of good quality data is a critical problem to conduct quality research in developing countries like Bangladesh. The period for estimating water requirements were selected carefully to avoid frequent missing data. There were lots of missing data before 1979 in Bogra, Rajshahi and Pabna and 1981 in Dinajpur. Therefore, the historical climate data for the period of 1979–2013 for Bogra, Rajshahi and Pabna, and for the period of 1981–2013 for Dinajpur were used for water requirement estimations in this study.

Understanding trends of changes

Trend analyses were performed in this study to investigate the direction of recent changes in different climatic parameters and water requirements. Investigation of trends is helpful in understanding the effects of climate change on evapotranspiration in the region under study (Eslamian et al., 2011). However, it is difficult to find out the exact trends due to existence of outliers. To eradicate the influence of outliers, the Sen's estimator of slope was used in this study. Sen’s slope method is not sensitive to outliers and gives a robust estimation of trend (Yue et al., 2002). Moreover, the Mann-Kendall statistic was computed to quantify the statistical significance of the trends.

Uncertainty in future climate scenarios

For identifying the impacts of future climate change on water demand of crops, good prediction of future climatic parameters, including not only temperature but also solar radiation, humidity and wind-speed are important. Climate models cannot exactly predict the future climate conditions. Future climate projections entail uncertainties from climate models’ parameterizations. Downscaling and bias correction based on observed historical climate data were followed as a treatment of uncertainties for improved prediction for the local conditions. A statistical downscaling technique was used to generate the future climate data for maximum and minimum temperatures, rainfall, wind speed and solar radiation. The downscaled model data were bias corrected by comparing the past model data with historical observed data. For bias correction, the monthly average WATCH Forcing data (Weedon et al., 2011) of maximum and minimum temperatures, sunshine hours and wind speed and monthly total WATCH forcing data of rainfall were compared to monthly observed station data.

Models used for simulating future climate can differ dramatically due to differences in the representation of sub-grid scale processes and other factors, including the applied numerical methods and models, and observational data sets, etc. (Najjar, 2014). It is difficult to identify in advance which method can better predict the future. Therefore, in climate change impact studies, several models are used to reflect the possible future situation. The multi-model average is often superior to any individual climate model (Reichler and Kim, 2008). Use of multi-model ensembles could better perform than any individual model for assessment of climate change impacts on agriculture (Asseng et al., 2015; IPCC, 2013; Moore et al., 2017). Hence, five model outputs were used instead of a single model in this study. All model estimates in this study mostly showed changes in same directions for all water requirement components. Hence, the findings of this study are robust. The range of variance in model outcomes should be taken as an indication of the range of uncertainty.

Since, the relative humidity predictions were not available from the GCM outputs, they were estimated following the ratio between actual water vapour pressure and saturation vapour pressure. The actual and saturation vapour pressure is a pure function of temperature and can be calculated by a common empirical interpolation function (Holbo, 1981; WMO, 1979). For humid temperate climates, when temperature is at its daily minimum, water vapour is saturated. Hence, the general assumption to estimate relative humidity from temperature data is to consider dew temperature as equal to the minimum temperature of the day (Eccel, 2012). No explicit uncertainty treatments were applied for the prediction of relative humidity.

Estimation of future growth duration of crops

Use of fixed growth duration of crops for the estimation of long-term changes in water requirements could be misleading because temperatures can vary greatly from year to year. Plants require a specific amount of heat to develop from one point in their lifecycle to another. Research has shown that measuring the heat accumulated over time provides a more accurate physiological estimate than counting calendar days (Miller et al., 2001). Therefore, the growing degree-days (*GDD*) method was applied for the prediction of changes in growing duration. The method of growing degree-days can consistently predict the growth stage days and permits accurate comparisons of crop development in different years at widely separated locations (Miller et al., 2001). However, the growth duration of crops may also change substantially because of changes in cultivated crop varieties. For the ease of assessment it was assumed in this study that the same crop cultivars will be cultivated in the future. This is helpful to understand the theoretical direction of changes.

Crop phenology may also be affected by lack of soil moisture (Miller et al., 2001). For example, if sufficient moisture does not exist at seeding, the accumulation of degree-days may be delayed accounting for longer duration. This occurs because the seed requires more time to take up sufficient moisture to begin the germination process. The rate of growth also increases in many crops in response to drought stress, since temperatures in the crop canopy may rise more than normal due to reduction in transpiration by the crop. Since, a continuous submergence (i.e. no water limit conditions) was considered in this study, the rice phenology will not be affected due to lack of moisture or drought stress.

Changes in photoperiod also has impacts on rice phenology. The most popular dry season crop, the high-yielding *Boro* rice was modelled in this study. The variations in different *Boro* varieties was not distinguished. However, according to Travis et al. (2015), out of 64 *Boro* cultivars 34 varieties are *aus-1*, 13 are *japonica*, six are *indica*, four are *admix*, two are *aus-admix*, one is *aus-2*. All but 9 cultivars from Bangladesh are predominately *aus-1* (Travis et al., 2015). *Aus* is listed as insensitive to photoperiod by Purseglove (1972). Therefore, though photoperiod is an important aspect when we work on crop phenological aspects, it is probably not a major issue in this study.

The growth duration of cultivated crops may change abruptly due to a change in crop varieties. It is difficult to address any changes in future crop varieties. However, to address this change in variety which could be important for adaptation planning, a longer duration variety with 16% increase in accumulated heat values for each stage was assumed. The water requirements of that possible longer-duration variety were also quantified (in Chapter 4). In present days, the accumulated heat values for currently used long duration varieties (e.g. BRRI dhan29) are about 16% higher compared to short-duration varieties (e.g. BRRI dhan28). However, the uncertainty is that the future possible long-duration variety may have a different accumulated heat values for each stage.

Estimation of water requirements

In order to assess the climate change impacts on the water requirements of *Boro* rice, the influence of management practices were excluded by modelling the rice growth in CropWat under a standardized schedule that provides irrigation water as required. The estimated values of net irrigation requirement using CropWat can differ from the actual field situation because of changes in variety of crop, water application method, specific soil condition, and crop density in the field.

The CropWat model uses a standard set of formulas (e.g. *Penman–Monteith* formula for ETo estimation etc.), which are applicable for all regions. Only the input parameters (climate data, crop data and soil data) and irrigation practices need to be specific to the region to obtain correct and acceptable results. The crop coefficient values and other crops data were collected from BARI, which are more specific and reliable for local condition than FAO standard values provided with CropWat. The Northwest of Bangladesh has a wide variety of soils, therefore, a standard representative soil for each district was used. Based on this locally specific data CropWat can successfully estimate water requirements.

In order to assess the climate impacts on the water requirements of *Boro* rice, the impact of management practices were excluded by modelling the rice growth in CropWat using a standardized schedule that provides irrigation water as required. To identify changing crop water requirements the irrigation water was provided (in CropWat) as required by the crop. For all simulations the same irrigation scheduling criteria were used. Summarizing, irrigation requirements, which change due to changes in ET_C (climate driven changes in ET_O and phenology) and due to changes in Rainfall patterns, were assessed.

There are large uncertainties in projections of future precipitation. To deal with these uncertainties a bias correction was applied for the correction of large biases in climate model and a multi-model ensemble (5 GCMs) was used as a control for differences in climate sensitivity between models. Although it is not possible to exactly predict the net irrigation requirement, the possible changes could be reflected based on different models that estimate and project the future precipitations. The results of this study show that all five climate models result in a change of net irrigation in the same direction (but, in different amounts). This gives a very strong indication of the direction of future changes. The range of model result can be used as indication for the uncertainty range.

This study has not investigated the changes in water requirements as affected by the changes in atmospheric CO_2 concentration. Several studies indicate that, increase in CO_2 concentration decreases evapotranspiration and increases water use efficiency (Baker and Allen Jr, 1993; Morison, 1985). Tao et al. (2008) indicate that evapotranspiration and irrigation water requirements would decrease more for simulations with consideration of CO_2 fertilization effects in comparison to the simulations without consideration of CO_2 fertilization effects in China. Since, water requirements of *Boro* rice in the Northwest districts of Bangladesh are showing decreasing trends without considering the impacts of elevated CO_2 in the atmosphere, consideration of impacts of changes in CO_2 concentration in the atmosphere is not contradictory, but could strengthen the conclusion of this study.

Threshold temperature during critical period

Spikelet sterility may occur at different temperature thresholds (Matthews et al., 1995; Nakagawa et al., 2003) since there is genotypic variation in spikelet sterility at high temperature (Matsui et al., 2001; Prasad et al., 2006; Satake and Yoshida, 1978). Also, a shorter more higher temperature durations may have the same effect as a longer less higher temperatures durations (Satake and Matsuo, 1995). Therefore, it is difficult to state a certain temperature as threshold temperature. To make this study simpler, 35°C and 25°C were stated as threshold maximum and minimum temperature. According to Laborte et al. (2012), the maximum temperature above 35°C for 10 days can cause day time heat stress, and the minimum temperature above 25°C for 15 days can cause night time heat stress to rice plant during the critical stages.

Categorization of measures and criteria for ranking

The identified adaptation options were divided into six broad categories, namely crop production management (CPM), land use management (LUM), water management (WM), environmental management (EM), social and institutional management (S&IM), and education and research (E&R). It is difficult to tag any specific category to some options. However, any categorization of adaptation options is unlikely to be universally agreed on, but the categorization take into account the diversity of adaptation measures for different sectors and stakeholders (Noble et al., 2014).

Four criteria – importance, urgency, no-regret characteristics, and co-benefits – were used to prioritize adaptation options. Three criteria – technical, social and institutional complexities – were used to assess the overall complexity of different adaptation measures. Although economic feasibility is an important aspect, it was not possible to address that in this study due to lack of data. However, the multi-Criteria Analysis used in this study (chapter 5) is an appropriate decision-support tool to rank adaptation options, especially when there is lack of data on the costs and benefits of the adaptation options (de Bruin et al., 2009).

6.5. Scientific contributions to understanding and managing agricultural water demand

This study addresses the needs for improved quantifications of recent and future impacts of climate change on water requirements of dry season *Boro* rice. The following points are the main scientific contributions of this study to understanding and managing agricultural water demand:

- **Importance of climatic parameters that influence evapotranspiration change over time**
  This study clearly shows that the importance of different climatic parameters that cause a change in water requirements may change over time due to the accelerated changes in those parameters. For example, the changes in humidity, wind-speed and sunshine hours mainly lead to decrease in reference crop evapotranspiration during recent decades in Northwest Bangladesh. In future, strong increase temperature will lead to the increase in reference crop evapotranspiration. Therefore, for the assessment of the impacts of climate change inclusion and proper assessment of changes in all climatic parameters is important.
- **Crop water requirement may decrease, despite an increase of daily evapotranspiration**
  This study clearly shows that quantification of changes in daily evapotranspiration is not sufficient for assessing the impacts of climate change on water requirements for crop agriculture. Water requirement for crop agriculture may decrease even under an increase of daily evapotranspiration due to changes in the length of the crop growing season. Hence, comments about future agricultural water demand based on only evapotranspiration study would not be appropriate.
- **Estimation of all water requirement components better reflect future consequences**
  This study figured out that estimation of different water requirement components (i.e. ET_O, $\sum ET_C$, $\sum ET_C - ER$ and Net irrigation) can better reflect on future possible consequences of climate change, instead of an overall estimate (i.e. Net or Gross irrigation requirement). This study confirms that there could be a small impact on net irrigation requirement but larger impacts on individual components such as ET_o, $\sum ET_C$, effective rainfall and $\sum ET_C - ER$ could exist due to climate change. It is important to understand those impacts for effective irrigation management. Therefore, studies should have a strong focus on all water requirement components for understanding and managing agricultural water demand. There is a strong relationship between water requirement components and changes in one component can lead to changes in subsequent components.
- **Crop's phenological response to climate change is vital for water demand estimation**
  This study strongly indicates that crop's phenological response to climate change, particularly changes in growth duration due to changes in temperature is vital for water demand estimation. A reduction in growth duration can substantially reduce the water requirement of a crop. Changes in growth duration affects total crop evapotranspiration, rainfall availability and total percolation during the crop cultivation periods.

- **Shifting trans-/planting dates of crops may have huge influence on annual water demand**
  Most scientific studies focus on the impact of shifting trans-/planting date on crop yield. This study shows that shifting trans-/planting dates of crops may have large influences on annual water demand for crop agriculture. Moreover, the influence of crop's phenological response is important to consider for studies on shifting transplanting dates. Shifting trans-/planting date under future climate may considerably affect the crop growing season and rainfall availability, and therefore, may substantially affect water demand.
- **Changes in rainfall availability during crop growth duration is vital for water demand estimation**
  For water demand management, it is not only important to access the changes in amount and seasonal distribution of rainfall in a region but also the changes in availability of rainfall during particular crop growth duration. Due to increased temperature, the crop growth duration would become shorter resulting in less rainfall availability during crop cultivation period.
- **Care is needed in selecting criteria for evaluating options**
  Prioritization of adaptation measures based on experts/stakeholders suggestions is only suitable as a starting point for adaptation planning. For detailed effective planning, quantitative and economic analyses of most effective adaptation measures are essential. This study shows that different complexity criteria (e.g. technical, social or institutional complexities) could be clearly differentiated from stakeholders comments but not priority criteria (e.g. important, urgency, no-regret characteristics and co-benefits). Therefore, care is needed in selecting criteria for prioritization of options.

6.6. Recommendations for agricultural water management

Adequate understanding of agricultural water demand is essential to face the challenges of inevitable climate change. The findings of this thesis suggest the following policy and program recommendations for better agricultural water management.

- **Improve data collection and dissemination**
  Set-up of well-equipped meteorological stations are essential for improved data collection of weather data. Many temperature measurements across Bangladesh may be skewed because the weather stations are located in towns (Brammer, 2014a, b). Thus, Brammer (2016b) also recommended to install more meteorological stations in Bangladesh, especially near rural agricultural lands. Also, local agricultural research institutes should focus on collection of good quality data on crops. Improved data collection and dissemination can support good quality research and help in decision making for the future.
- **Regular monitoring of changes in agricultural practices**
  Changes in agricultural practices affect water demand for crop agriculture. Therefore, regular monitoring of changes in local cropping pattern, growth duration, cropping intensity, water withdrawal and farmers preference in water management practices are important. The monitoring of environmental factors, crop cultivation areas and crop condition is also important for planners and administrators to cope with drought (Brammer, 1987). Regular observation of changes in agricultural practices may assist in research and adaptation.

- **Conservation of recharge potential area**

  This study clearly showed that, during the last few decades, the overexploitation of groundwater in the Northwest Bangladesh is not because of any increase in actual crop water requirement or net irrigation need, but probably because of expansion of the *Boro* cultivation area and low recharge potential due to urbanization. Adham et al. (2010) also reported that 85% area in Rajshahi has low recharge potentiality and only 8.6% of the total average annual precipitation percolates into subsurface to recharge the groundwater. Hence, conservation of recharge potential area like forests and agricultural lands are essential. Urbanization accelerates development of concrete structures like roads, buildings etc. that reduce the percolation amount. Therefore, the government must take initiative to promote green cities and identify measures to support percolation in urban areas.

- **Continue large scale *Boro* cultivation with efficient water management practices**

  Cultivation of high-yielding irrigated *Boro* rice is very important for the food security of Bangladesh. Currently, the major concern about *Boro* rice cultivation is the withdrawal of groundwater resources. Since, *Boro* rice will not require more water due to climate change, it will not be very problematic to continue large scale *Boro* cultivation in Northwest Bangladesh. A study by Kirby et al. (2015) indicated that the rate of decline in groundwater tables would reduce and could even attain a new equilibrium assuming no further increase in the groundwater irrigated area. According to Faisal and Parveen (2004), if the water availability for crop production remains unchanged in the dry season, then there should be enough water to meet the irrigation requirements in 2030 and 2050. Parvin and Rahman (2009) suggested for expansion of irrigated *Boro* areas with necessary policy formulations to ensure long-run sustainability groundwater resource.

- **Promote intelligent selection of sowing date**

  This study reflects that selection of sowing date is very important from water demand management perspective. Since irrigation demand is much less for late planting, farmers under water-limited situation can be recommended to choose a late-planting date taking into account of the impacts of high temperature stress. For regions with high water availability, the early planting of a long-duration high-yielding cultivar would be the optimal choice in the future. Any long-duration variety is not recommended for the low-lying *Haor* areas where flash floods may cause damage to *Boro* rice before harvesting.

- **Alertness for heavy rainfall during harvest**

  A later planting date can substantially reduce the amount of irrigation required for *Boro* cultivation, but may reduce yield due to heavy rainfall events before harvesting. Shahid (2011) reported that significant change in the extreme rainfall indices are observed in Northwest Bangladesh. A forecast and warning system is needed to inform farmers about the possible extreme rainfall events. In areas with early heavy rainfall the early planting of short-duration *Boro* cultivars are recommended. Analysis of rainfall across the whole country could be useful to support adaptation planning (Hossain et al., 2014).

- **Investment in capacity building to reduce complexities of efficient measures**
  Special attention is required to transform more complex prioritized options into implementable feasible options. The complex prioritized measures could be transformed into feasible ones and promoted by capacity building at national and local levels and mainstreaming climate change adaptation into development process.
- **Investment in agricultural water management research**
  Investment in agricultural water management research would contribute to the water and food security of the country. Investment to explore and identify new techniques of agricultural water management are essential for both short- and long-term development.

6.7. Outlook and recommendations for future research

This research was conducted to answer two research questions as discussed before. The following points are important for the future research related to this field.

- **Studies on sensitivity of reference evapotranspiration to climate variables**
  Studies on sensitivity of reference evapotranspiration to climate variables in different regions is important. According to Admasu et al. (2014), the sensitivity of reference crop evapotranspiration could be different for different agro-ecological zones. How the different combinations of changes in climatic variables affect reference crop evapotranspiration could be important to understand the future direction of changes in water demand.
- **Understand and better predict climate variables**
  Good prediction of future climatic parameters, including not only temperature but also solar radiation, humidity and wind-speed are important for identifying impacts of future climate change on water demand and yield of crops. Studies are required to better understand the changes in regional climate system to accurately predict the changes. Rainfall is a very critical parameters for the accurate estimation of irrigation demand. Not only the magnitude of rainfall, but also the seasonal distribution is changing as a result of anthropogenic climate change. Since, the rainfall patterns widely vary in different locations, some studies are required at finer scale to understand the possible changes in inter- and intra-annual distribution of rainfall.
- **Quantification of water requirements at finer scale**
  Water requirement estimations for different crops and varieties, water application methods and soil conditions could add to the detail understanding of water demand and be helpful for water demand management. As the physical geography of Bangladesh is very diverse (Brammer, 2016a), impacts of climate change are not uniform throughout the country and distribution of rainfall could differently affect different regions. Some finer scale studies to understand the changes in future water requirements can be helpful for better agricultural diversification and water management planning.
- **Understand the phenological aspects of all major crops**
  While conducting this study we realize that there is lack of information on phenological aspects of major crops which are essential to estimate water requirement of all crops. Studies on phenological aspects of crops may broaden our existing knowledge about crops response to

climate change and help for planning future cropping pattern. Moreover, determination of accumulated heat values at different stages of major crops may support water requirement estimation for all major crops.

- **Assessment of changes in land use and cropping intensity**
  As found from this study, recent changes in agricultural land use, i.e. changes in crop cultivation area, irrigated area had strong influence on overall water demand for a region. Research to identify future possible changes in land use in terms of changes in cultivable area, rice cultivation area, irrigated area could add much to overall water demand estimation for a region. This study also clearly shows the importance to understand the changes in cropping intensity to predict future water demand. No explicit studies examined the relationships between climate variability and cropping intensity (Iizumi and Ramankutty, 2015).
- **Exploration of on-farm agricultural techniques**
  On-farm agricultural techniques (e.g. shifting planting dates, adjusting irrigation scheme, etc.) have large potential to cope with climate change. Moreover, on-farm agricultural techniques are simple, cost-effective and easy to implement. All applicable on-farm agricultural techniques are needed to assessed to understand the how adjustment is those techniques may cope with climate change.
- **Identification of temperature-tolerant rice cultivars**
  From this study this is evident that temperature-tolerant rice cultivars are very essential for future food security and water demand management. Extensive research is needed to support the identification of temperature-tolerant rice cultivars. Sarker et al. (2012) also suggested a provision of fund for the research and development of temperature-tolerant rice varieties, particularly for *Aman* and *Boro* rice.

The most important future research recommendation in-line with this research would be the assessment of phenological aspects of major crops and thereafter, exploration of on-farm agricultural techniques based on the knowledge of phenological response of major crops to climate change. Assessment of phenological response of major crops to climate change may support improved agronomic and water management decisions like selecting best cropping pattern for a region, preparing the most suitable crop calendar, adjusting irrigation scheme, choosing appropriate varieties etc.

Appendix A

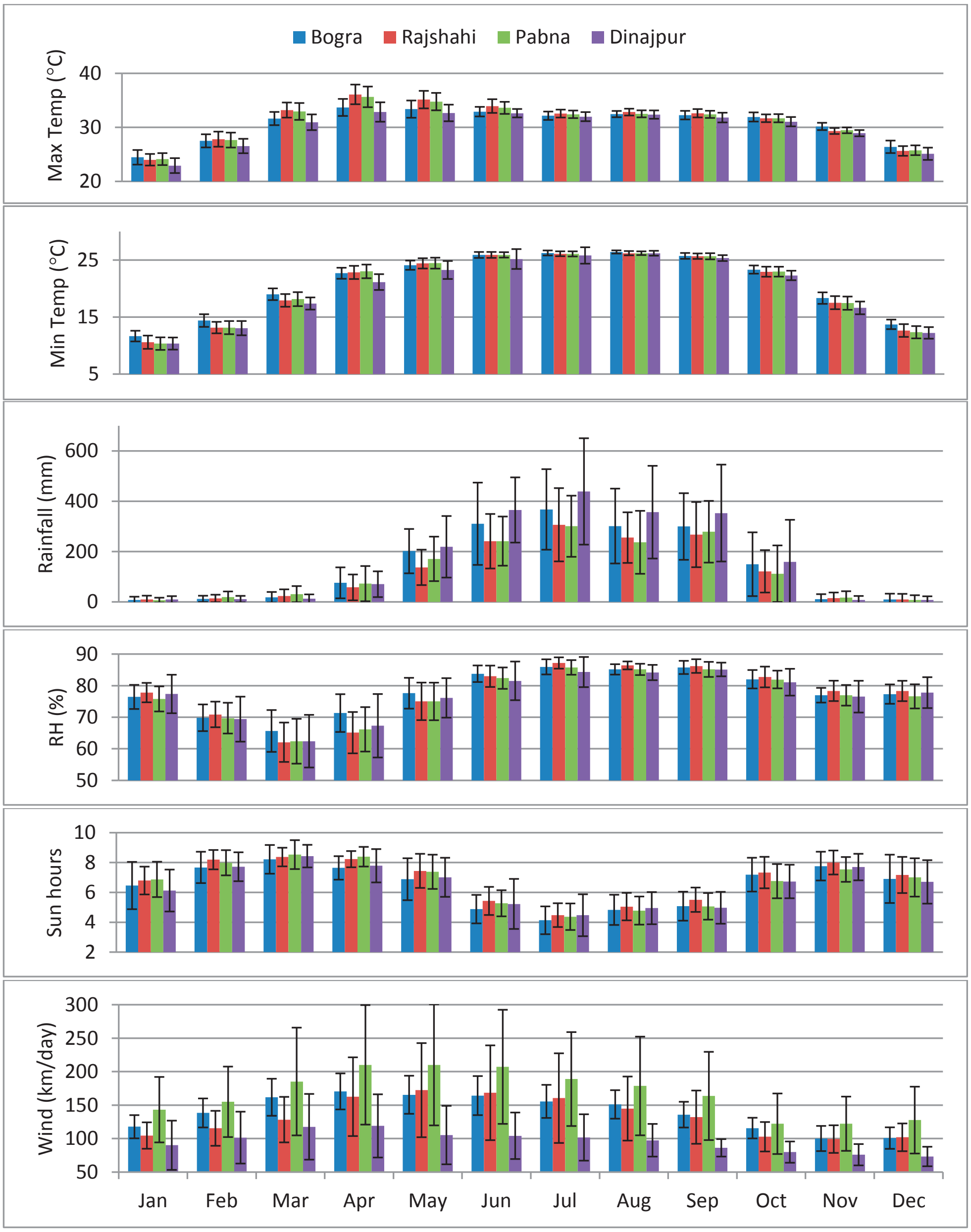

Fig. A.1 Mean and standard deviation of climatic parameters in four Northwest districts for the period of 1979–2013.

Table A.1

Mann–Kendall test for monthly average minimum and maximum temperature in four Northwest districts for the period of 1979–2013.

Month	Minimum Temperature				Maximum Temperature			
	Bogra	Rajshahi	Pabna	Dinajpur	Bogra	Rajshahi	Pabna	Dinajpur
January	–1.48	–1.84^{+}	–0.79	0.23	–3.64***	–1.85^{+}	–2.64**	–2.36*
February	2.26*	0.90	2.35*	2.67**	1.73^{+}	1.58	1.94^{+}	1.24
March	2.69**	2.28*	2.29*	2.89**	–0.41	0.36	0.56	0.08
April	1.34	2.13*	1.94^{+}	3.56***	–1.34	–0.65	–0.52	–1.02
May	2.12*	1.61	1.81^{+}	3.13**	1.31	1.07	0.73	1.38
June	0.87	0.98	2.21*	2.37*	1.29	2.17*	1.86^{+}	1.18
July	3.80***	3.19**	3.01**	4.00***	3.30***	3.59***	3.98***	3.03**
August	3.22**	2.67**	3.15**	3.45***	2.29*	3.18**	3.14**	1.97*
September	3.37***	1.34	1.69^{+}	3.95***	2.82**	2.31*	3.08**	4.05***
October	1.53	0.31	1.14	1.94^{+}	1.37	0.88	1.08	1.27
November	1.09	–0.14	0.28	1.71^{+}	–0.34	0.19	0.81	1.88^{+}
December	0.83	0.53	0.98	1.60	–1.15	–1.28	–0.82	–0.98

$^{+}$, *, ** and *** signs indicate significant at 0.10, 0.05, 0.01 and 0.001 level of significance, respectively.

Table A.2

Mann–Kendall test for monthly average relative humidity and wind speed in four Northwest districts for the period of 1979–2013.

Month	Relative humidity				Wind speed			
	Bogra	Rajshahi	Pabna	Dinajpur	Bogra	Rajshahi	Pabna	Dinajpur
January	**3.24****	**4.12*****	**3.68*****	**2.91****	–1.07	–**3.90*****	–**5.10*****	–**3.34*****
February	1.86^{+}	**2.16***	**2.47***	**2.94****	–1.52	–**3.95*****	–**5.67*****	–**5.36*****
March	**3.35*****	**2.62****	**3.36*****	**3.90*****	–**1.97***	–**4.52*****	–**6.26*****	–**5.35*****
April	**2.95****	**2.44***	**3.36*****	**3.99*****	–**2.90****	–**5.65*****	–**6.65*****	–**5.69*****
May	–1.29	1.17	**1.98***	**2.58****	–1.32	–**6.24*****	–**6.81*****	–**4.47*****
June	–0.82	–0.70	1.12	**2.22***	–1.60	–**6.26*****	–**7.19*****	–**4.99*****
July	–**3.50*****	–**2.65****	–0.33	–0.11	–0.91	–**6.18*****	–**6.65*****	–**4.56*****
August	–1.57	–0.20	1.95^{+}	**2.11***	–**2.77****	–**6.04*****	–**6.52*****	–**5.20*****
September	–**2.69****	0.68	1.02	–0.83	–0.09	–**5.56*****	–**5.74*****	–**3.73*****
October	–0.67	**2.32***	1.58	1.86^{+}	–1.32	–**3.53*****	–**4.05*****	–**2.98****
November	0.21	**3.06****	**2.23***	1.71^{+}	–**3.34*****	–**3.87*****	–**5.46*****	–**2.92****
December	2.15	**2.79****	**2.96****	**2.58****	–**3.23****	–**4.73*****	–**5.92*****	–**3.83*****

$^{+}$, *, ** and *** signs indicate significant at 0.10, 0.05, 0.01 and 0.001 level of significance, respectively.

Table A.3

Mann–Kendall test for monthly average sun shine hours and total rainfall in four Northwest districts for the period of 1979–2013.

Month	Sun shine hours				Rainfall			
	Bogra	Rajshahi	Pabna	Dinajpur	Bogra	Rajshahi	Pabna	Dinajpur
January	–**5.36***	–**4.02***	–**4.69***	–**4.28***	–0.74	–1.26	–1.22	–1.60
February	–**2.95**	–0.46	–1.68⁺	–**2.37*	–1.49	–1.90⁺	–1.75⁺	0.06
March	–**3.85***	–1.41	–**2.30*	–**2.63**	–0.81	–0.03	–0.61	–0.08
April	–**3.39***	–**3.23**	–**3.35***	–**4.18***	–0.48	–0.57	–0.17	0.70
May	–**2.30*	–1.38	–1.01	–0.30	–1.72⁺	0.48	–1.92⁺	–0.67
June	–**2.65**	–0.41	–0.48	–1.63	–0.40	0.09	–0.95	**2.46*
July	1.05	1.92⁺	1.21	0.34	–**2.36*	–1.80⁺	–1.42	–1.66⁺
August	–1.59	–0.94	1.35	1.02	0.01	–1.09	–0.18	–0.73
September	–1.35	–0.09	2.64	**2.82**	–1.35	–0.65	–0.54	–1.56
October	–**2.00*	–**2.09*	1.53	1.46	0.81	–0.10	0.61	0.28
November	–**3.21**	–1.28	–0.10	–0.03	–0.51	–1.04	–0.65	–0.12
December	–**3.37***	–**4.19***	–**3.42***	–**4.13***	–**2.53*	–**2.29*	–1.42	–**2.52*

⁺, *, ** and *** signs indicate significant at 0.10, 0.05, 0.01 and 0.001 level of significance, respectively.

Appendix B

Table B.1

Mann-Kendall trends of estimated reference crop evapotranspiration during dry months for 2035–2065 and 2065–2095 time series in Bogra.

Trends during	Month	CNRM-CM5		EC-Earth		HadGEM2-ES		IPSL-CM5A-LR		MPI-ESM-LR	
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
2035 to 2065	Jan	**2.11***	0.48	**2.11***	0.51	**2.48***	**3.06****	–1.73⁺	1.39	1.39	1.67⁺
	Feb	1.05	–0.27	1.94⁺	0.65	**2.99****	**4.22*****	1.87⁺	1.56	1.70⁺	**2.07***
	Mar	1.02	–1.16	1.02	0.54	**2.89****	**2.96****	0.58	**2.35***	0.41	1.73⁺
	Apr	0.51	0.58	0.92	–0.54	1.12	**2.18***	–1.43	1.56	**2.52***	**2.14***
	Nov	0.34	–0.24	1.29	1.36	**2.75****	**2.35***	0.54	0.48	1.67⁺	1.87⁺
	Dec	1.87⁺	–1.12	1.50	0.48	**3.20****	**2.35***	–0.03	1.05	–0.88	0.88
2065 to 2095	Jan	–0.24	1.80⁺	1.70⁺	1.73⁺	–0.14	**3.88*****	0.82	0.07	1.16	**2.52***
	Feb	–1.43	1.05	0.92	1.29	1.26	**3.50*****	0.54	0.78	0.37	1.80⁺
	Mar	–0.20	–0.75	1.36	–0.10	1.36	**3.13****	0.48	1.29	–0.68	1.94⁺
	Apr	0.61	0.07	1.26	0.68	1.94⁺	1.26	0.58	1.50	–0.31	**2.62****
	Nov	0.20	1.33	**2.72****	0.85	1.56	**4.01*****	**1.97***	1.16	1.53	0.71
	Dec	0.20	**3.03****	1.56	1.09	**2.11***	**4.05*****	0.27	0.48	0.99	1.39

⁺, *, ** and *** signs indicate significant at 0.10, 0.05, 0.01 and 0.001 level of significance, respectively.

Table B.2

Mann-Kendall trend of estimated reference crop evapotranspiration during dry months for 2035–2065 and 2065–2095 time series in Pabna.

Trends during	Month	CNRM-CM5		EC-Earth		HadGEM2-ES		IPSL-CM5A-LR		MPI-ESM-LR	
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
2035 to 2065	Jan	**2.21***	0.14	1.87⁺	0.34	**2.69****	**2.79****	–1.36	1.19	1.84⁺	1.60
	Feb	0.92	–0.68	1.53	0.17	**3.26****	**3.50*****	**2.18***	1.53	**1.97***	1.77⁺
	Mar	0.95	–1.33	0.75	0.71	**2.18***	**2.24***	0.99	**2.79****	0.95	0.88
	Apr	0.48	0.41	0.78	–0.61	1.26	**2.65****	–1.67⁺	1.56	**2.35***	**2.48***
	Nov	0.24	–0.54	1.19	0.82	**2.65****	1.56	0.88	1.05	1.56	1.90⁺
	Dec	1.77⁺	–1.36	1.50	0.17	**2.92****	**2.96****	–0.07	1.36	–0.92	0.75
2065 to 2095	Jan	–0.65	1.53	1.67⁺	1.33	1.36	**4.11*****	0.78	0.27	1.19	**2.14***
	Feb	–1.56	0.61	0.07	1.63	0.61	**3.50*****	0.37	0.54	0.24	1.53
	Mar	–0.54	–0.92	1.50	–0.03	0.92	**2.96****	0.03	0.95	–1.02	1.56
	Apr	0.34	0.00	1.12	0.58	1.84⁺	1.43	0.03	1.12	–0.58	**2.21***
	Nov	0.03	1.12	**2.62****	0.61	**2.62****	**4.66*****	1.53	1.05	**2.01***	0.92
	Dec	0.03	**3.03****	0.85	0.75	1.84⁺	**4.25*****	–0.03	–0.17	1.22	1.16

⁺, *, ** and *** signs indicate significant at 0.10, 0.05, 0.01 and 0.001 level of significance, respectively.

Table B.3

Mann-Kendall trend of estimated reference crop evapotranspiration during dry months for 2035–2065 and 2065–2095 time series in Dinajpur.

Trends during	Month	CNRM-CM5		EC-Earth		HadGEM2-ES		IPSL-CM5A-LR		MPI-ESM-LR	
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
2035 to 2065	Jan	1.43	0.03	**1.97***	0.00	**2.75****	**2.41***	**–2.07***	1.12	0.65	0.58
	Feb	1.43	–0.10	**2.48***	0.75	1.19	**2.62****	0.17	1.56	1.26	1.90^{+}
	Mar	1.12	–1.19	1.09	0.27	**2.07***	**2.72****	0.88	1.67^{+}	0.44	1.29
	Apr	0.14	0.65	0.61	–0.92	1.53	**2.79****	-1.67^{+}	1.39	**2.41***	**2.18***
	Nov	**2.18***	0.61	0.78	**2.35***	**3.43*****	1.73^{+}	0.14	0.14	1.77^{+}	2.21
	Dec	1.87^{+}	–0.71	1.26	0.37	**3.26****	**2.21***	–0.14	0.65	–0.07	0.44
2065 to 2095	Jan	0.14	**3.20****	1.39	1.84^{+}	–0.17	**2.14***	0.78	–0.51	1.22	**3.20****
	Feb	–1.12	1.05	1.29	**2.01***	1.26	**3.09****	0.41	0.58	–0.14	1.46
	Mar	0.14	–0.71	1.22	–0.68	1.39	**2.48***	0.61	0.54	–0.78	**2.07***
	Apr	0.58	–0.31	0.71	0.82	1.73^{+}	1.63	0.75	1.53	–0.17	**2.72****
	Nov	0.00	**3.50*****	**2.45***	0.58	1.09	**2.79****	**2.48***	1.12	0.44	1.63
	Dec	1.09	**3.50*****	0.75	0.92	1.36	**3.81*****	0.03	1.09	0.61	**2.62****

$^{+}$, *, ** and *** signs indicate significant at 0.10, 0.05, 0.01 and 0.001 level of significance, respectively.

Appendix C

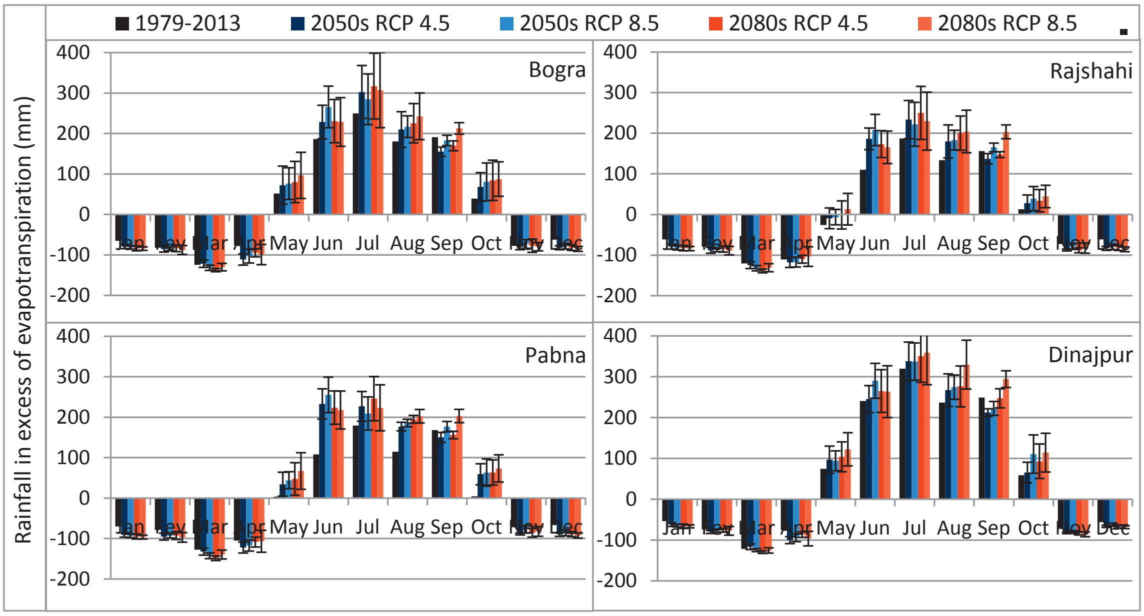

Fig. C.1 Future changes in monthly rainfall deficit.

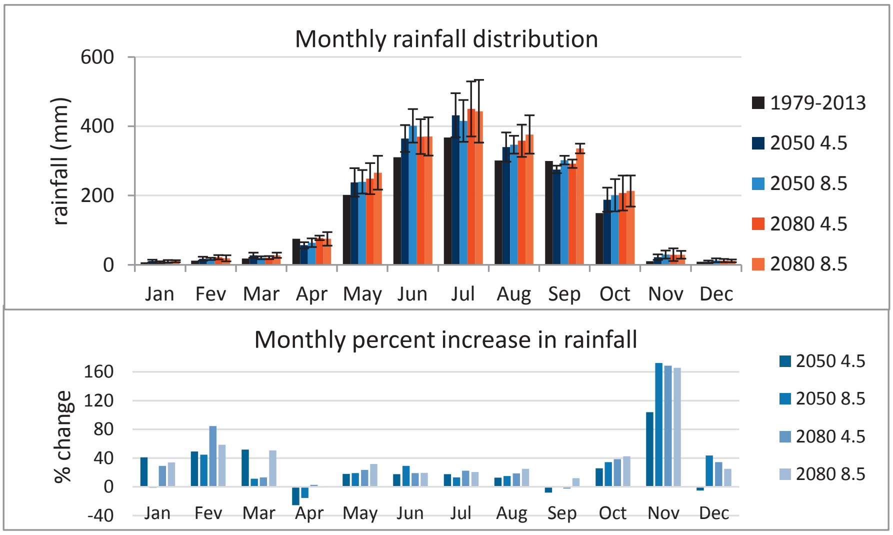

Fig. C.2 Future monthly rainfall distribution and percent change (average of five models) in Bogra district; the error bars indicate variations by different model estimates.

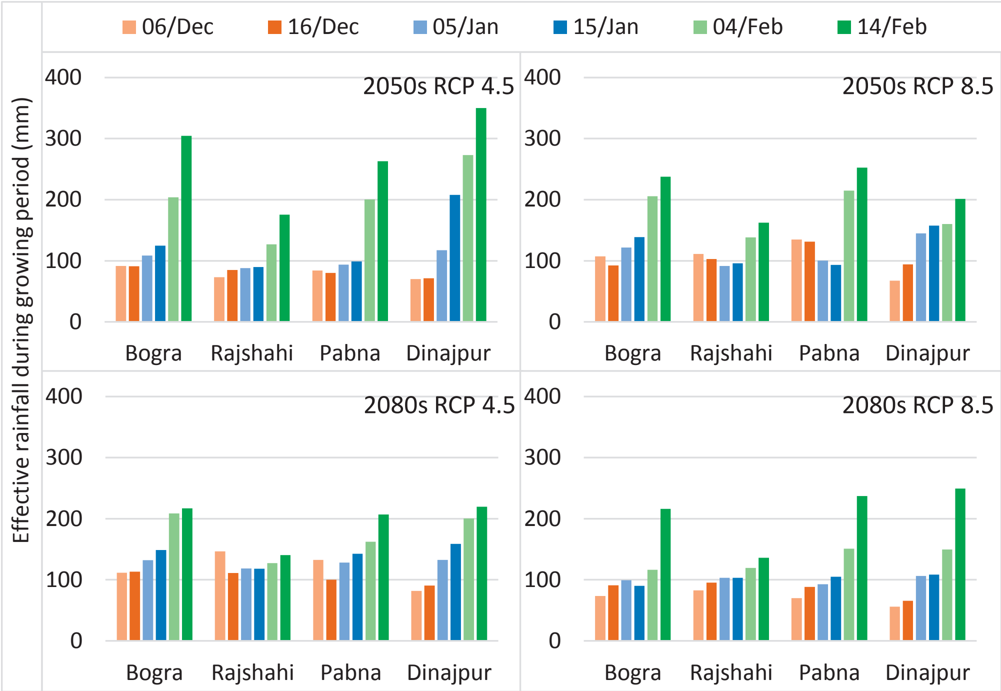

Fig. C.3 Effective rainfall (for the average of five models) during *Boro* rice growth duration using six different transplanting dates for RCPs 4.5 and 8.5 and two future periods 2035–65 (2050s) and 2065–95 (2080s).

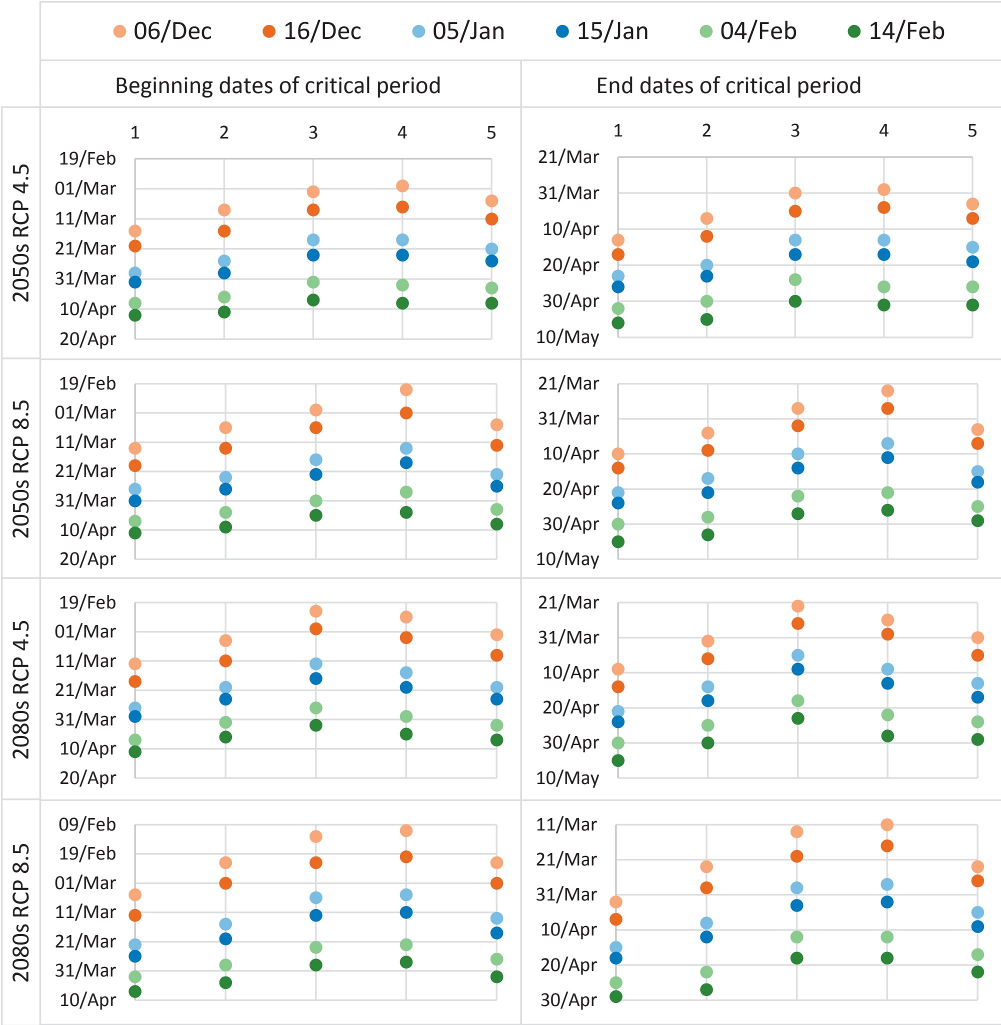

Fig. C.4 Estimated beginning and end date of critical period of *Boro* rice in Bogra under six different transplanting dates for RCPs 4.5 and 8.5 and two future periods 2035–65 (2050s) and 2065–95 (2080s) for five models (1 = CNRM-CM5, 2 = EC-Earth, 3 = HadGEM2-ES, 4 = IPSL-CM5A-LR, and 5 = MPI-ESM-LR).

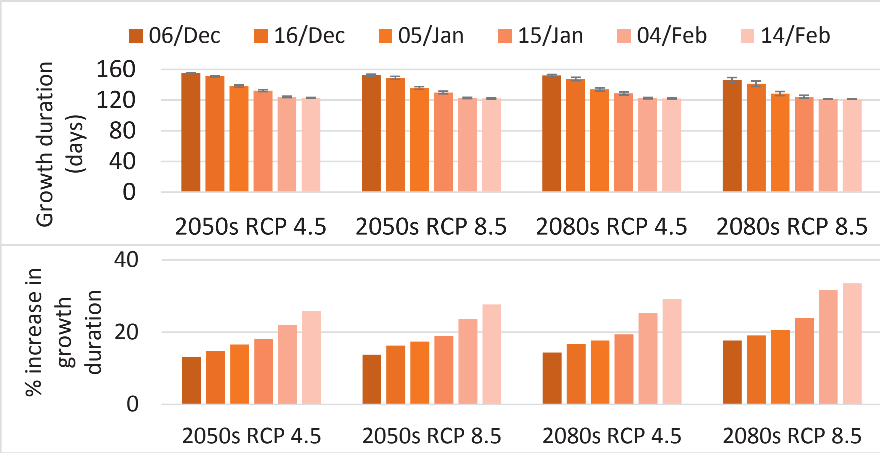

Fig. C.5 Growth-stage-days and percent increase in growth-stage-days (average of five models) for long-duration cultivars (top) compared to that for usual cultivars (bottom) for six different transplanting dates for RCPs 4.5 and 8.5 and two future periods 2035–65 (2050s) and 2065–95 (2080s) in Bogra.

Appendix D

Table D.1

Key adaptation needs (modified) selected from four major recent climate change policy plan in Bangladesh that are applicable for drought-prone Northwest Bangladesh.

Policy/Action	Authority	Key adaptation needs (modified for drought prone NW BD)
National Adaptation Program of Action (NAPA) in 2005	Ministry of Environment and Forest	• Capacity building for integrating climate change to agricultural water management • Information dissemination to local farmers and stakeholders • Mainstreaming adaptation into policies and programmes in agricultural and water sectors • Research on drought tolerant crop varieties • Insurance to cope with loss due to drought
Bangladesh Climate Change Strategy and Action Plan (BCCSAP) in 2009	Ministry of Environment and Forest	• Institutional capacity building for research, and dissemination of drought- and heat-resistant cultivars • Development of drought- and heat-resistant cropping system • Development of drought management options • Awareness building for better utilization of water resources • Risk management against drought and heat stresses • Monitoring changes and their impacts
Second National Communication of Bangladesh to the UNFCCC in 2012	Ministry of Environment and Forest	• New crop varieties • Water management innovations • Agricultural subsidies, insurance, and credit support • Crop diversification • Irrigation management
Bangladesh Delta Plan 2100 (BDP2100) in 2017	Bangladesh Planning Commission	• Additional surface irrigation • Improved irrigation technology, irrigation water saving, and precision irrigated agriculture • Crop diversification and intensification • Less water demanding crops • Wastewater reuse • Aquifer storage and recharge • Drought control centres • Training and capacity building • Participatory water management • Water pricing • Transboundary cooperation

Table D.2

Adaptation options related to crop production management.

SL	Adaptation options	Priority	Complexity
1	Identification and adoption of suitable cropping pattern	3.71	2.74
2	Adjusting planting time of different crops and varieties	3.50	2.57
3	Choice of drought-resistant and high-temperature tolerant crop varieties	3.77	2.71
4	Development and growing of crops for biomass production	2.12	2.90
5	Soil moisture conservation practices; e.g. mulching	3.65	2.39
6	Dry direct seeded rice production technology	2.39	2.53
7	Zero and minimum tillage to reduce soil and water losses	2.91	2.97
8	Wide row spacing to increase rainfall utilization	2.70	2.65
9	Strip intercropping with crops of different root systems to maximize soil water utilization	2.74	2.84
10	Transplantation at deeper depths for better root proliferation and facilitating moisture extraction during drought	2.03	2.80
11	Adoption of more intense rice cropping system	2.48	2.54
12	More fruit cultivation instead of rice	2.89	2.67
13	More vegetables cultivation instead of rice	2.88	2.46
14	Non-rice grain cultivation instead of rice	3.15	2.30
15	Construction of greenhouses/crop houses for fruits and vegetables cultivation	2.59	3.34
16	Integrated crop management practices	4.00	2.69
17	Close monitoring and evaluation of the farming activities	3.26	2.83
18	Rain-fed crop cultivation	3.46	2.21

Table D.3

Adaptation options related to land use management.

SL	Adaptation options	Priority	Complexity
19	Relocation or mobilization of farms	2.03	3.58
20	Restructuring of agricultural lands	2.48	3.17
21	Increasing crop lands by clustering scattered households	2.97	3.86
22	Reallocation of nursery plots	1.79	2.31
23	Conservation of agricultural lands	3.90	2.59
24	Char land and River bank management	3.67	2.98
25	Hilly land management	3.24	3.06

Table D.4

Adaptation options related to water management.

SL	Adaptation options	Priority	Complexity
26	Adjusting irrigation scheme; irrigation system evaluation and adjustment	3.84	2.65
27	Adjustment of irrigation method (e.g. drip, sprinkler or buried pipe irrigation)	4.03	2.70
28	Rain water harvesting and utilization	3.69	2.68
29	Integrated water management practices	4.07	2.77
30	Deficit irrigation practices for optimum economic benefit	3.11	2.70
31	Alternate Wetting and Drying (AWD) method for rice cultivation	3.93	2.01
32	Dredging of river bed to support surface water flow and increase storage	3.73	2.96
33	Reconnection of water systems	3.10	3.32
34	Construction of more sluices and weirs	2.67	2.88
35	Construction and Re-excavation of canals and other water conveyance structures	3.42	2.64
36	Enhancing capacity of sluices and weirs	2.75	2.58
37	Using wastewater for irrigation, especially during droughts	3.01	2.57
38	Re-excavation of traditional ponds	3.00	2.09
39	Maintain higher ground water table by limiting water withdrawal	3.52	2.99
40	Fair (re)allocation of water among different sectors (e.g. domestic, industrial and agriculture)	2.83	3.11
41	Fair (re)allocation of water among different regions (more to affected areas)	2.52	3.35
42	Risk based water allocation policy	2.71	3.08
43	Adopting water measurement measures to increase water productivity	3.66	2.54
44	Water pricing to minimize water loss and reduce water market monopoly	3.40	2.75

Table D.5

Adaptation options related to environmental management.

SL	Adaptation options	Priority	Complexity
45	Reduced fertilizer application to reduce water pollution	3.20	2.79
46	Waste management to reduce water pollution	3.54	3.46
47	Reduced groundwater withdrawal to reduce groundwater pollution	3.06	2.87
48	Implementation of effective agro-environmental schemes	3.21	3.31
49	Integrated nature and water management	3.25	2.75
50	Restoration of ecosystems	3.21	3.50
51	Afforestation, forest management and mix of tree species	3.11	2.53
52	Monitoring nature, interpreting changes and informing	2.81	2.91
53	Establishment and management of protected areas	2.80	2.97

Table D.6

Adaptation options related to social and institutional functions.

SL	Adaptation options	Priority	Complexity
54	New institutional alliances/associations	2.57	2.97
55	Insurances against drought related damages or financial incentives for drought period farming	3.20	2.71
56	Providing electricity to under-developed areas for running pumps during dry periods	3.51	2.53
57	Establishing area based local co-operation for irrigation system management and monitoring	3.06	2.54
58	International co-operation to increase surface water flow	4.39	3.34
59	Co-operation of local stakeholders for surface water management	3.35	2.59
60	Infrastructural development for irrigation and farm management	3.23	2.79
61	Training programs for on-farm water management	3.35	1.97
62	Developing meteorological stations to support better forecasting	3.41	2.40
63	Stimulating exchange of results and ideas between different projects	3.15	2.33
64	Promoting non-crop agriculture along with crop agriculture	2.84	2.50
65	Climate risk management measures	3.70	3.34
66	Farmers participatory approach for learning and adopting new technologies	3.54	2.50

Table D.7

Adaptation options related to education and research progress.

SL	Adaptation options	Priority	Complexity
67	Development and dissemination of updated irrigation technologies	3.82	2.54
68	Research on local drought management	3.42	2.57
69	Education and research on climate-smart agriculture	3.84	2.68
70	Education and research on conservation agriculture	3.35	2.56
71	Education and research on integrated water resources management	3.70	2.71
72	Training program for local farmers to deal with climate change and local water management	3.54	2.30

Abbreviations

AWD	Alternate Wetting and Drying
BADC	Bangladesh Agricultural Development Corporation
BARI	Bangladesh Agricultural Research Institute
BAU	Bangladesh Agricultural University
BBS	Bangladesh Bureau of Statistics
BCAS	Bangladesh Centre for Advanced Studies
BCCSAP	Bangladesh Climate Change Strategy and Action Plan
BDP2100	Bangladesh Delta Plan 2100
BINA	Bangladesh Institute of Nuclear Agriculture
BMD	Bangladesh Meteorological Department
BMDA	Barind Multipurpose Development Authority
BRRI	Bangladesh Rice Research Institute
BSMRAU	Bangabandhu Sheikh Mujibur Rahman Agricultural University
BSRI	Bangladesh Sugarcrop Research Institute
BWDB	Bangladesh Water Development Board
CEGIS	Center for Environmental and Geographic Information Services
CPM	Crop Production Management measures
DAE	Department of Agricultural Extension
E&R	Education and Research related measures
EM	Environmental Management measures
FAO	Food and Agriculture Organization
ICM	Integrated Crop Management
IWM	Institute of Water Modeling
IWRM	Integrated Water Resources Management
LUM	Land Use Management measures
MCA	Multi-Criteria Analysis

MoA	Ministry of Agriculture
MoEF	Ministry of Environment and Forest
NAPA	National Adaptation Programme of Action
NWMP	National Water Management Plan
RDA	Rural Development Academy
S&IM	Social and Institutional Management measures
SAU	Sylhet Agricultural University
SRDI	Soil Resources Development Institute
UNDP	United Nations Development Programme
UNFCCC	United Nations Framework Convention on Climate Change
WARPO	Water Resources Planning Organization
WM	Water Management measures

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Summary

Climate change not only affect crop yield and agricultural production but also water demand for crop agriculture. Understanding the changes in agricultural water demand in the context of climate change is vital for water resources management and agricultural planning. In addition to the assessment of changes in reference crop evapotranspiration, assessment of changes in crop water demand and irrigation requirement taking into account the crop's phenological response to increased temperature may better reflect the impacts of climate change on agricultural water demand. Since the changes in irrigation requirement may substantially vary from one region to another and from one cropping-season to another, the regional scale assessment of changes in water requirement is very important. Understanding of changes in water demand due to climate change is primarily more important for drought-prone regions of the world. The drought-prone Northwest Bangladesh is vulnerable to the impacts of climate change because of less water availability in the dry period and high agricultural water demand, particularly for dry season rice cultivation. This study quantified recent and future possible changes in crop water demand and irrigation requirement of dry season *Boro* rice in Northwest Bangladesh.

This study first assessed recent climate change impacts on water requirements of dry season *Boro* rice. The reference crop evapotranspiration, potential crop water requirement, effective rainfall during the crop growing period, potential irrigation requirement for crop evapotranspiration and net irrigation requirement of *Boro* rice were estimated using observed daily climate data in the CropWat model for the period of 1980 to 2013 for four Northwest districts. The consequence of recent climate change on water demand do not show any adverse impact on agricultural water demand. Significant decreasing trends of reference crop evapotranspiration were observed in most of the dry months due to increasing relative humidity and decreasing wind-speed and sun-shine hours despite some increase in temperatures. Changes in climatic conditions during the last few decades have not only decreased the climatic water requirement (ET_O), but also the irrigation requirement of dry season *Boro* rice. The net irrigation requirement of *Boro* rice has decreased by 11% during the last three decades at an average rate of 4.4 mm $year^{-1}$, despite decreasing effective rainfall, mainly because of high rate of decrease of crop evapotranspiration (5.9 mm $year^{-1}$). Therefore, this assessment supports that climate change can reduced water demands in some regions because of positive changes in humidity, wind-speed and/or sun-shine hours, regardless of global warming.

Next, this study quantified future climate change impacts on water requirements of dry season *Boro* rice. Climate scenarios were constructed from the outputs of five global circulation models for moderate (RCP 4.5) and rapid (RCP 8.5) climate change scenarios using a combination of statistical downscaling and bias correction. The generated climate data were used as input for CropWat to estimate water requirements of *Boro* rice for 2050s and 2080s. Increasing trends of daily reference crop evapotranspiration were found in most of the dry months due to increasing temperatures. However, potential crop water requirement of *Boro* rice will reduce by 6.5% and 10.9% for RCP 4.5 and 8.5, respectively for 2050s; and by 8.3% and 17.6% for RCP 4.5 and 8.5, respectively for 2080s

compared to the base period (1980–2013). Potential crop water requirement will decrease because of shortened rice growing duration due to the phenological response of rice to higher temperatures. The total net irrigation requirement of *Boro* rice will decrease by 1.6% in 2050s and 7.4% in 2080s for RCP 8.5 scenario on average for all models and districts. Therefore, climate change will lead to an increase in daily reference crop evapotranspiration, i.e. daily climatic water demand by crop, but will not increase the overall water requirement of *Boro* rice, because of crop's phenological response to increased temperature that reduces the number of growing days. The shorter growing duration of crops will provide scope to increase the cropping intensity by growing more number of crops each year on a single piece of land. As the daily ET_o will increase in the future, the agricultural water demand during the dry season still may increase if farmers take advantage of the shorter *Boro* season to cultivate an increased number of crops.

In a next step, this study assessed the effect of shifting trans-/planting date of dry season *Boro* rice as an adaptation strategy to reduce water use under future climate change. Number of days exceeding the threshold temperatures (maximum of 35 °C and minimum of 25 °C) was counted for critical period of *Boro* rice to understand compatibility of the changed planting dates. A delay in trans-/planting date accelerates growth of *Boro* rice and, consequently, reduces potential crop water requirement compared to an early planting. Compared to the early planting, the potential crop water requirements (averaged over all districts and models) reduced by 6.5 and 5.9% in 2050s for RCP 4.5 and 8.5, respectively, and by 5.7 and 0.6% in 2080s for RCP 4.5 and 8.5, respectively in case of late planting. Increased rainfall availability during the later periods of crop growth further contributes to reduce irrigation requirement under late planting. Therefore, the late planting is better choice than the early planting in the future from a water demand perspective. On the other hand, there will be more chances of both day- and night-time heat stress for late planting compared to early planting strategies of *Boro* rice. The normal planting dates also show the possibility of day-time heat stress in the future. Hence, shifting the planting date of the dry season rice has the potential to substantially reduce irrigation requirement, but the option is highly limited by the possible high temperature stress. However, late planting of temperature-tolerant cultivars or early planting of high-yielding varieties would be recommended based on local water availability.

Finally, this study identified and prioritized adaptation measures for improved agricultural water management in Northwest Bangladesh based on experts'/stakeholders' judgment following a multi-criteria analysis. A broad set of 72 measures was identified and classified. Results indicate that Local experts/stakeholders mainly prefer integrated, cooperative and advanced technological strategies that are mostly *out-system dependent*. Transboundary co-operation was ranked as the top-priority measure. Integrated water resources management and integrated crop management were the top-ranked options from the water and crop production management categories. Most of the top listed option involve high technical, social and/or institutional complexity. Increasing crop land by clustering scattered households and training programs for on-farm water management were the most and least complex measures, respectively. Stakeholders prefer higher scale *out-system dependent* strategies that aim to minimise the impacts of climate change on agricultural systems, rather than *in-system dependent* options that focus on changing the agricultural system itself to cope with the impacts.

Overall, this study addressed two important knowledge gaps by quantifying recent and future changes in water requirements of dry season rice and identifying strategies to improve water demand management in Northwest Bangladesh. The synthesis of this study point out two main conclusions. First, climate change will not increase the water requirements of rice but annual agricultural water demand may increase due to increase in cropping intensity. Second, the preference of integrated, co-operative and advanced technological strategies which are complex and *out-system dependent* involve uncertainties, whereas local *in-system dependent* adaptations have ample opportunities to cope with climate change. This study recommend to improve data collection and management, monitor the changes in agricultural practices and promote intelligent selection of cropping pattern, conserve recharge potential areas, continue large-scale *Boro* cultivation with efficient water management practices, promote intelligent selection of sowing date and crop varieties, develop temperature-tolerant rice cultivars and invest in capacity building to reduce complexities of efficient measures.

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About the author

Tapos Kumar Acharjee was born on 22nd February 1990 in Bogra, Bangladesh. He studied (2008–2011) B. Sc. Agricultural Engineering in Bangladesh Agricultural University and graduated with 1st merit position. He wrote his B. Sc. project report on “Rainfall-induced leaching of saline soil”. He has completed his MS in Irrigation and Water Management (2012–2013). The title of his MS thesis was “Effects of sugar mill’s wastewater on growth and yield of mustard”. In 2013, he joined as a lecturer in the department of Irrigation and Water Management in Bangladesh Agricultural University. Later, he received the fellowship from the Nuffic NICHE/BGD/155 project for his PhD study.

Tapos started his PhD in the Water Systems and Global Change group (back then Earth System Science), Wageningen University in January 2014. In his PhD research he explored the changes in water requirements of dry season rice under climate change. He has quantified recent and future changes in water requirements of *Boro* rice and developed adaptation strategies in Northwest Bangladesh. Currently, Tapos is working as an Assistant Professor in the department of Irrigation and Water Management in Bangladesh Agricultural University.

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- *Future irrigation water requirements in the northwest zone of Bangladesh: developing scenarios and analysing adaptation strategies*. Nuffic NICHE/BGD/155 PhD seminar, 31 January 2015, Dhaka, Bangladesh
- *Impacts of climate change on past trends of water requirements of dry period crops in the north-west zone of Bangladesh*. Wageningen 3rd PhD symposium, Diversity in Science, 26th of April 2016, Wageningen, The Netherlands
- *Scenarios of future water requirements of dry season Boro rice in the North-West Bangladesh.* 4th PhD symposium, Science: From Local to Global, 3 may 2017, Wageningen, The Netherlands

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