12-2019

# Hydro-Climatic Changes and Corresponding Impacts on Agricultural Water Demand in the Ganges Delta of Bangladesh

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# HYDRO-CLIMATIC CHANGES AND CORRESPONDING IMPACTS ON AGRICULTURAL WATER DEMAND IN THE GANGES DELTA OF BANGLADESH

by

Sonia Binte Murshed

A dissertation submitted in partial fulfillment
of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

in

Civil and Environmental Engineering

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UTAH STATE UNIVERSITY
Logan, Utah

2019

ABSTRACT

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by

Sonia Binte Murshed, Doctor of Philosophy

Utah State University, 2019

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Freshwater scarcity is the primary cause of many water-related problems such as salinity intrusion, excessive sedimentation, drainage congestion in the Bangladesh part of the Ganges Delta. These calamities trigger some critical issues such as decrease in soil fertility, loss of agricultural land, floods and droughts, out-migration of local people. Reduction of fresh surface water stimulates higher groundwater withdrawal. As an agriculture-dominant region, agriculture accounts for 96% of total water withdrawal in the Ganges Delta region. This research deals with the practical concerns of a transboundary river basin, suffering from both water quantity and quality issues. The upstream of Farakka Barrage in the Indian Ganges is the key controlling factor in the downstream flows and water availability in the Ganges Delta of Bangladesh. Therefore, geopolitics plays an integral part in the overall water allocation issue. We assessed the

observed human and climate-induced changes in the hydrologic regime of the region and its consequences, considering both surface and groundwater. Flow duration and mass curves, rainfall elasticity and temperature sensitivity, climate indices, are some of the methods used to understand the current status of freshwater availability. Agricultural water demand was predicted for this century (2020-2100) considering moderate and extreme carbon emission scenarios (RCP 4.5 and 8.5) of the Coupled Model Inter-comparison Project Phase 5. We also estimated evapotranspiration (ET) using meteorological data to understand total water loss and crop water requirements. We used the random forest algorithm to predict future land cover data and incorporated the data into the complementary relationship method to understand the changes in future ET. Significant uncertainties have been found in the predictions from different regional climate models. Irrigation demand may increase by 18% to 60% in this century from the historical (2001-2015) mean. The comparison of future irrigation demand with freshwater availability pointed towards an unsustainable agriculture condition. Appropriate measures should be taken to deal with the consequences of human interventions and climate change in this region. This study is an attempt to understand the key science-based concerns behind the freshwater scarcity and agriculture sustainability.

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(186 pages)

# PUBLIC ABSTRACT

Hydro-Climatic Changes and Corresponding Impacts on Agricultural Water Demand in the Ganges Delta of Bangladesh

Sonia Binte Murshed

The Ganges Delta in Bangladesh, a transboundary rural river basin, is an example of water-related calamities due to natural and human-induced stresses. It is an agriculture-dominated area with the presence of Sundarbans mangrove forest. Recently this area is facing unfavorable conditions due to limitations in quantity, quality, and timing of available freshwater. As a result, floods, droughts, water scarcity, stream depletion, salinity intrusion, excessive sedimentation are becoming common phenomena. These calamities are making this area unsuitable for agriculture and vulnerable to the Sundarbans' ecosystem. This study aims to provide technical insight into issues related to water scarcity and projected agricultural water demand for 2020-2100 considering the climate change uncertainties.

We addressed three critical areas to attain this purpose. As a first task, this study attempted to analyze and understand the observed hydrological changes over the past six decades to fathom the critical reasons for freshwater scarcity. Secondly, interdependency, availability, and accessibility of surface water and groundwater were analyzed to investigate the adequacy of current water demand and supply in agriculture, industrial and domestic sectors. Irrigation demand is much higher than others and occupies 93% of

the total water demand. Similarly, irrigation is 96% of total water withdrawal. This high demand in the agriculture sector led to our next objective to estimate agricultural demand for this century. It helps to understand an overall agricultural water consumption scenario for the future. This study provides necessary background information, which is vital for hydro-economically feasible agricultural water management plans.

# ACKNOWLEDGMENTS

I am deeply indebted to many people throughout my Ph.D. study, a journey to fulfill one of my long-cherished dreams. This journey helped me to believe that our goals are achievable if we work hard for them.

I would like to express my sincere gratitude to my advisor Dr. Jagath Kaluarachchi, for his continuous guidance during my Ph.D. study. He patiently dealt with me at the times when I had slow research progress, made mistakes, and struggled with time management and health issues. Each meeting with him motivated me to go forward. My research life was easy because of his generous support, which helped me to overcome many difficulties. Allowing my son to be present in several research meetings during his sickness is something I wholeheartedly appreciate.

Besides my advisor, I would like to thank my Ph.D. committee members: Dr. Richard Peralta, Dr. Mac McKee, Dr. Rezaur Rahman, and Dr. Ronald Sims, for their insightful comments and encouragement. Their meaningful feedback and guidance helped me to shape many of my research contributions and methods. I fully acknowledge the funding support from the Utah Water research laboratory and the International Water Management Institute.

I am thankful to my water lab colleagues Nazmus Sazib, Homin Kim, Hadia Akber, Noha Moghazy, Rick Lyons, Partha Majumder, Caleb Buahin, and many others for their support in numerous ways. I am also grateful to M. Alfi Hasan, Firoza Akhter, Mohammad Saifur Rahman, and Bilal Iqbal who work in different organizations but

extended their support towards my research.

My sincere thanks also go to my colleagues of the Institute of Water and Flood Management of Bangladesh University of Engineering and Technology for their continuous support and guidance. Special thanks to Sara Nowreen, who not only did all the hard work of collecting my research data but also helped me in many ways and provided thoughtful suggestions. She made my research life manageable.

Great thanks to my friends Oumou Diallo, Rola Adnan Jalloun, Mayada Alawad, Shante Majumder and Shamsun Nahar for their support during the crucial time when I was alone with my son. They supported me at the time when I needed the most. I am also thankful to the "Evening Care" of Utah State University, which provided free services for taking care of kids, and allowing parents to work in labs in evenings.

I would like to thank my parents Murshed and Jesmina, my aunt Sultana, my brother Minhaz and sister in law Shumiya, my cousin Nafia for their continuous encouragement. I would also like to thank my in-laws Farouk, Raihana, Faisal, and Faria for their support during this journey. Special gratitude to my husband Fahmid for his generous support to make my Ph.D. life easier. A big hug and lots of love for my son Farhan with whom I began my Ph.D. journey, who sacrificed a lot of mommy-time and is waiting eagerly for its successful completion.

Sonia Binte Murshed

CONTENTS

Page

# LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

Figure Page

# CHAPTER 1

# INTRODUCTION

## Motivation

Ganges Delta of Bangladesh, an agrarian region, is facing challenges to sustain its agriculture. This area is frequently affected by extreme hydrological events such as saltwater intrusion, floods, water logging, water scarcity, droughts, cyclones, erosion, and excessive sedimentation (Ministry of Agriculture and FAO, 2013; Mirza, 2004). In addition, high inter-annual variation of freshwater availability is the most critical part of this area's hydrologic system. Heavy monsoon rainfall in the wet season (June-Oct) and a contrasting scenario during the dry season (Nov-May) is a common climatic phenomenon in this region (Banglapedia, 2014). Water scarcity is very prominent during the dry season due to upstream water diversion by the Farakka barrage (Adel, 2002). Climate change is making this low lying area more vulnerable to these extreme hydrological phenomena (Jeuland et al., 2013; Mondal et al., 2019). This study deals with the probable causes and consequences of existing water scarcity issues, assess climate change impacts on future (2020-2100) water availability and its impact on agricultural water demand.

Freshwater flow plays a crucial role in Deltaic coast areas, where the imbalance between fresh and saline water flow causes salinity intrusion problems (Cooper, 1959; Mahmuduzzaman et al., 2014). It increases salinity in inland freshwater and soil, leading to loss of soil fertility, decrease in agricultural land and consequently reduced crop production. The maximum soil salinity ranges from 7.2 to 19.2 ppt (SRDI, 2017). It indicates an alarming condition for crop production as the World bank (Dasgupta et al.,

2014) found a 15.6% decrease in rice yields when soil salinity exceeds 2.56 ppt.

Moreover, the Farakka barrage not only obstructs freshwater flow but also traps sediment. It creates a hungry river condition and increases river erosion and sedimentation (Kondolf, 1997). A recent study by SRDI (2017) found an increase in flooding depth and duration in the study area. This study (SRDI, 2017) also observed delayed water recession after rainfall, which reduces field capacity. All of these have severe negative impacts on agriculture. Around three billion dollars' economic loss was estimated from 1976 to 1993 due to lower freshwater flow from the Farakka barrage (Kawser and Samad, 2016).

The region is also ecologically significant because of the presence of Sundarbans mangrove forest. Its importance is recognized by Ramsar Convention (1992) and UNESCO (1997) because it serves as a protecting barrier from cyclones, storm surges, and coastal erosion (CEGIS, 2007; Mukhopadhyay et al., 2015; Ronnbaack, 1999). A mangrove forest requires a certain salinity threshold from a mixture of saline and freshwater flow. However, the depletion of freshwater flow is also affecting the major and higher market value tree species (heretiera fomes) and termed as "Salinity induced mangrove migration" by World Bank's environment research team (Dasgupta, Sobhan, & Wheeler, 2016). Mukhpadhyay et al. (2015) predicted 17% loss of Bangladesh Sundarbans due to high salinity.

Managing water resources for agriculture can minimize some of these problems related to freshwater scarcity. Downstream suffers from the cumulative effect of upstream water-related activities (Young and Loomis, 2014). However, the practical implication of management approaches is not easy for a transboundary river basin (Wolf

et al., 1999). This study provides enough background information which will lead to formulating proper water management options in the future to sustain agriculture.

**Objectives**

The objective of this study is to understand the key concerns behind existing freshwater scarcity and therefore assess the climate change impact on agricultural water demand. The specific objectives are -

a) to understand the changes in the existing hydrologic regime regarding water availability, accessibility, and climate variability and relevant consequences
b) to have an in-depth understanding of water supply-demand and relevant constraints for water security and finally,
c) to project climate-change driven agricultural demand considering the hydro-climatic effects

**Research Questions**

This study addresses the following key themes and questions:

1. Observed changes in the surface water hydrologic regime and its consequences
   a) What are the changes in the hydrologic regime of the Ganges Delta of Bangladesh over the past six decades?
   b) How does the water supply in the region change during this period?
   c) Do the Farakka Barrage operation, and corresponding treaties affect the water supply to downstream users?

d) How does the water supply change with time compared to the demands from various user sectors? Are there apparent conflicts regarding deficits affecting rural economies?

2. Freshwater scarcity

    a) What are the prevailing situation of surface water and groundwater availability and demand in the region?

    b) What are the key water quality issues affecting freshwater scarcity?

    c) Are groundwater resources sustainable, especially in the presence of dry season withdrawals?

3. Agricultural water demand

    a) What will be the agricultural demand in 2030, 2050 and 2100?

    b) What are the uncertainties of future freshwater availability?

    c) How do hydro-climatic forecasts affect water resource decision making?

**Dissertation Organization**

This dissertation consists of three main sections in compliance with three main objectives. Chapter 2 discusses the changes in the existing hydrologic regime and its consequences due to human and climate-induced stresses. It gives key insights to the change-causing factors, differentiates their impacts and points the pivotal issues need to be considered for future water management. Chapter 3 measures freshwater sustainability, considering water supply and demands, seasonal availability,

sustainability, and relevant constraints for water security. This part of the study addresses both water quality and quantity of surface water and groundwater sources. Chapter 4 addresses the hydro-climatic effects on agricultural water demand. This chapter deals with the quantification of uncertainties resulting from different climate models. Finally, chapter 5 summarizes the key findings of this study, which will lead to future water management options to sustain agriculture.

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# CHAPTER 2

## CHANGES IN HYDROLOGY OF THE GANGES DELTA OF BANGLADESH AND CORRESPONDING IMPACTS ON WATER RESOURCES[1]

## ABSTRACT

The Ganges Delta in Bangladesh is an example of water-related catastrophes in a major rural river basin where limitations in quantity, quality, and timing of available water are producing disastrous conditions. Water availability limitations are modifying the hydrologic characteristics especially when water allocation is controlled from the upstream Farakka Barrage. This study presents the changes and consequences in the hydrologic regime due to climate and human-induced stresses. Flow duration curves (FDCs), rainfall elasticity, and temperature sensitivity were used to assess the pre- and post-barrage water flow patterns. Hydrologic and climate indices were computed to provide insight on hydro-climatic variability and trend. Significant increases of temperature, evapotranspiration, hot days, heating and cooling degree days indicate the region is heading towards a warmer climate. Moreover, increase of high-intensity rainfall of short duration is making the region prone to extreme floods. FDCs depict a large reduction in river flows between pre- and post-barrage periods, resulting in lower water storage capacity. The reduction of freshwater flow increased the extent and intensity of

[1]Murshed, S.B., M.R. Rahman, and J.J. Kaluarachchi. 2019. “Changes in Hydrology of the Ganges Delta of Bangladesh and Corresponding Impacts on Water Resources.” Journal of the American Water Resources Association 55 (4): 800–823. https://doi.org/10.1111/17521688.12775.

salinity intrusion. This freshwater scarcity is reducing livelihood options considerably and indirectly forcing population migration from the delta region. Understanding the causes and directions of hydrologic changes is essential to formulate improve water resources management in the region.

## INTRODUCTION

Climate and human-induced changes are affecting the quantity, quality, and timing of available freshwater (Han et al. 2019; Khazaei et al. 2019; Barnett et al. 2008; Magilligan and Nislow 2005). Any disruption in these three parameters can lead to a catastrophic condition. Bangladesh, a lower riparian country in South Asia, is a classic example of a region prone to water-related disasters due to the erratic changes in this combination. Too much water in the wet season produces floods whereas too little water in the dry season generates droughts, salinity intrusion, and stream depletion (Banglapedia 2014; Mirza 2004a; FAP 4a 1993). Transboundary river basins are more susceptible to these water-related disasters due to inconsistent patterns of rainfall and ad-hoc management of water resources (Petersen-Perlman, Veilleux, and Wolf 2017; Salehin et al. 2011; Wolf et al. 1999). Studies conducted in many river basins (Raadgever et al. 2008; Amarasinghe et al. 2016) have helped to derive various management solutions for different problems given the individual characteristics and unique features of each river basin. Consequently, every river basin needs to be carefully studied for hydrologic characteristics, water use priorities, and future challenges before a management approach is proposed. Given the similar challenges faced by the Ganges Delta region of Bangladesh, this study attempts to analyze and understand the observed hydrological

changes of the region over the past six decades (1948-2015). The purpose of this study is to understand the changes and dynamics of hydrology, so that the reasons for freshwater scarcity can be assessed.

The Ganges River Basin is a transboundary river basin that covers parts of Tibet, Nepal, India, and Bangladesh. The lower end of Ganges River Basin, termed as the Ganges Delta, discharges into the Bay of Bengal. It is the largest delta globally and one of the most fertile regions of the world (Most et al. 2009). Figure 2-1 shows the Bangladesh part of the Ganges Delta, which covers approximately 42,000 $km^2$ (BBS, 2013) and consists of 28% of the total land area and 20.2% of the population of Bangladesh (BBS 2013). Aside from the deltaic characteristics of fertile land and coastal resources, the presence of Sundarbans Mangrove Forest adds special ecological and economic value to the area. Sundarbans, the world's largest mangrove forest, was declared a Ramsar Site in 1992 and a World Heritage Site by UNESCO in 1997 in recognition of its richness in biodiversity. Approximately 60% and 40% of Sundarbans occupy Bangladesh and India, respectively, with a total area of 10,000 $km^2$ (Banglapedia 2014; Agrawala et al. 2003). Millions of people in Bangladesh and India depend on Sundarbans for their livelihood through fishing, timber harvesting, wildlife, and tourism (FAO 1994; Sadik 2009). In addition, the forest acts as a protective barrier against tidal surges, cyclones and coastal erosions (Mukhopadhyay et al. 2015; Ronnbaack 1999; CEGIS 2007).

For the past 30 years, the Ganges Delta has been vulnerable to multiple stresses of various scales. These include upstream catchment activities, new dams/ barrages, lower freshwater flows, land cover, subsidence, and marine processes such as ocean circulation,

cyclones, and storms (Amarasinghe et al. 2016; Akter et al. 2015; Brown and Nicholls 2015; Syvitski et al. 2009). This River Basin has more than 1000 dams of different heights ranging from 10 m to 260 m (World Bank 2014). It also has 181 barrages and weirs ("India-WRIS Wiki." 2015) to manage water, particularly in the dry season. The Farakka barrage is located on the upstream boundary between India and Bangladesh and has been in operation since 1975. This barrage plays an important role in the supply of dry season freshwater flows from the Ganges to the delta region. Several treaties were signed since the operation of the barrage, including the 1975 interim agreement, the 1977 Ganges water agreement, the 1985 agreement, and the latest 1996 agreement for a 30-year period (Tabassum 2003; Rahaman 2009). There was no water-sharing treaty from 1986 to 1989. A major drawback of these treaties is that the amount of water diverted from upstream of the Farakka barrage is not specified (Jeuland et al. 2013).

Any decrease in natural flow by dams/ barrages can lead to "hungry water" condition at the downstream where sediment-starved water increases riverbank erosion and sedimentation (Kondolf 1997). It reduces the water carrying capacity of rivers. Because of this impact, recurrence of flooding during the wet season and reduced navigability in the dry season was observed (OGDA 1999). Other impacts include subsidence, and increase of soil and water salinity (Kawser and Samad 2016; Akter et al. 2015; Dasgupta et al. 2014; NPA 2005; Agrawala et al. 2003). In fact, saline water (hence salinity) intrusion towards inland is a major consequence of low upstream freshwater flow in this coastal area. It happens mostly due to the imbalance between fresh and saline water (Mahmuduzzaman et al. 2014; Cooper 1959). Sea level rise, due to climate change, is another reason for increasing salinity (Dasgupta et al. 2014). It adds

more stress to this already vulnerable Sundarbans region (Dasgupta et al. 2014; Hussain et al. 2012). There is a high probability of reducing the extent of the Bangladesh Sundarbans by 17% by 2105 due to high salinity (Mukhopadhyay et al. 2015). The high salt content in water and soil is limiting crop growth (SRDI 2009). It was estimated that the economic loss due to the diversion of water caused by the Farakka barrage is around three billion dollars from 1976 to 1993 (Kawser and Samad 2016).

Acute shortages of freshwater flows, especially during the dry season, limit irrigation which in turn affects agricultural productivity (Whitehead et al. 2015; FAP 4a 1993). The Ganges-Kabodak project is the largest existing irrigation project in the study area, irrigating 1400 $km^2$. With decreasing flow in the Ganges, major disruptions arose during this project, especially from 1993 to 1996 (ADB 1998). A major part (14000 $km^2$) of the southern delta region has polders, which are round-shaped embankments built in the 1960's to protect crops from floods and saline water intrusion (OGDA 1999). Due to river sediment deposition, land elevations inside the empoldered area are now below the river bed, resulting in water-logged conditions. This leads to lower soil fertility, reduced fish productions, and increased soil and water salinity (Nowreen, Jalal, and Khan 2014). In essence, the Bangladesh part of the Ganges Delta region is facing severe salinity build-up and reduced river carrying capacities.

The existing data and information available from these studies suggest that water scarcity, salinity, and increasing demand in the Ganges Delta region of Bangladesh is affecting the rural livelihood and ecology of Sundarbans. The objective of this study is to identify the major changes to the hydrologic regime of the Ganges Delta of Bangladesh and to assess the corresponding impacts on freshwater availability. Both climate and

human-induced interventions, namely the Farakka barrage, were addressed to detect the hydrologic changes. In addition, we also identified the dominant factors responsible for these changes. Several studies (World Bank 2014; Jeuland et al. 2013; CCC 2009; Adel 2002) assessed the climatic impact on this Delta region's hydrology, but this paper first considers actual evapotranspiration (ETa) in the study. The variability of Ganges river flow was analyzed using water release from the Farakka barrage which again depends on water sharing treaties between India and Bangladesh. The hydrologic alteration was assessed using hydrologic indices (Monk et al. 2011; The Nature Conservancy 2009). Application of climate indices to this study area is a newer approach to reveal the climatic variability. Murshed et al. (2013) used 11 rainfall indices to assess the hydro-climatic patterns of Bangladesh. A part of this study conducted the same assessments, along with additional indices that focus on extreme rainfall and temperature events. The findings from these analyses help to reveal the causes for ongoing floods, droughts, and water scarcity, the common extreme phenomena in this study area. Although drought and water scarcity, both indicate the shortage of water but the origin of these calamities are different. Drought is a natural hazard, caused mainly due to climatic variability whereas water scarcity is a long-term water imbalance caused by anthropogenic factors (Van Loon and Van Lanen 2013). Both are connected and can be triggered by each other. Propagation of drought in water scarce region has a serious impact (Wilhite 2002). The consequences of altered hydrologic conditions on salinity and sedimentation were also assessed. In addition, temporal changes in surface water withdrawal, land use, and demographic patterns are discussed to understand the magnitude of the changes in fresh surface water availability.  Knowing the interrelationships among different historical

changes, human interventions, climate variability and corresponding trends of hydrology helps in addressing future water management approaches (Black 2019; Johns et al. 1999). Moreover, we need to keep in mind the increasing influence of climate change, population growth, and urbanization taking place in the region (S. N. Islam, Reinstädtler, and Gnauck 2017; Choudhury et al. 2012).

# METHODOLOGY

The methodology section was divided into three parts. First, detection of changes in the hydrological input and identification of probable causes. This part addressed the methodology to detect trends of key hydro-climatological variables, potential directions of extreme climate and changes in low flow conditions of Ganges and Gorai rivers. In the second part, how these changes in hydro-climatic variables had influenced flood, drought and water scarcity problems were addressed. Finally, the procedures used to identify corresponding impacts on instream water availability, demographics and land use patterns were discussed.

## Change detection in the Hydrologic Region

### *Hydro-climatological Variables*

The key hydro-climatological variables selected here are rainfall, temperature, relative humidity, wind speed, evapotranspiration (ET), and streamflow which influence water balance and therefore freshwater availability. Meteorological data were collected from the Bangladesh Meteorological Department (BMD) and hydrological data from the Bangladesh Water Development Board (BWDB). These time-series data did not fall into identical time periods. The longest running meteorological stations were set up in 1949

and flow data for Ganges River were available from 1934. Data selected includes time-series with more than 30 years and fewer than 10% missing values. The missing meteorological data were replaced with average seasonal values. The average density of rainfall stations is one station for every 615 $km^2$. Stations measuring other parameters, such as temperature, relative humidity, and wind speed, have an average area of 3027 $km^2$ per station, which fulfills the station density requirements of the World Meteorological Organization (WMOa, 2008). Double mass curves (DMC) of accumulation of one quantity against the accumulation of another, are used to check data consistency (Searcy and Hardison 1960). Mean values were used in many cases to represent the entire study area given the minimal elevation difference.

We computed actual evapotranspiration (ETa) using the modified complementary relationship model proposed by Anayah and Kaluarachchi (2012). The advantage of this approach is that it provides calibration-free regional values of ETa using meteorological data only. This methodology was previously validated at 34 global locations ranging from tropical to subarctic (Anayah et al. 2013). This method uses maximum and minimum temperatures, relative humidity, and wind speed of 12 BMD stations. The model equations are given below –

$$D = E_a / [E_a + (R_n - G_{soil})] \qquad (1)$$

$$E_a = 0.35(\beta + 0.54U)\,[(e_s - e_a)\,a_1] \qquad (2)$$

$$G_{soil} = 1/\,(c_1 + c_2\, e^{c_3 D}) \qquad (3)$$

$$ETW = \alpha \frac{\Delta}{\gamma + \Delta} (R_n - G_{soil}) \qquad (4)$$

$$ETa = ETW\,[2G_1 / (G_1 + 1)] \qquad (5)$$

$$ETP = 2\,ETW - ET \qquad (6)$$

where, ETa is in mm/day, ETW is ET in wet environment (mm/day), ETP is potential ET (mm/day), $\gamma$ is psychrometric constant (kPa/◦C), $\Delta$ is rate of change of saturation vapor pressure with temperature (kPa/◦C), D is surface dryness, $R_n$ is net radiation (mm/day), $G_{soil}$ is soil heat flux (mm/day), $c_1 = 1.0$, $c_2 = 0.028$, and $c_3 = 8.045$. As the daily values of $G_{soil}$ is relatively insignificant comparing to $R_n$, it is assumed $G_{soil} \approx 0$. $E_a$ is drying power of air (mm/day) using advection-aridity approach (Brutsaert and Stricker 1979) , $\beta$ =1.0, U is the wind speed at 2 m above ground level (m/s), $e_s$ is saturation vapor pressure (mbar), $e_a$ is the vapor pressure of air (mbar), $a_1$ is a unit conversion factor equals to 0.75 mm Hg/mbar, $\alpha$ is Albedo, and $G_1$ is relative evaporation that happens under similar wind and humidity conditions from a saturated surface at the actual temperature.

The study period was divided into pre- and post-barrage periods to assess the effect of upstream water diversion at the Farakka barrage. The post-barrage period was divided into three distinct periods based on the existence of various water sharing treaties. The receivable amount of water flows in the Bangladesh part of the Ganges River entirely depends on these treaties.  In addition, seasonal analyses focusing the dry (Nov-May) and wet seasons (June-Oct) were conducted to capture the variation in water availability.

***Calculation of Climate Indices***

Fourteen climate indices were analyzed to understand the extreme patterns of rainfall and temperature. These indices were adopted from the Expert Team on Climate Risk and Sector-specific Indices (ET CRSCI) (Alexander, Yang, and Perkins 2013;

WMO 2012) and selected based on the study area's hydro-climatic conditions (Table 2-1). For climate indices, the data period of 1961-2015 was used on a calendar year basis with R-based software, ClimPACT (Alexander, Yang, and Perkins 2013). The rest of the analyses were performed from 1949 to 2015 water years (WY). In Bangladesh, a water year is from April 1st to March 31st.

***Change Detection on River Water***

Flow duration curves (FDCs) which represent discharge against the percent of time the flow was equaled or exceeded (Vogel and Fennessey 1995), are effective to reveal quantitative changes in the river flow. We used FDC of daily flow data to detect these changes in flow characteristics of the Ganges and Gorai Rivers. The latter is the major spill channel towards Sundarbans and controls the salinity and siltation rates in the tidal zone (FAP 4b 1993), and therefore has an important environmental significance to the study region. These curves are plotted for pre- (1949-1976) and three distinct post-barrage periods (1976-1988, 1989-1996, 1997-2015). Values of 20% (Q20) and 90% (Q90) of river flows were used as high and low flow thresholds, respectively (WMO 2008). We also computed the slope of FDC (SFDC) between the 33% (Q33) and 66% (Q66) values (Sawicz et al. 2011) and compared the changes from the pre-barrage period to understand the flow regime. SFDC can be defined as follows

$$SFDC = [\ln (Q33)-\ln (Q66)] / (0.66-0.33) \quad (7)$$

The Mann-Kendall trend test and Pettit's test were performed to detect trend and abrupt changes on mean annual minima of 7-day, 30-day and 90-day average flows. These flow indices of annual lowest flows for a given duration help to understand the

magnitude and direction of extremely low flows (Richter et al. 1996).

The combined influence of annual and dry season anomalies of rainfall and temperature on streamflow were assessed by plotting contour lines in temperature and rainfall plane (Risbey and Entekhabi 1996; Fu et al. 2011). Contour lines of percentage change of streamflow are plotted as a function of percentage of rainfall change and temperature change. Changes are measured from their mean values of the pre-barrage period (1949-1975 WY). In addition, rainfall elasticity and temperature sensitivity were computed with the proportional change in streamflow divided by the proportional change in rainfall or temperature (Sankarasubramanian, Vogel, and Limbrunner 2001). These non-parametric estimators were used to assess the response of streamflow variations to long-term seasonal changes of rainfall and temperature (Vano and Lettenmaier 2014). Moreover, double mass curves (DMC) of accumulated flow versus accumulated rainfall were used to quantify climatic and anthropogenic impact on the Ganges River (Gao et al. 2017). Pettitt test was done on DMC slope to detect the change-point year considering the impact of rainfall on streamflow.

***Statistical Tests***

Trend analyses were conducted on hydro-climatological variables and indices using the Mann-Kendall trend test (Mann 1945; Kendall 1975). The magnitude of trends was estimated by the Sen’s slope test (Sen 1968). These tests were done using *zoo*, *Kendall* and *trend* packages within the R software (R version 3.2.4). The results from these tests were considered statistically significant when 2-sided p-value is less than 0.025.

## Identifying Major Causes of Floods, Droughts and Water Scarcity

Flow mass curves (FMC) of cumulative discharge volume against time of two extremes (1988 and 1998) and one normal flood events were plotted to understand the Ganges' contribution to flooding events. In this case, average flow from 1980 to 1986 (except flow from 1984 flood year) was considered as normal flooding year. Furthermore, water level data of six major stations (namely SW90, SW99, SW91.9R, SW244, SW107.2 and SW39) were compared with the danger level of respective stations to understand the effect of river flows on floods (Figure 2-1). Variability in hydro-climatic factors was used to detect the causes of droughts and water scarcity.

## Measuring Effects due to the Hydro-climatic Variability

### *Assessing Salinity and Sedimentation Trends*

The Mann-Kendall trend test and Sen's slope test were conducted on salinity data spanning 15 years (1997-2011) to assess the changes in surface water salinity. The same tests were also applied to maximum sediment concentration data at two stations, namely SW90 (2000-2008) and SW91.9 (1992-2010) of the Ganges River. The daily data of salinity and sediment were not continuous. These analyses offer a glimpse of the salinity and sedimentation of the study area.

### *Estimating Surface Water Availability*

Total rainfall volume and ET loss were calculated using the Thiessen polygon method. Flows from the major rivers (i.e., the Ganges, Jamuna, and Meghna), were distributed through the study area assuming river flow is proportional to the river width (MPO 1987b). Flow data from five major discharge stations (SW90, SW93.5L, SW99,

SW 4A, and SW273) were considered as incoming stream flows to the study area (Figure 2-1). Current surface water availability was determined for the data period from 1997 to 2015 (WY) which falls under the 1996 water-sharing treaty. Total available fresh surface water supply was calculated using rainfall, stream flows, and ET volumes. Available water for instream use was calculated using water availability and water use considering dry and wet season variations.

***Quantifying Surface Water Use***

Surface water is greatly influenced by land use, population density, agriculture, and industrial activities, among many other factors (Ashraf et al. 2019; Wu et al. 2019). Freshwater withdrawals for agriculture, industry, and domestic purposes were determined using the procedures described by MPO (1986, 1987a). The 2011 census data (BBS 2013) were used for this purpose. Irrigation equipment data (2009-2012, 2015, 2016) were collected from the Bangladesh Agriculture Development Corporation (BADC).

For minor irrigation in Bangladesh, surface water is mostly used with low-lift pumps (Ministry of Agriculture and FAO 2013). Irrigation water use was computed using the pump data including number of units, discharge, and average hours of operation (MPO 1987a). Discharge and yearly operating hours for low-lift pumps (LLP) are 43 L/s and 800 hours (MPO 1987a). The G-K and Barisal irrigation projects are considered major irrigation systems in the study area. Current water abstraction data for these projects is not available, therefore the known data from 1983 was used.

The population has increased by 40% from 1981 to 2011 (BBS 2013) and this information was used to compute domestic water use. For industries, 5% annual growth

(BBS 2005) was used to calculate the surface water use. Surface water withdrawals by the industry sector were changed from 129 million $m^3$ /year in 1982 (MPO 1986) to 507 million $m^3$/year in 2011.

***Analyzing Demographic Pattern and Land Use Changes***

The decadal demographic changes between 1981, 2001, and 2011 for each district were analyzed to understand the migration pattern. In addition, three land use maps were studied to assess the changes in land use patterns. One is a 0.5 km resolution MODIS land cover map spanning ten years from 2001 to 2010 with a collection of 5.1 MCD12Q1 land cover data (downloaded from https://landcover.usgs.gov/global_climatology.php, accessed in July 2017). Two other land use maps for 2012 and 2014 were collected from the Center for Environmental and Geographic Information Services of Bangladesh. The 2014 map covered only 90% of the study area, and therefore the remaining 10% was obtained from the 2012 map. The changes in land area corresponding to normal flooding depth over the past 22 years (1986-2008) were analyzed to assess the flooding conditions. In addition, a 1 km MODIS annual maximum green vegetation fraction spanning from 2001 to 2012, along with 5 MOD13A2 normalized difference vegetation index (NDVI) data (downloaded from http://landcover.usgs.gov/green_veg.php, accessed in July 2017) were used to assess the spatial extent of green vegetation and the Sundarbans Mangrove Forest.

## RESULTS AND DISCUSSION

This study assessed the hydro-climatic variability over the past 66 years at four different time slots, namely pre- and three distinctive post-barrage periods. The time slots

are in different length, and we recognize the fact that the sensitivity of the trend results is subjected to time-length of data (Monk et al. 2011). However, it gives information of how hydro-climatic variation and water diversion by the Farakka barrage have jointly influenced surface water availability. We attempted to find the impact of climatic parameters on surface water resources, synchronizing them with water release through Farakka barrage. The hydro-climatic assessments lead to identifying the key causes of floods, droughts and water scarcity. Finally, the consequences of an erratic pattern of surface water availability are discussed in connection with available water for instream use, changes in salinity, land use, and demographic patterns.

## Hydro-climatic Variability

### *Changes in the Climatic Pattern*

The temporal analyses of temperature and ETa have shown increasing trends as presented in Figure 2-2. Temperature change is statistically more prominent in the post-barrage periods. The rising trend of temperature is obviously increasing atmospheric moisture demand and eventually enhancing ET. These upward trends are noticeable over large parts of the study area in the wet season (82% stations) than in the dry season (45% stations). Particularly, the coastal part shows rising of temperature and ET through the seasons. Higher ET may influence higher salinity in coastal rivers and consequently may pose a threat to the Sundarbans ecosystem.

The temperature change is also assessed by eight temperature indices which represent extreme temperature conditions. The changes in climate indices are presented in Figure 2-3. The rising trend of SU30 and TXx indicates that the upper range of

temperature is increasing. Moreover, a significant increase of HDDheat and CDDcold suggests more energy is required to heat and cool the internal environment. Again, increasing CSDI and decreasing TNn indicates a trend in increase of extremity and duration of cold days. These observations indicate the increase of extreme temperatures, in both the high and low ends of the spectrum, while the change in extreme high temperatures is more pronounced than the extreme cold temperatures. The increase in overall temperature, along with extreme values, has a great influence on increasing ET. A marginal rise in mean temperature also contributes to higher ET. ETa in the recent period of 1997 to 2015 (WY) shows about 110% volume increase compared to the pre-barrage period ($23x10^3$ million $m^3$). These observations indicate that the study area is moving towards a warmer climate which has a profound impact on surface water availability. The seasonal variations of temperature and ETa are not significant, unlike rainfall which has high seasonal variation.

High interannual rainfall variation, ranging from 250 mm to 2000 mm, is a characteristic of this study area. Dry and wet period indicators, i.e., CDD and CWD, are increasing. These observations suggest longer consecutive dry and wet periods thereby, intensifying both dry and wet seasons and possibly affecting crop production. Longer successive wet periods can reduce drainage capacity and produce floods. In addition, there is an overall decrease in SDII and PRCPTOT, and change in SDII is statistically significant. Hence, mean rainfall intensity is decreasing with less annual total rainfall. Accompanying this rainfall condition with increasing CDD signals higher possibility of meteorological drought. A similar finding was made by Sillmann et al. (2013) for the Mediterranean region. Further, the northern part of the study area shows an increase of

contribution from extremely wet days (R95pTOT, R99pTOT) whereas the southern part or the coastal area shows the opposite behavior. Therefore, Sundarbans and the surrounding area are facing less rainfall with higher temperature and ET, making it more volatile part of the study area.

Past literature on temperature and ET provide both similar and conflicting results compared to the findings of this study. FAP 4a (1993) found no particular trend for temperature but Hoque et al. (1996) noticed a definite rising trend in the post-Farakka period which is equivalent to the findings of CCC (2009) for the whole of Bangladesh. Similar results were also demonstrated by Adel (2002) along with a decrease in minimum temperature. The sharp decline of the Ganges' flow was identified as a reason for this temperature variation (Mirza 2004b; Hoque et al. 1996; Adel 2002). CCC(2009) found a decreasing trend for reference crop ET ($ET_{ref}$) from 1960 to 2001. They argued that the decreasing trend of sunshine duration serves as supporting evidence. This result supports the findings of ETa from our study. According to Bouchet (1963)'s hypothesis, rising ETa supports the decrease of $ET_{ref}$ (Irmak 2011). In addition, Adel (2002) found a decrease in rainfall in the Ganges basin of Bangladesh, which matches with this study's findings of decreased rainfall over the past 66 years. Although CCC (2009) showed the increase of rainfall in the dry season for Bangladesh as a whole, the overall contribution of the dry season rainfall is negligible compared to the wet season.

***Changes in River Flow Behavior***

River flow is a major contributing factor in surface water resources besides climatic variables. FDC was used to understand the combined effect of physiographic and

climatic influences on river flow behavior in the study area (WMO 2008; Lamb, Faulkner, and Zaidman 2010). A severe change in upstream flow at two major streamflow stations, SW90 (1935-2015 WY) and SW99 (1965-2015 WY), has been identified as an after-effect of the Farakka barrage operation. SW90 is located at the entry point to the Bangladesh part of the Ganges River, and SW99 measures the Gorai River flows towards Sundarbans (Figure 2-1). The shape of the FDC for the Ganges River shows a steep gradient, as per Figure 2-4. It indicates higher variability in daily stream flows and extreme high and low flows into the study area. The Gorai River shows a similar pattern (Figure 2-5). There are sharp drops in 95 percentile (Q95) values. At SW90, low flow (Q90) decreased 49%, 73%, and 52% in the periods (WY) of 1976-1989, 1990-1996, and 1997-2015, respectively, compared to the pre-barrage period. It is an indication of the significant reduction of dry season flow. However, wet season flow (i.e., high flow, Q20) increases slightly, 4% during the first treaty period, whereas the subsequent periods without and with treaties show a 14% and 4% decrease respectively. Although the Farakka barrage does not have any control over wet season flow, there are other dams and barrages upstream of the Farakka barrage which affects the amount of flow. Both dry and wet season flows decrease for the Gorai River at SW99 while the decreasing percentage is much higher in the dry season compared to the wet season. Dry season flow (Q90) decreased 99% between 1990 and 1996 (WY), suggesting serious concerns in the period without the treaty. The Gorai River is the only water carrying distributary towards Sundarbans. Therefore, the Sundarbans Mangrove Forest faced a continuous shortage of water in the post-barrage period from 1976 to 2015 (WY). Q90 and Q95 for both rivers show a similar decreasing trend (Figures 2-4 and 2-5) with Q95

being the most commonly used flow statistic to assess downstream water quality (Bojinski 2010; WMO 2008). A drastic reduction in Q95 with the ongoing construction of Rampal coal-fired power plant (Lemly 2018; Chowdhury 2017), located 9 km downstream to Sundarbans, indicates a potential threat to its ecosystem, especially for water quantity and quality.

Also SW90 and SW99 show higher values of SFDC (Table 2-2) representing higher flow variability. There is an increase in the change in slopes from the pre-barrage period, making the SFDCs steeper. The highest changes, namely 46% for SW90 and 176% for SW99, are noticed during the period without a treaty. As suggested by Castellarin et al. (2012) these findings indicate that the study area is characterized with low catchment storage capacity, resulting in lower base flow and higher frequency of extreme low runoff.

The minimum 7-day, 30-day, and 90-day average flows are relevant to the surface water irrigation system (WMO 2008). These low flow statistics show a significant decreasing trend for the Ganges River (Table 2-3). The Pettitt test on streamflow points toward the year 1975 (WY 1976) as the major turning point for the Gange's low flow statistics. When the Farakka barrage began operating, there followed a drastic reduction of dry season flows, immediately affecting the Bangladesh portion of the Ganges River. Major changes in the Gorai River began in 1979. DMC also shows the same change-point year considering the impact of rainfall on the Ganges River. The contributions of rainfall and human intervention in lowering river flow are -86.3% and 186.3% respectively. It emphasizes the fact that human intervention, namely Farakka barrage is the key dominating factor for the changes in Ganges flow.

The contour plots (Figure 2-6) of the percentage change of flow related to the percentage change in rainfall and change in temperature at post-barrage period revealed some key influences on the flow pattern. These changes were estimated to address the mean pre-barrage condition. Figure 2-6 shows that there is not much impact of rainfall and temperature changes on Ganges and Gorai River flows. Further analyses were performed to assess the seasonal hydrologic sensitivities on river flows by rainfall elasticity and temperature sensitivity. These two indicators provide an overall assessment whether the change in rainfall or temperature has more influence on the change in river flows (Vano and Lettenmaier 2014). Figure 2-7 shows that the coefficient of determination ($R^2$) for rainfall elasticity ranges from 0.002 to 0.04. Temperature sensitivity also shows similar results of $R^2$ ranging from 0.0002 to 0.02. Hence, neither the rainfall change nor the temperature change is the key dominating factor influencing the flow variability of the study area. It is therefore evident that upstream water diversion structures play a dominant role in controlling freshwater flow.

The understanding of basic changes in hydro-climatological variables directs to further study on identification of causes behind floods, droughts and water scarcity in the region.

**Linkage of Hydro-climatological Variables to Flood, Drought and Water Scarcity**

We analyzed four extreme events, including two floods (1988, 1998) and two droughts (1999, 2006), along with river water levels, sedimentation, and anomalies of hydro-climatological factors to understand the causes for these calamities.

Flooding is a common phenomenon in the study area since 84% of the area is

under normal flooding depth, i.e. 30 cm to >180 cm (BBS 2013). The high land area above normal flooding reduced 24% over the last 22 years (1986 -2008) which is shown in Table 2-4. Flooding is considered a disaster only when it exceeds the normal flooding depth. The decadal analyses of water level above the danger level (i.e., flooding) for the Ganges River shows a vast difference over the period from 1911 to 2014. The number of flooding years was seven in the decade of 1911-1920, whereas it was only one in 2001-2010, as shown in Figure 2-8. The water level in the Ganges River did not cross the danger level in 2004-2014. Both the trend of annual maximum water level and maximum water level above danger level shows a statistically significant decreasing trend (Table 2-5). Even the number of the days above river danger level also exhibits a significant decreasing trend, as shown in Table 2-6. The Jamuna River also contributes to the floods of this area. There are not many statistically significant changes in the water level of the Jamuna River over the last 49 years (1951-2014), as depicted in Table 2-5 and Figure 2-8. The reasons for the two extreme flood events of 1988 and 1998 are the synchronization of high flows in three major rivers (i.e., the Ganges, Jamuna, and Meghna), along with the increase of heavy rainfall (Banglapedia 2014). The FMC of these three major rivers (Figure 2-9) show their contribution in those two extreme flooding events. The Ganges River contributed about 20% water volume to both flooding events, and as such is not considered to have had a large influence on flooding. The Farakka barrage influences the river erosion and sedimentation processes. Both SW90 and SW91.9L stations are showing a statistically significant increasing trend (2-sided p-value =< 2.22e-16) of sediment concentration in the Ganges River, indicating that the barrage is reducing the water carrying capacity of rivers and consequently obstructing the drainage system for

heavy rainfalls. River sedimentation is also creating the same drainage congestion inside the polder area by raising the river level relative to the surrounding land. The analyses of three tidal stations (SW244, SW107.2, and SW39) show an increasing trend (Table 2-6) of the water level, indicating that the backwater effect hampers the smooth drain-out of flooding water into the Bay of Bengal. In summary, flooding events of the study area are mainly controlled by drainage congestion due to high sedimentation, land subsidence, and backwater effects. These are creating waterlogged conditions for rainfall, which is the major source of flooding events.

Contrarily to flood, water scarcity is another common phenomenon in the Ganges Delta. The Ganges' flow reduced drastically at the downstream of Farakka barrage after its operation began. It can be visualized clearly in Figures 2-10 and 2-11 where the hydro-climatological anomalies are shown for dry and wet seasons respectively. These anomalies were measured from the mean of the pre-barrage period. Dry season flow anomalies can be decreased up to 60% per year in post-barrage periods and show a statistically significant negative trend. Reduced dry season flow, along with the negligible dry season rainfall, makes this deltaic land a water scarce region.

In addition, temperature and ETa have a statistically significant increasing trend over the last 65 years (1949-2015 WY) as shown in Table 2-7. Although higher temperature is conducive to higher rainfall, it also increases ET, declining surface water availability and thus triggering drought-prone conditions. In fact, ETa can act as a reliable measure of drought (Kim and Kaluarachchi 2019). Rahman and Lateh (2016) analyzed droughts in the period of 1971-2010 and pointed that the following calendar years were drought-affected in many districts of the lower end of the Ganges Delta: 1975-

1979, 1981, 1982, 1985, 1989, 1990, 1994, 1995, 1997, 1999, 2004, 2006, 2008-2010. Among them, 1999 and 2006, were the extremes (Figures 2-10 and 2-11). Continuous positive anomalies of temperature and ETa can be found from 1995 onward. As there are no statistically significant changes in rainfall (Table 2-7), most droughts in this area are initiated by increasing trend of temperature, aggravated by low streamflow and can be assessed as hydrological droughts (Anne F. Van Loon 2015). In fact, temperature induced droughts are becoming more common among severe drought types (Bradley Udall and Overpeck 2017; Anne F. Van Loon 2015). Sometimes floods and droughts happened in the same water year. Both the 1998 extreme flood and the 1999 extreme drought events happened in the 1999 water year. The dry season (Nov-May) comes after the wet season (April-Oct) in the hydrologic year of Bangladesh. Extreme floods sometimes deteriorate the soil conditions, and thus it loses the ability to hold enough soil moisture, which may result in drought. Similar observations were also found in New Orleans in 2011 (NOAA 2011).

## Major Effects of Erratic SW Availability

### *Salinity, Land Use, and Demographic Patterns*

Water availability greatly influences salinity, land use, and demography. Salinity is increasing due to the severe reduction of upstream freshwater flow. As the end of the dry season, the month of May shows the highest salinity concentration. Figure 2-12 compares the surface water salinity between 2001 and 2015 for May. It shows a drastic change in salinity during this 15-year period. The southwestern part of the study area, including a significant part of Sundarbans, suffered from salinity greater than 20 ppt in

2015. It is beyond the acceptable limit (20 ppt) for most mangrove species (Clough 1984). Further, 65% of stations show an increase in salinity ranging from 3.5% – 1950% during March over a ten-year period (2001 -2011). The spatial extent of salinity towards the inland is increasing which is becoming a key controlling factor for changing land use and demographic patterns.

According to Figure 2-13, some significant changes were noted after studying the three land use maps from 2001 to 2014. Agricultural land occupied 32% of the study area in 2014 which is almost half of what it was in the MODIS land use map from 2001 to 2010, which showed nearly 62%. The spatial extent of vegetation cover is also assessed by comparing annual maximum vegetation fraction (1 km MODIS NDVI) data from 2001 to 2012. It shows a statistically significant increasing trend for barren and sparsely vegetated land. However, the overall trend of dense vegetation fraction of more than 60% is decreasing. Lower availability of fresh water flow along with climatic variability are key factors in these changes. A similar observation was made by Lázár et al. (2015) who identified salinity and temperature stresses as limiting factors to crop productivity. Therefore, the agricultural land and forest cover are decreasing while the cultivation of Boro, a type of winter rice, is increasing. Currently, 16% of the land area is cultivated with Boro rice. Cultivation of this crop is increasing not only in the study area but also throughout Bangladesh. The area of freshwater decreased from 2.9% to 1.8% over 14 years' period. This may be attributed to the reduction of upstream freshwater flow and increasing trends of temperature and ET. We also found an increase of saline water fish farming which is currently occupying 1.42% of the study area. It is an indication of adjusting livelihoods due to increasing salinity resulting from upstream water diversions

which has detrimental impacts on soil quality and freshwater bodies (Barai et al. 2019; M. M. Rahman et al. 2013). Islam and Tabeta (2019) found an increase of soil salinity more than 6 times and in some cases 10 to 15 times from 1984 to 2014. In addition, Urban and rural settlements are showing contrasting rising and falling trends wherein the urban population has grown more rapidly at 484% over a 14-year period.

Another outcome of freshwater scarcity is the recent change in demographic patterns. Figure 2-14 shows a decrease in the decadal percentage change of population. Khulna, a major port city, shows a 7.5% decrease from 1991 to 2001, and a 2.52% decrease from 2001 to 2011. Another important district, Barisal, shows about a 25% decrease in population from 2001 to 2011, whereas it previously showed an increase of 14% and 29% in the periods of 1981-1991 and 1991-2001, respectively. These results suggest that the decadal demographic change is downward in key locations with high economic activity. It is an unusual phenomenon for an overpopulated country such as Bangladesh. The primary reasons are the lack of livelihood options, limited availability of water at times, a decline of agricultural land, and environmental degradation. However, we found decrease in migration in the period 2001-2011 than in 1991-2001 for Khulna district. The economic activities for male population at Khulna decreased in 2001 compared to 1991 but it increased in 2011 from 2001 (BBS 2015). Naturally, male dominated labor force (BBS 2009) dictates the migration rate in the study area.

***Instream water availability.***

Instream water is a key parameter to understand the environmental and ecological conditions of the study area. A preliminary assessment of available water for instream use

was done by deducting the off stream (irrigation, industrial and domestic) water withdrawal from total surface water availability. This study identifies not only the major water withdrawal amounts but also the changes in the last three decades.

The highest portion (≈94%) of available fresh water in the study area is used for irrigation. High seasonal variability in rainfall affects the seasonal water demand for irrigation. The withdrawal pattern of surface water for minor irrigation (e.g., low-lift pumps) showed a 498% increase mostly during the dry season in the past 30 years. This is primarily due to the increase in the cultivation of Boro rice to meet the demand of a growing population. Major irrigation projects in the study area mostly use surface water from rivers. The performances of these projects have been interrupted because of the decline of stream flows. The industrial sector is the second prominent user of surface water. There is 956% increase in industrial water withdrawal over the past 30 years (Table 2-8). Surface water use for domestic purposes is almost negligible compared to other uses.

Table 2-9 shows the details of water available for instream use in dry and wet seasons. On average, a variation of around 83% in instream water volume between wet and dry seasons is found for the period 1997-2015 (WY). This variation is mostly attributed to the diversion of upstream river flow, low rainfall during the dry season, and increasing trends for both temperature and ET. This inconsistent pattern of available instream water is a forewarning to take immediate steps to deal with water scarcity.

This paper delivered the key hydrologic scenario of the Ganges Delta of Bangladesh. Farakka barrage plays a dominant role in changing the hydrologic features. A significant increase of temperature is not only triggering droughts but also increasing

ET and consequently contributing to water scarcity. In addition, Farakka barrage and polders are responsible for higher sedimentation leading to waterlogged/flooding conditions. Salinity intrusion is a major disruptive consequence of lower upstream flow. It is decreasing the agriculture land, and compelling people to migrate from the study area. Understanding these restricting factors can be the initial steps for developing proper water management options.

## CONCLUSIONS

The Ganges Delta in Bangladesh has been suffering from extreme water-related disasters such as droughts, flooding, cyclones, water logging, water scarcity, river erosion, etc. This study addresses the changes in the hydrologic regime and its effects on surface water resources. Comparative analyses were conducted to assess the pre- and post-barrage water flow conditions and to link them with climate variability. It also explores some key consequences of freshwater availability on instream water, land use, and demographic patterns.

The results show a high seasonal variation of freshwater resources. Dry seasons are experiencing freshwater scarcity due to the diversion of upstream water flow, low rainfall, and rising trends in temperature and ETa. Increasing temperatures, along with water diversion, play a significant role in freshwater availability. Moreover, the Farakka barrage is the key controlling factor in reducing flows in the Ganges and Gorai Rivers, thus inducing drought-prone conditions. To make conditions worse, longer consecutive dry and wet days are intensifying drought and flood situations. Further, the increase of short duration high-intensity rainfall is producing water-logged conditions in many parts

of the study area. The changes in this streamflow regime is characterized by steep FDCs, indicating lower storage capacity and base flow, and higher occurrence of extreme low flows. A tentative estimation of instream water availability shows great variability (≈83%) between wet and dry seasons.

This study also addresses the effect of freshwater scarcity on salinity, land use changes, and demographic patterns. Lack of fresh water flow causes salinity to intrude the study area from the Bay of Bengal. This condition is severely aggravated during the dry season. The cultivation of saline water fish is increasing as an adaption to saline water and soil, which reduces soil fertility. The infertile soil, along with water-logged conditions, tends to decrease agricultural land area. The decreasing trend of dense vegetation cover indicates a spatial reduction of Sundarbans Mangrove Forest. Although it appears that there is plenty of water in the study area, the portion of fresh water is diminishing alarmingly. These unfavorable conditions force people to migrate to other regions. Recent data shows a decline in decadal population in key locations of this study area.

The results and information derived from this study are intended to improve the conceptual understanding of key factors affecting the hydrological regime and its future direction. In essence, the hydrological regime of the Ganges Delta in Bangladesh is facing adverse impacts from the upstream water diversion and climate variability, resulting in serious socio-economic and ecosystem changes affecting economic productivity and rural livelihood. The upstream water diversion amount needs to be reassessed. These results can be used for future studies related to mitigation of these negative impacts together with climate change concerns.

ACKNOWLEDGMENTS

This study is funded by the Utah Water Research Laboratory of Utah State University with travel support for field work provided by the International Water Management Institute, Sri Lanka.

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Table 2-1. Climate Indices.

| Indices | | Description | Unit |
|---|---|---|---|
| Temperature | SU30 | summer days>30°C | days |
| | TXx | monthly maximum value of daily maximum temperature | °C |
| | TNn | monthly minimum of daily minimum temperature | °C |
| | TXn | monthly minimum of daily maximum temperature | °C |
| | TNx | monthly maximum of daily minimum temperature | °C |
| | CSDI | cold spell duration indicator (annual count of days with at least 6 consecutive days when min temp<10th percentile) | days |
| | HDDheat | heating degree days* | °C |
| | CDDcold | cooling degree days* | °C |
| Rainfall | CDD | consecutive dry days | days |
| | CWD | consecutive wet days | days |
| | SDII | simple daily intensity index | mm/day |
| | PRCPTOT | annual total wet-day precipitation | mm |
| | R95pToT | annual percentage of rainfall>95th percentile / PRCPTOT | % |
| | R99pTOT | annual percentage of rainfall>99th percentile / PRCPTOT | % |

* A degree day is a measure of the energy required to heat or cool buildings (https://www.weather.gov/ffc/degdays, accessed on 07/13/2017). The threshold temperatures used for this study are 15°C and 30°C for HDDheat and CDDcold, respectively as mentioned by Adel (2002).

Table 2-2. Changes in slopes of FDCs.

| Station | Period | Q33% (m3/sec) | Q66% (m3/sec) | Slope of FDC | Change in slope from pre-barrage period (%) |
|---|---|---|---|---|---|
| SW90 | Pre-barrage period | 8870 | 2760 | 3.54 | |
| | Post-barrage with treaty 1 | 7760 | 1660 | 4.67 | 32 |
| | Post-barrage without treaty | 7310 | 1330 | 5.16 | 46 |
| | Post-barrage with treaty 2 | 7129.6 | 1566 | 4.59 | 30 |
| SW99 | Pre-barrage period | 1300 | 311 | 4.33 | |
| | Post-barrage with treaty 1 | 1090 | 138 | 6.26 | 77 |
| | Post-barrage without treaty | 1660 | 66 | 9.77 | 176 |
| | Post-barrage with treaty 2 | 1165.29 | 144.17 | 6.33 | 79 |

Table 2-3. Changes in minimum D-day average flow (D = 7-day, 30-day, and 90-day).

| Station | Low flow indices | Mann-Kendall trend test: 2-sided p-value | Sen's Slope | Pettit's test results (K, p-value) | Pettit's probable change point | Year of change |
|---|---|---|---|---|---|---|
| SW90 (Ganges River) | Minimum 7-day average flow | 2.36E-08 | -16.94 | 1586, 3.602e-12 | 42 | 1975 |
| | Minimum 30-day average flow | 1.19E-07 | -16.14 | 1580, 4.418e-12 | 42 | 1975 |
| | Minimum 90-day average flow | 7.20E-08 | -15.816 | 1606, 1.813e-12 | 42 | 1975 |
| SW99 (Gorai River) | Minimum 7-day average flow | 0.60882 | -0.2642 | 308, 0.02974 | 17 | 1980 |
| | Minimum 30-day average flow | 0.76377 | -0.2468 | 294, 0.04323 | 17 | 1980 |
| | Minimum 90-day average flow | 0.33371 | -0.6422 | 316, 0.02383 | 16 | 1979 |

Table 2-4. Changes in land types concerning flooding depth.

| Land type | Area in sq. km (MPO, 1986) | Area in sq. km (BBS, 2013) | Change (%) | Remarks |
|---|---|---|---|---|
| High land (F0) | 6157 | 4955 | -24 | Above normal flooding (F0 = 0 to 30 cm intermittently flooded land) |
| Medium land (F1+F2) | 17385 | 19201 | 9 | Normally flooded land (occasional basis) (F1 = 30 to 90 cm seasonally flooded land F2 = 90 to 180 cm seasonally flooded land) |
| Low land (F3+F4) | 1548 | 5137 | 70 | Normally flooded land (flooded every year) (F3 and F4 = More than 180 cm seasonally flooded land) |
| Total | 25090 | 29293 | 14 | Change in land area |

Flood depth criteria: (FAP 4c 1993)

Table 2-5. Trend of water level crossing the danger level.

| River | Station ID | Trend | 2-sided p-value | Slope | Slope Unit |
|---|---|---|---|---|---|
| Ganges | SW90 (DL= 14.25) | Annual Max Water Level | 6.7E-05 | -2.9E-01 | m, PWD/ Year |
| | | Trend of years per decade when Max WL > DL | 3.2E-02 | -5.0E-01 | m, PWD/ Decade |
| Jamuna (Upper part) | SW46.9 (DL=19.5) | Annual Max Water Level | 1.1E-01 | 1.7E-01 | m, PWD/ Year |
| | | Trend of years per decade when Max WL > DL | 1.0E+00 | 0.0E+00 | m, PWD/ Decade |
| Jamuna + Ganges | SW91.9R (DL=8.65) | Annual Max Water Level | 3.6E-01 | 3.4E-03 | m, PWD/ Year |
| | | Trend of years per decade when Max WL > DL | 7.9E-01 | 1.3E-01 | m, PWD/ Decade |

Table 2-6. Trend of days above danger level (flood depth).

| Trend: Days above Danger Level | | | | |
|---|---|---|---|---|
| Water Level Stations | | Data Period | 2 sided p-value | Slope |
| Non-Tidal | SW90 | 1910-2014 | 1.5E-05 | -7.7E-02 |
| | SW99 | 1968-2014 | 1.5E-01 | 0.0E+00 |
| | SW91.9R | 1964-2014 | 6.8E-01 | 0.0E+00 |
| Tidal | SW244 | 1960-2009 | 4.5E-01 | 9.4E-02 |
| | SW107.2 | 1976-2009 | 6.2E-01 | 0.0E+00 |
| | SW39 | 1976-2009 | 2.2E-16 | 6.7E+00 |

Table 2-7. Trend of hydro-climatological anomalies (1949-2015).

| Hydro-climatological Factors | Season | 2-sided p-value | Slope |
|---|---|---|---|
| Rainfall | Wet Season | 0.12 | 0.13 |
| Evapotranspiration | | 0.0002 | 0.16 |
| Temperature | | 0.12 | 0.01 |
| Discharge | | 0.03 | -0.29 |
| Rainfall | Dry Season | 0.21 | 0.27 |
| Evapotranspiration | | 0.0002 | 0.21 |
| Temperature | | 0.0000001 | 0.06 |
| Discharge | | 0.00005 | -0.73 |

Anomalies: deviation from the mean of the pre-barrage period (1949-1974).

Table 2-8. Water abstraction data from surface water sources for 2011.

| Month | Volume (million $m^3$) | | | |
|---|---|---|---|---|
| | Minor irrigation | Major irrigation | Domestic | Industry |
| Jul | 0 | 212 | 0.12 | 42 |
| Aug | 0 | 169 | 0.12 | 42 |
| Sep | 0 | 199 | 0.12 | 42 |
| Oct | 0 | 180 | 0.12 | 42 |
| Nov | 36 | 139 | 0.12 | 42 |
| Dec | 323 | 0 | 0.12 | 42 |
| Jan | 1178 | 9 | 0.12 | 42 |
| Feb | 1183 | 40 | 0.12 | 42 |
| Mar | 1727 | 160 | 0.12 | 42 |
| Apr | 1399 | 174 | 0.12 | 42 |
| May | 681 | 189 | 0.12 | 42 |
| Jun | 36 | 244 | 0.12 | 42 |
| Percent change in water use (from 1983 to 2011) | 498 | 0 | 40 | 956 |

Table 2-9. Available water for instream use in 2011.

| Criteria | Volume ($km^3$) | Instream Use ($km^3$) |
|---|---|---|
| Mean (Rainfall-ET) in the dry season | -10 | |
| Flow entering in the dry season | 190 | 128 |
| Mean dry season surface water abstraction | -52 | |
| Mean (Rainfall-ET) in the wet season | 45 | |
| Flow entering in the wet season | 717 | 760.5 |
| Mean wet season surface water abstraction* | -1.5 | |

* Surface water abstraction is low in the wet season due to heavy rainfall

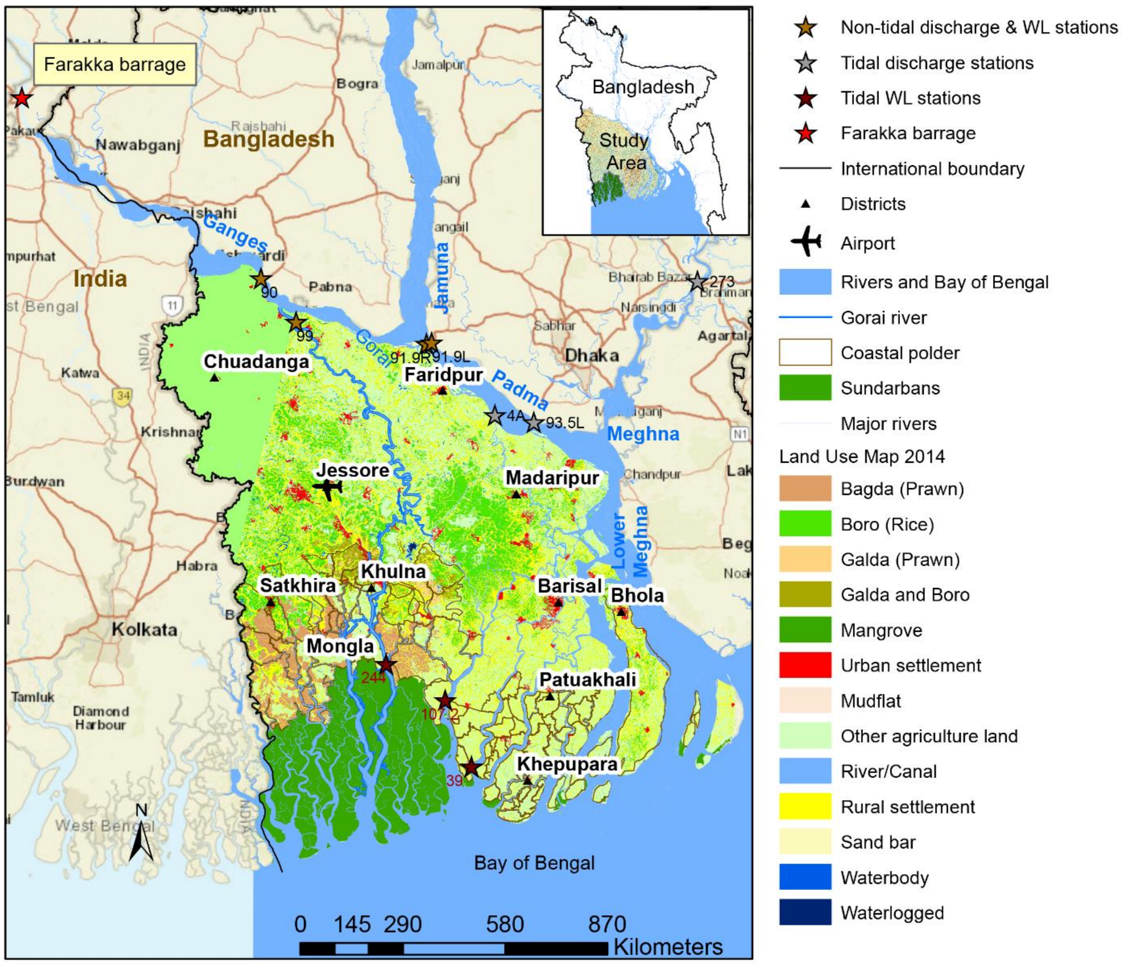



Figure 2-1. Physical description of the Ganges Delta of Bangladesh and surrounding areas.

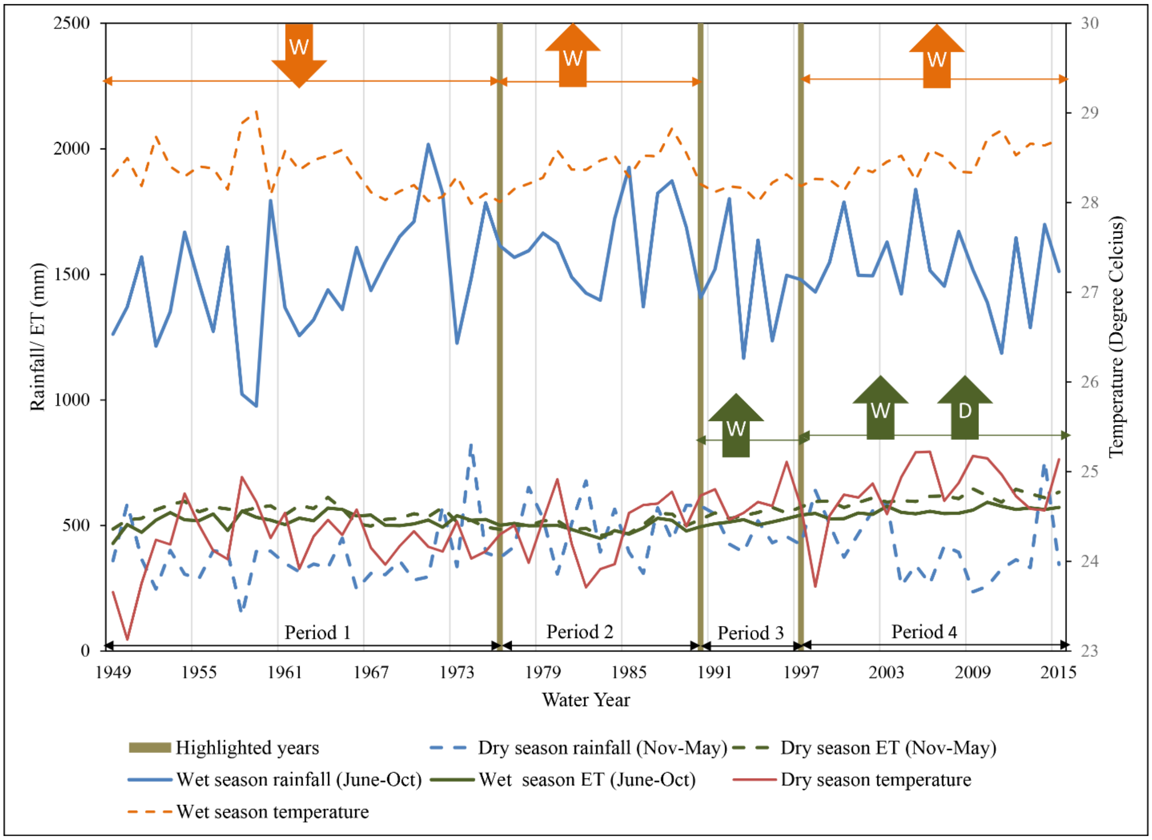



Figure 2-2. Seasonal variation of rainfall, temperature, and ET.

Period 1: Pre-barrage period (before 1976)

Period 2: Post-barrage period with treaties and agreements (1976-1989)

Period 3: Post-barrage without treaty (1990-1996)

Period 4: Post-barrage period after 1996 treaty (1997-2015)

W = significant trend in the wet season, D = significant trend in the dry season

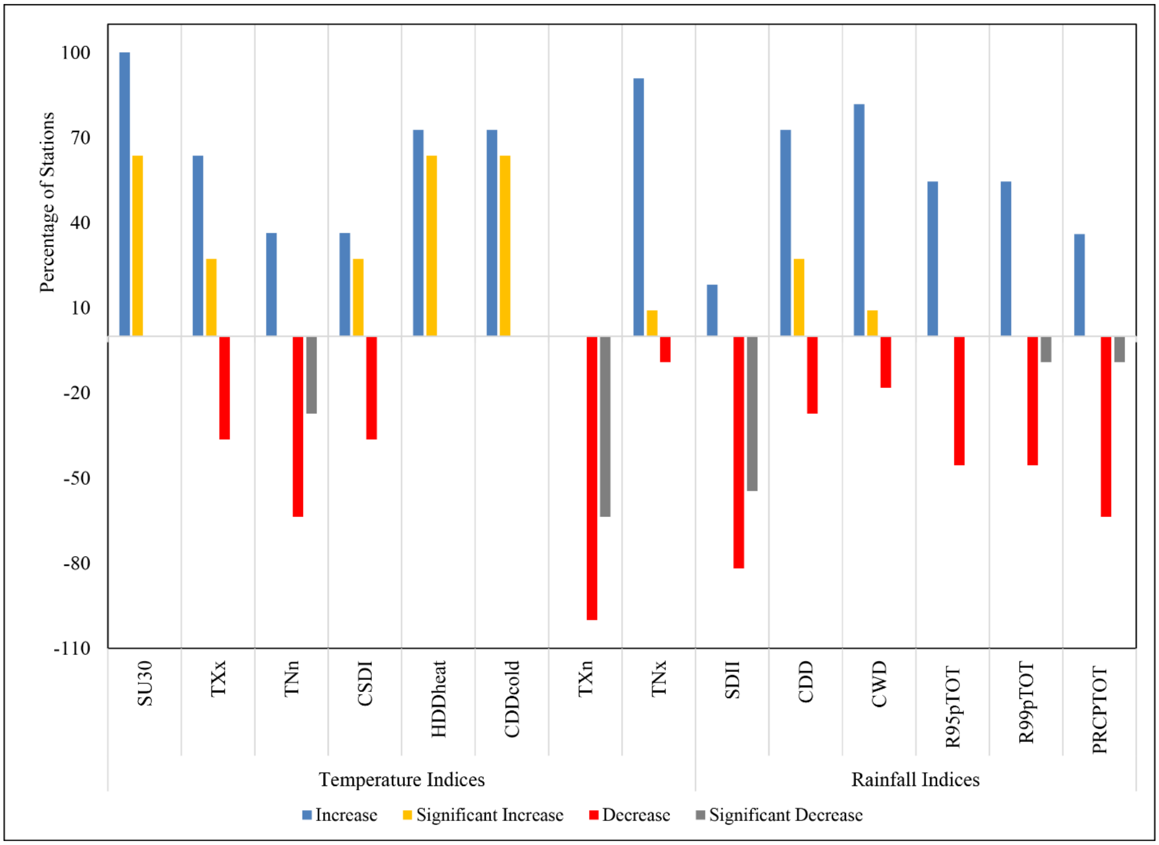



Figure 2-3. Rainfall and temperature indices used in the study area across all monitoring stations

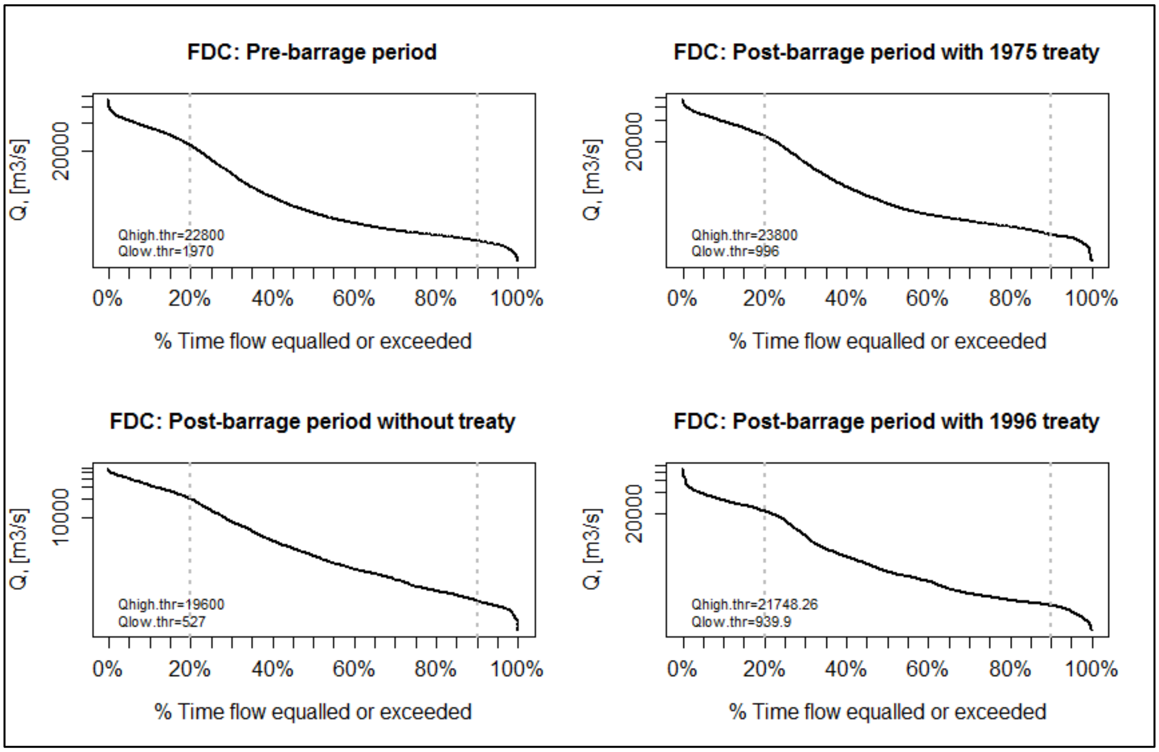



Figure 2-4. Flow duration curves at SW90 for the Ganges River during pre- and post-barrage periods

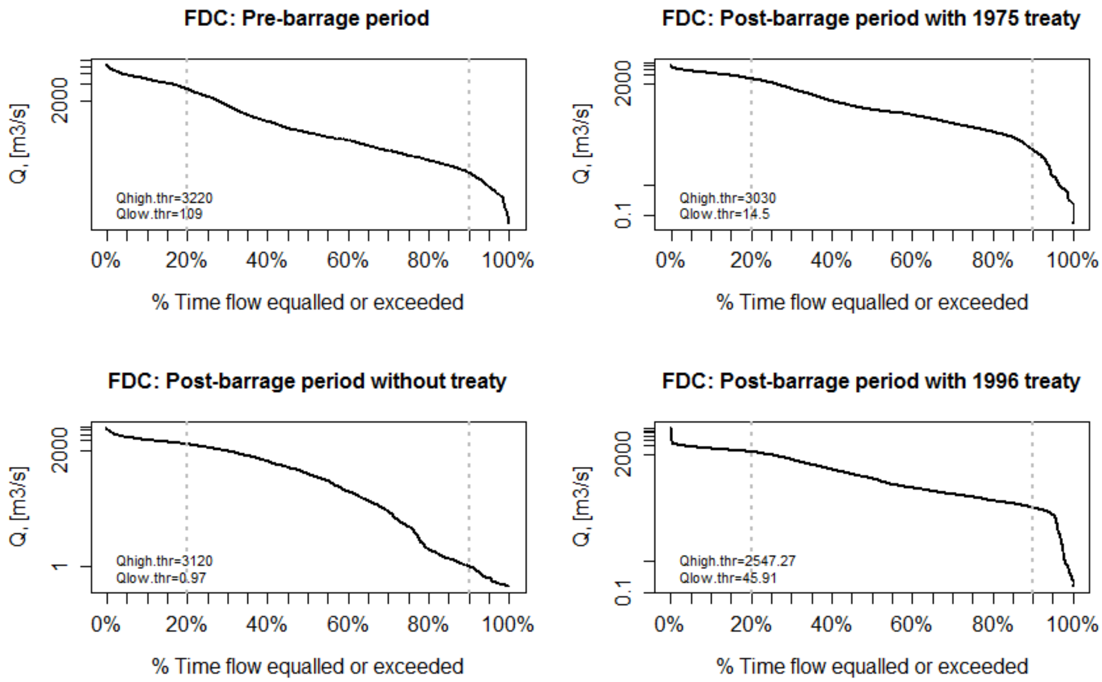
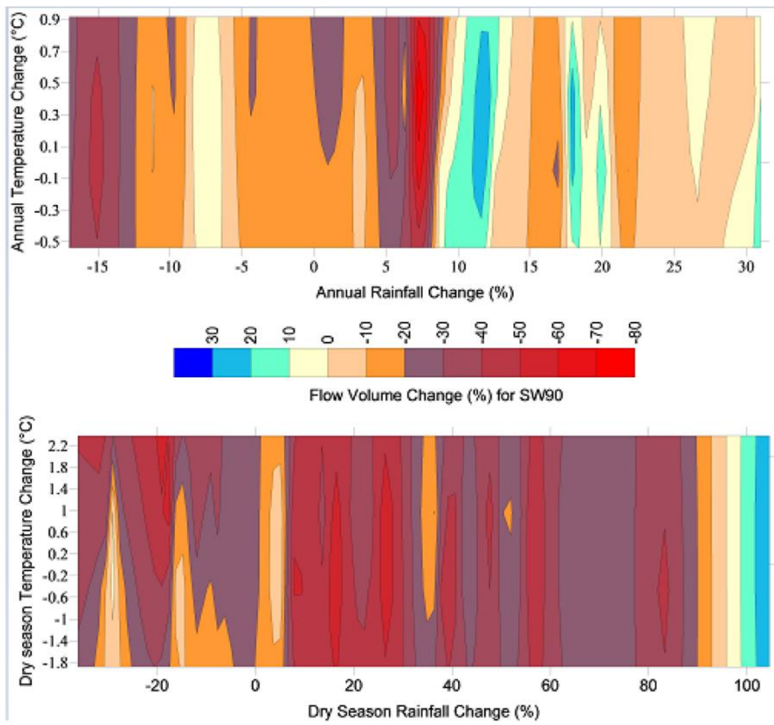



Figure 2-5. Flow duration curves at SW99 for the Gorai River during pre- and post-barrage periods.

a)




b)

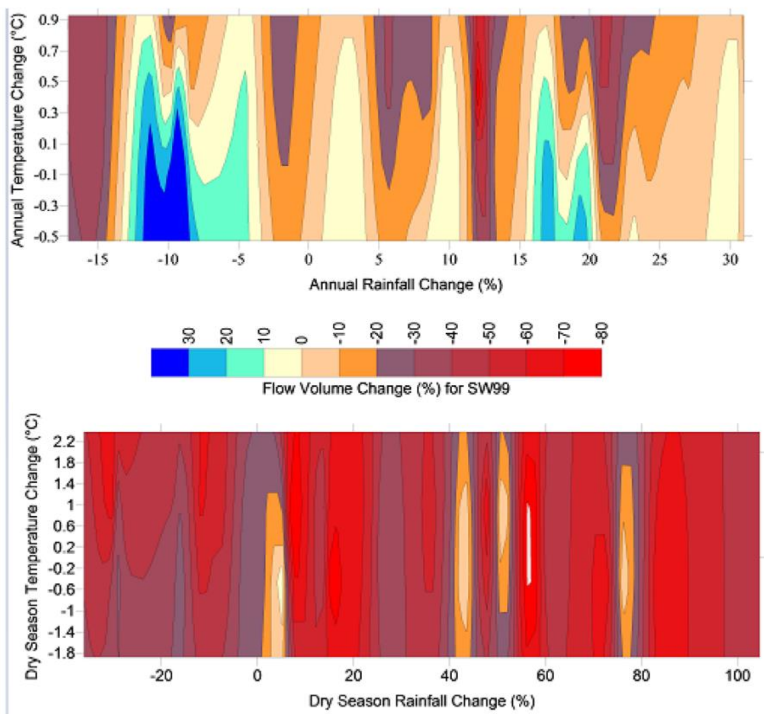



Figure 2-6. Contour plot of percentage river flow change as a function of rainfall change and temperature change at a) SW90 and b) SW99.

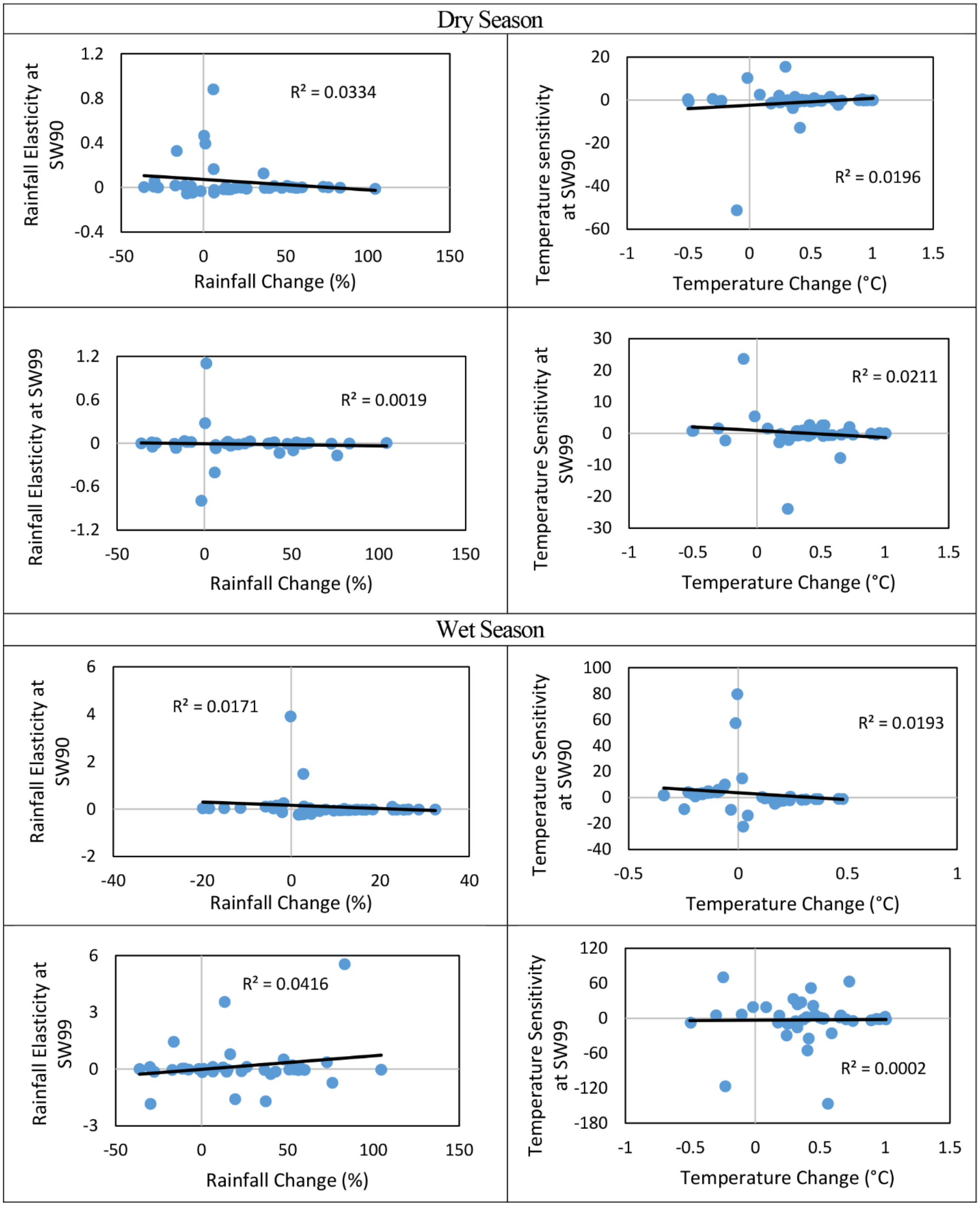



Figure 2-7. Rainfall elasticity and temperature sensitivity.

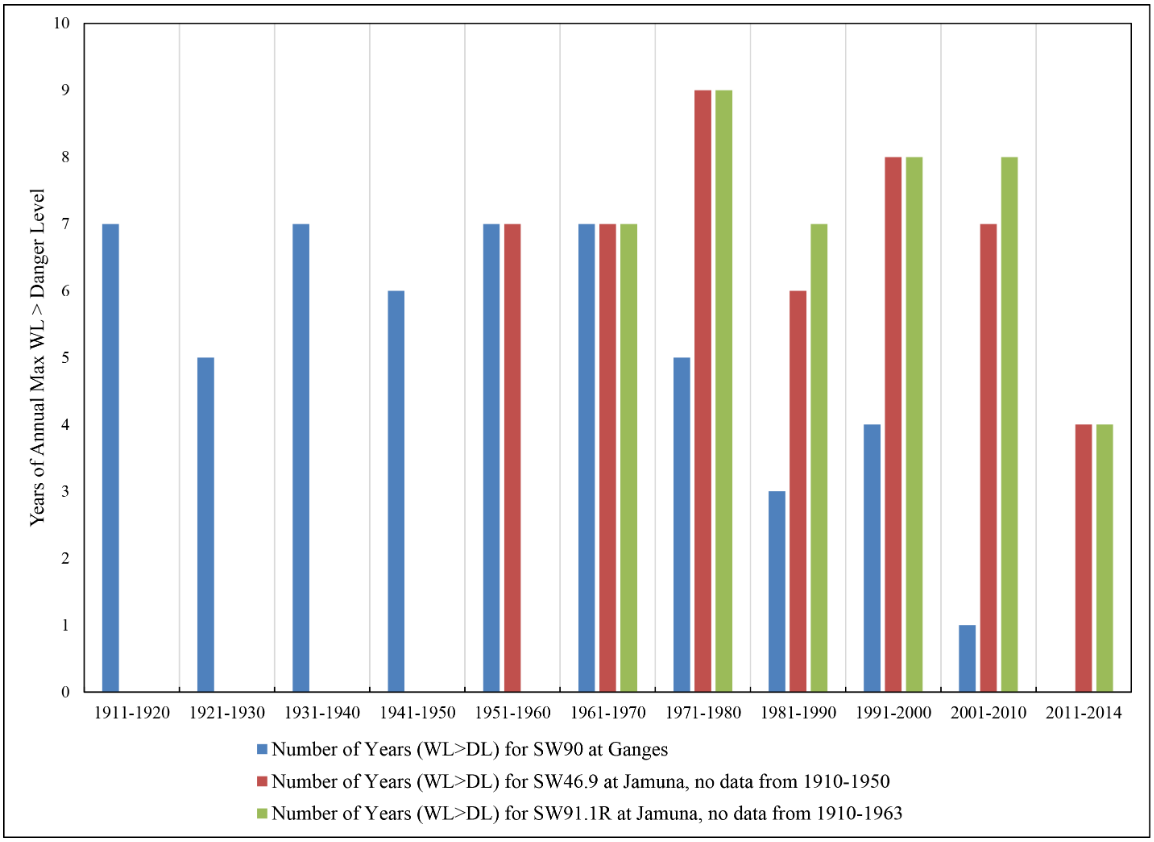



Figure 2-8. Number of years the annual maximum water level crossed the danger level.

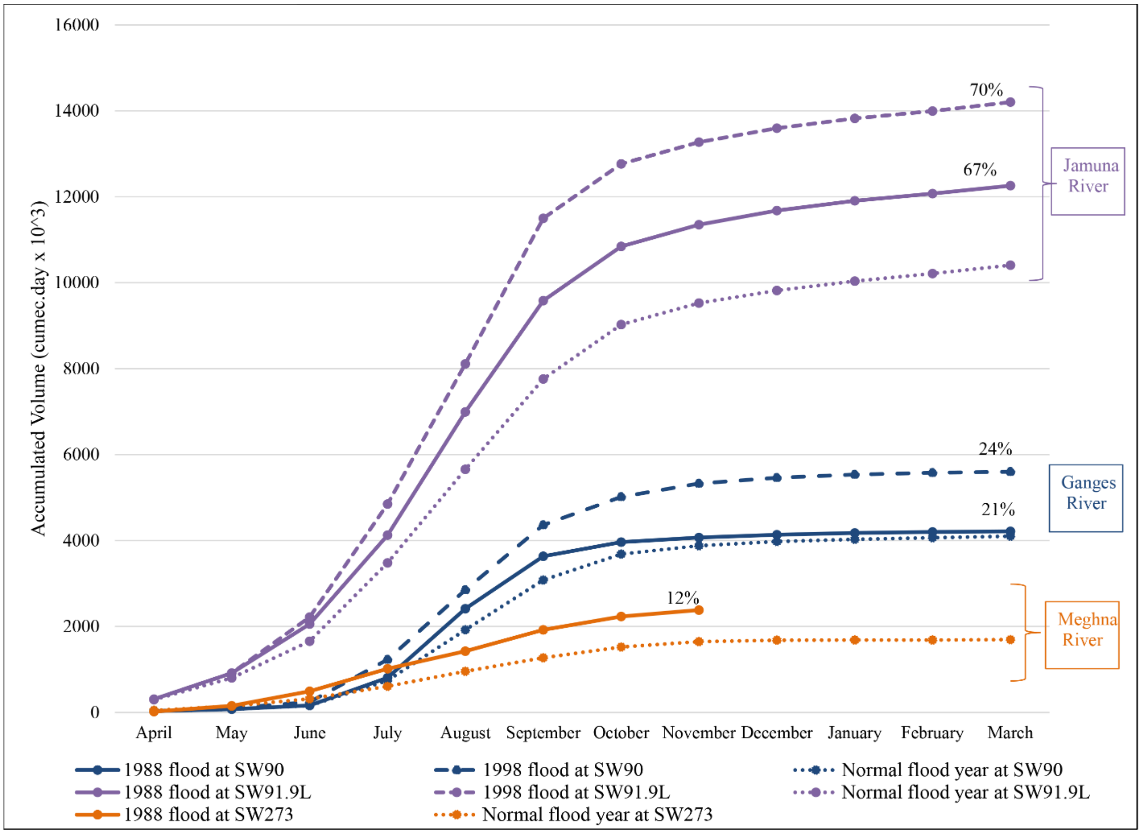



Figure 2-9. Comparison of flow mass curves for 1988 and 1998 extreme floods and normal flooding years (contributions of floods are shown above each curve in %).

Normal flooding year = average flow 1980-1986 (except for the 1984 flood year)

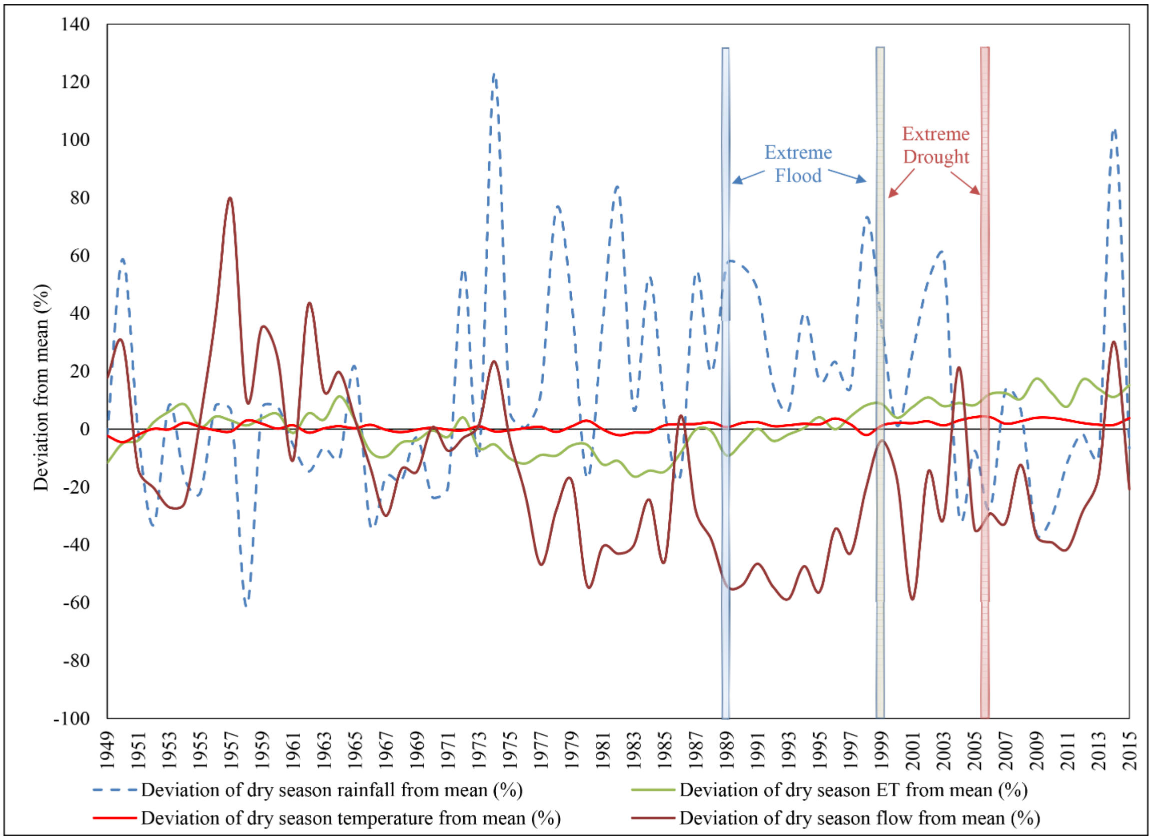



Figure 2-10. Deviation of hydro-climatological parameters in the dry season from the mean of the pre-barrage period (1949-1975).

Note: Dry season rainfall is presented as a dotted line because of its negligible influence on flood and drought conditions.

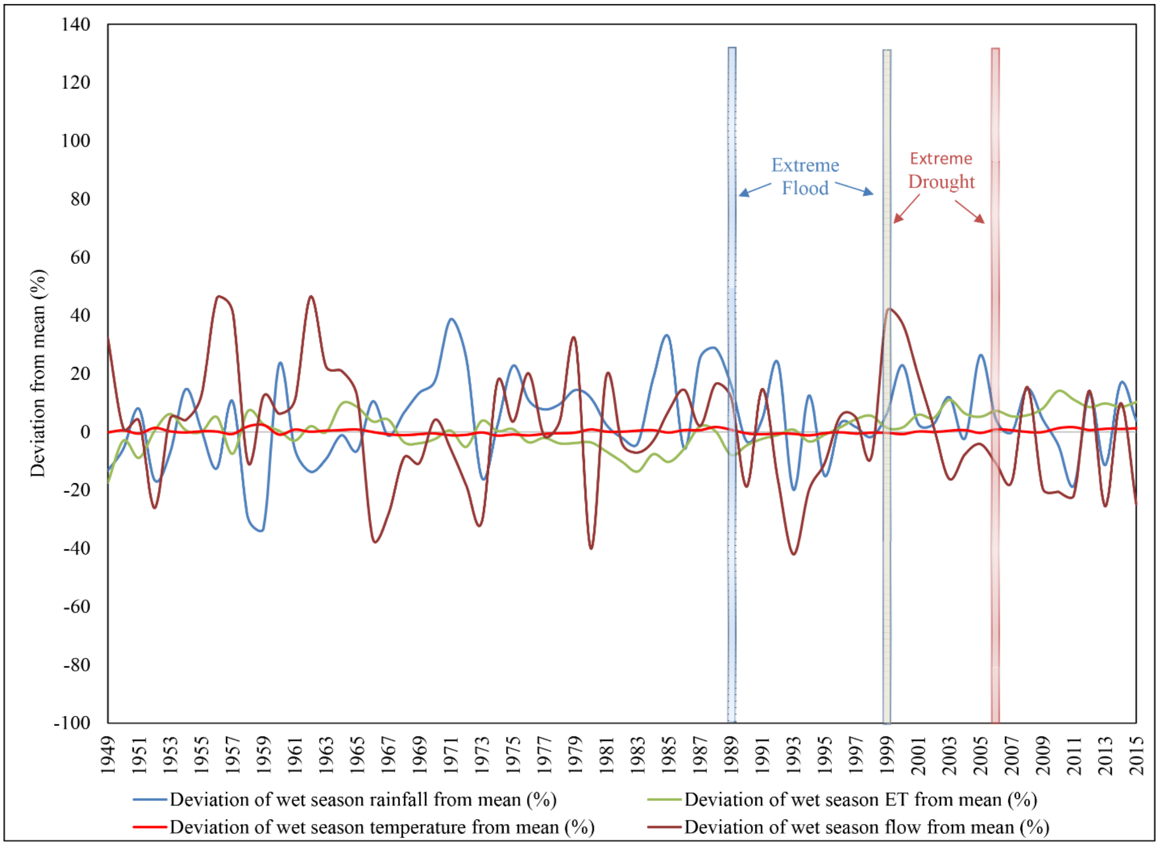



Figure 2-11. Deviation of hydro-climatological parameters in the wet season from the mean of the pre-barrage period (1949-1975).

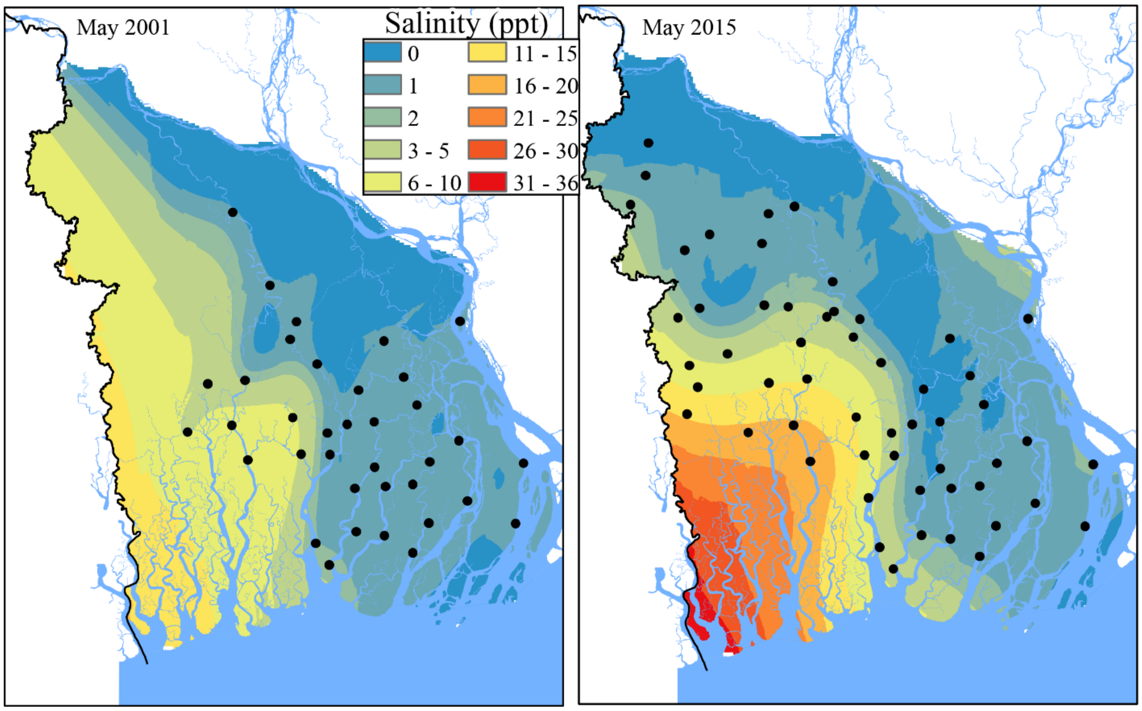



Figure 2-12. Surface water salinity (black dots indicate salinity measuring stations).

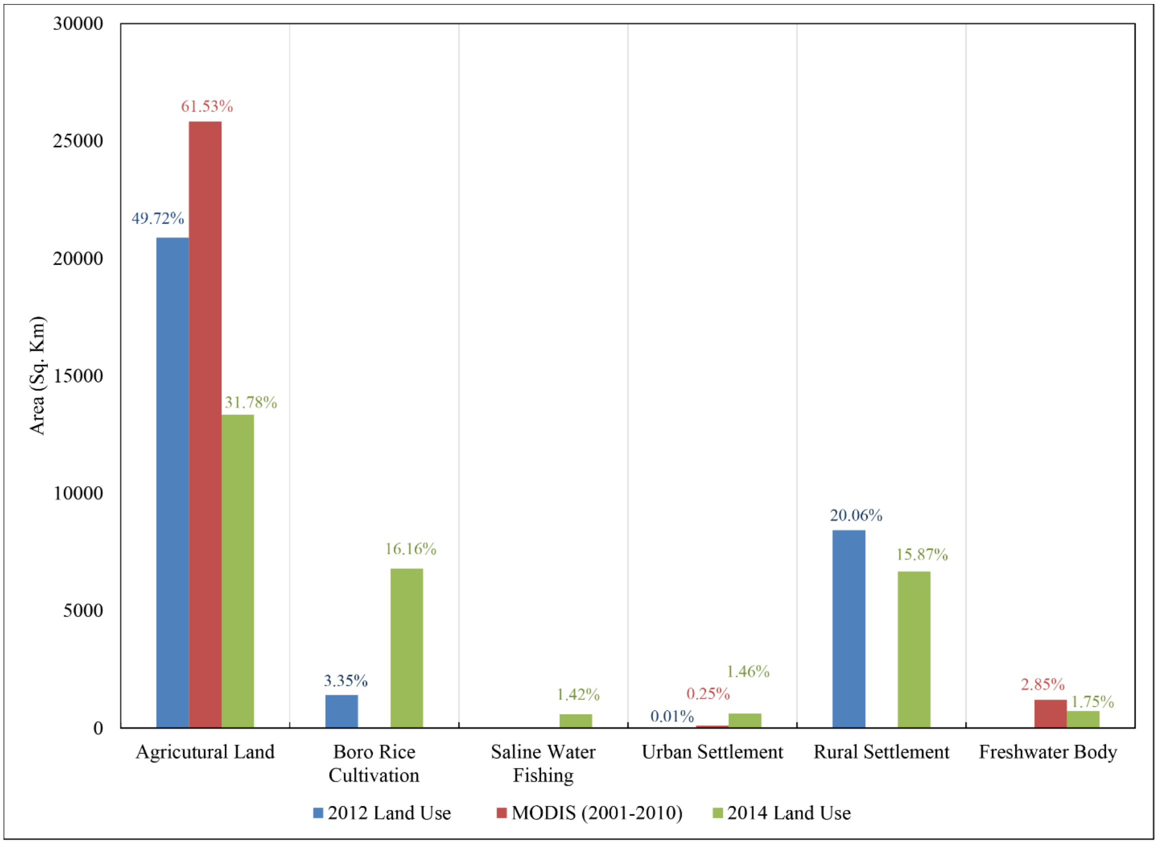



Figure 2-13. Change in land use patterns between 2001 and 2014.

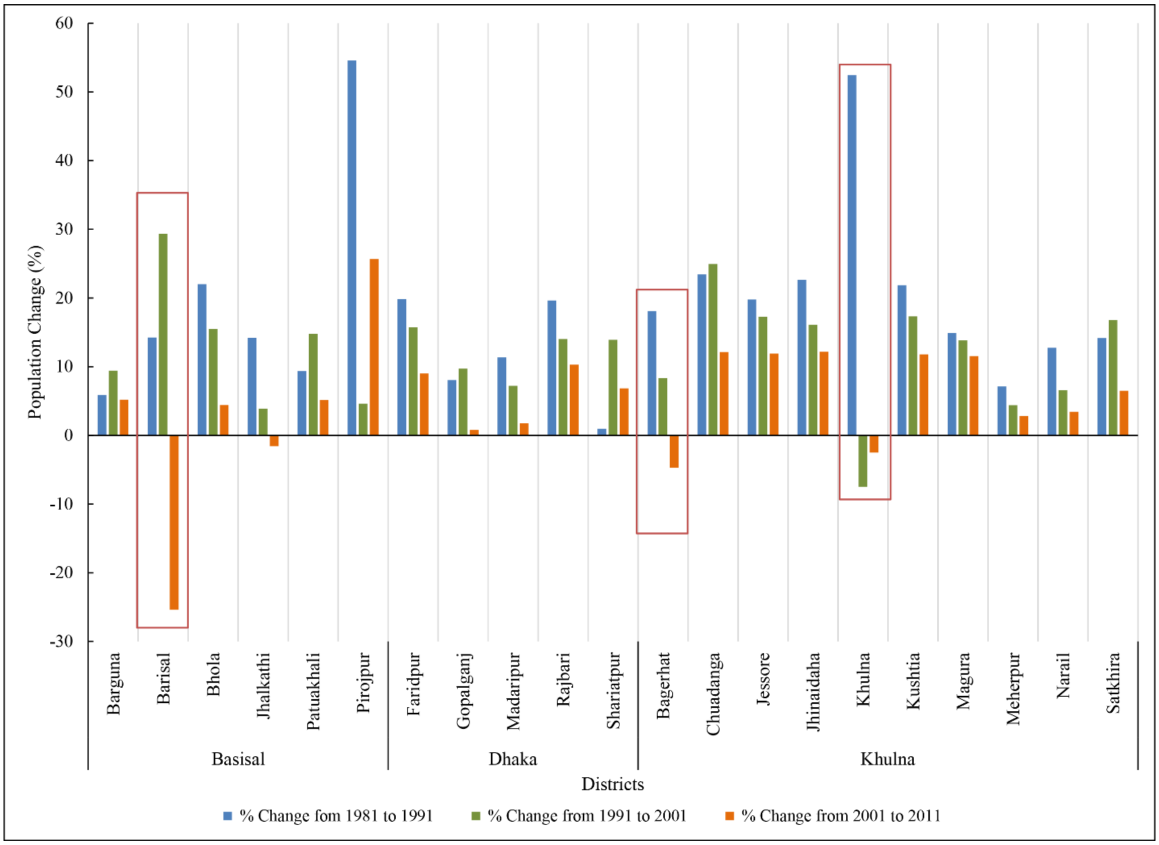



Figure 2-14. Decadal percentage change in demographic patterns.

# CHAPTER 3

# SCARCITY OF FRESH WATER RESOURCES IN THE GANGES DELTA OF BANGLADESH[2]


## ABSTRACT

Understanding the interdependency, availability, and accessibility of surface water and groundwater plays a major role in identifying and managing water security. The Ganges Delta in Bangladesh is a classic example of a water insecurity scenario in a transboundary river basin where concerns in quantity, quality, and timing of available water are producing disastrous conditions. This study examines surface water and groundwater uses and demands, seasonal availability, sustainability, and potential water security concerns. Human interventions that can influence seasonal water availability and shifting demands between surface water and groundwater are also examined. Surface water availability was analyzed using streamflow including the effects of upstream water diversions, rainfall, temperature, and evapotranspiration. Groundwater data were collected from 283 locations established by the Bangladesh Water Development Board. Total water storage anomaly data from the GRACE satellite (2002 -2016) was analyzed to assess changes in groundwater availability. Both in situ and GRACE data show a significant declining trend in groundwater. Comparisons of groundwater recharge and withdrawal amounts in six different years (1983, 2009-2012, 2015) indicate an unsustainable water withdrawal condition. Irrigation is the largest sector of off-stream


[2] Murshed, S.B., Kaluarachchi, J.J., 2018. Scarcity of fresh water resources in the Ganges Delta of Bangladesh. Water Security. 4–5, 8–18. https://doi.org/10.1016/j.wasec.2018.11.002

water use with total water withdrawal amounting to 31% for surface water and 68% for groundwater. The region's domestic water use entirely depends on groundwater, which is problematic due to arsenic pollution. This study provides insight into the changes in surface water and groundwater resources and limitations to freshwater availability, thereby encouraging a better management strategy for water resources in the region.

## INTRODUCTION

Access to freshwater is considered one of the basic human needs [1]. However, this vital finite resource for human survival is becoming increasingly scarce [2]. Four billion people around the world suffer from water scarcity [3]. The increase of irrigation to meet growing needs is a major source of freshwater consumption [1], [4]. Further, population growth, expansion of the industrial sector, water use in energy development, inter-annual climate variability, and climate change, are some of the key reasons behind freshwater scarcity [5], [6]. Sometimes uneven geopolitical relationships, poverty, and related discriminations play a dominant role in water scarcity rather than the physical availability of water [7]. Water security is produced with access and control over water [8]. The downstream river basins are the most affected victims of water scarcity [9].

Freshwater scarcity is a burning issue in the lower Ganges Basin, namely the Ganges Delta of Bangladesh (Figure 3-1). It is an agriculturally dominated area with the presence of the Sundarbans Mangrove Forest. The latter was declared a Ramsar site in 1992 and a World Heritage Site by UNESCO in 1997 in recognition of its wealth of biodiversity. It is also a densely populated area of 42,000 $km^2$ with a population of 30.5

million [10]. The freshwater flow of this area is largely dominated by the Farakka barrage, an upstream water diversion structure located in India, about 17 km from the Bangladesh border. Although India and Bangladesh have water-sharing treaties, there is no basin-wide treaty for the Ganges River which has led to a state of contentious water management [11]. This barrage drastically reduces freshwater flow in the Ganges River, especially during the dry season [12]. The reduction of upstream flows intrudes salinity which changes the ecosystem and impacts soil fertility [13], [14]. The flat land of the study area also allows tides to travel up to 200 km upstream [13]. Spring tides, which are 2.5-3 times higher than neap tides [15], intrude a greater volume of saline water into the area. Salinity can be worsened due to rising sea levels [1], [13]. High sedimentation and river erosion are also associated with the reduction of upstream flow [13], [16], [17]. Freshwater availability varies throughout the year and is insufficient to meet demands, especially during the dry season. Despite the critical importance of freshwater in delta areas, geopolitics often play a significant role in water allocation.

Surface water (SW) and groundwater (GW) are the two intertwined vital sources of fresh water. Depletion of one source results in more withdrawal from the other and ultimately leads to the exhaustion of both. After the Farakka barrage began operating in 1975, fresh water was drastically depleted, resulting in the extensive use of GW [12]. GW withdrawal increased further after 1980 as a preferred water supply source [18], [19].

Water quality has become an essential factor in considering water stress [9]. A significant part of the study area is also contaminated with arsenic [20], [21]. This arsenic contamination is occurring naturally largely due to the existence of organic-rich surface

sediments [22], [23]. As such, both quality and quantity of water need to be considered when addressing the freshwater scarcity in this region. As always, supply and demand are critical components for proper water management [24].

Water scarcity can be measured by the concept of water shortage (low availability per capita) and water stress (high consumption relative to availability) [25]. This study addresses the freshwater scarcity by focusing on the inter-annual variability of SW and GW sources, their uses and demands, along with issues regarding quality. Understanding the contextual scenario of water availability will lead to the formulation of management plans that can minimize water security in this freshwater deficit region.

## DATA AND METHODOLOGY

### Hydro-meteorological Data

SW availability was analyzed with in situ measurements of 58 rainfall stations, 11 temperature stations, and flow data for the Ganges River. We considered observed flow from “SW 90” (Figure 3-1a) as it provides the incoming flow of the Ganges River to Bangladesh. These data were collected from the Bangladesh Water Development Board (BWDB) and the Bangladesh Meteorological Department (BMD) and did not fall into identical time periods. The longest climatic record was found from 1949 to 2015. The stations having data for at least 30 years with less than 10% missing values, were considered for analyses. Mean values were used to represent the study area because of its minimal elevation difference. Actual Evapotranspiration ($ET_a$) was computed using the

complementary relationship model developed by Anayah and Kaluarachchi [26]. This model gives calibration-free regional values of $ET_a$ using meteorological data only. The seasonal variation of these key SW components was studied to examine the inter-annual variation. The wet season in this region is from June to October and the dry season is from November to May. Moreover, the entire study period was divided into pre- (1949-1974) and post-barrage (1975-2015) time periods to assess the influence of the Farakka barrage on SW availability.

GW also plays a significant role in meeting the water demand of the study area. Water table (WT) data were collected from 283 BWDB piezometer wells (Figure 3-1a). The data period is from 1968 to 2014 although not all the stations have the same data duration. Data were selected based on a minimum 30-year duration and disregarded wells with five or more years of consecutive missing values. The dominant use for GW withdrawal is irrigation. As such, GW data was divided into pre- (1968-1980) and post-(1981-2014) GW irrigation periods to assess the influence of irrigation on GW depth.

This study also focuses on remote sensing (RS) observations along with in situ data to address possible changes in water availability. Gravity Recovery and Climate Experiment (GRACE) satellite data from 2002-2016 (downloaded from ftp://neoftp.sci.gsfc.nasa.gov/geotiff.float/GRACE_LWE_M/, accessed on April 2017) was used to study the total water storage anomalies ($\Delta$TWS) which include the integrated contributions of GW, SW, soil water, snow, ice, and biomass [27]. Considering Bangladesh's hydro-climatic conditions, changes in GW storage ($\Delta$GW) were determined by deducting soil moisture anomaly ($\Delta$SM) data from $\Delta$TWS [27], [28].

$$\Delta GW = \Delta TWS - \Delta SM \quad (1)$$

Soil moisture data were downloaded from the NOAH land surface model of the Global Land Data Assimilation Systems (GLDAS) missions (https://disc.sci.gsfc.nasa.gov/datasets?keywords=GLDAS, accessed in March 2018). NOAH was chosen from among the four land surface models (NOAH, CLM, MOSAIC, and VIC) because of its applicability in the Indian Subcontinent [28]. GRACE provides monthly, 1° x 1° resolution data with cm equivalent depth. ΔSM from NOAH was collected with the same temporal and spatial resolution as the GRACE data. This resolution constrains the application of GRACE data for small-scale water management and requires a study area size of around 200,000 $km^2$[29]. Artificial neural network [30], filtering, and rescaling approaches [29] are some of the methods used to apply GRACE data in areas below the recommended size. Since our purpose in using the GRACE technique was not to estimate the exact amount of water storage but rather to gain insight on the change of water storage over time, we applied the Arc GIS spatial analyst tool to extract ΔTWS and ΔSM data for 283 well locations. This bilinear interpolation technique does not capture the regional processes but was able to depict the temporal changes of GW storage. Thus extracted RS values and in situ GW data can be compared in specific locations.

## Climate Variability and Anthropogenic Effects on SW Availability

Seasonal double mass curves (DMC) of cumulative values of river flow against cumulative values of effective rainfall (Figure 3-2) were used to identify the key

contributing factors on changes in SW [31]–[34]. Effective rainfall is the rainfall which actually contributes to the river flow. Following the procedures from Searcy and Hardison [34], we found the effective rainfall for this study region is equivalent to the observed rainfall in a water year (WY), which is from March to April. River flow is considered as an important indicator of climate variability as it is the residual of precipitation after fulfilling evapotranspiration (ET) demands [34]. In addition, the Pettit test was applied to DMC slopes to detect the transition year of flow data.

**SW and GW Withdrawal**

The amount of water withdrawal for GW irrigation and SW minor irrigation was computed using pump and tube-well data including the number of units, discharge, pump efficiency, and average hours of operation [35]. Irrigation equipment data for six years (2009-2012, 2015, 2016) were collected from the Bangladesh Agriculture Development Corporation (BADC). The water withdrawal data is the representation of the average values from these six years. The current water withdrawal amount for major irrigation projects, namely the Ganges-Kobadak and Barisal irrigation projects, are not available. Instead, the known data from 1982-1983 [35] was used for this study.

GW withdrawal was also measured using ΔTWS and ΔSM data [28] as given below:

$$\text{Net GW withdrawal at xth year} = \Delta GW_{wet} \text{ at (x-1)th year} - \Delta GW_{dry} \text{ at xth year} \tag{2}$$

Here a year is considered a water year (WY) and $\Delta GW_{wet}$ and $\Delta GW_{dry}$ are the changes in GW storage during the wet (June-Oct) and dry (Nov-May) seasons, respectively. Therefore:

Net GW withdrawal at xth year =

$$\Delta GW \text{ for October at } (x\text{-}1)^{th} \text{ year} - \Delta GW \text{ for May at } x^{th} \text{ year} \quad (3)$$

We used population census data from 1981, 1991, 2001, and 2011 to compute the domestic water withdrawal amount for the years 2009-2012 and 2015. Annual average growth of industries in Bangladesh from 1980 to 1998 was 5% [36]. This 5% growth value was used to calculate the SW and GW withdrawal for industries due to data unavailability.

**Water Demand**

Water demand is a key factor for measuring water scarcity. The FAO (Food and Agriculture Organization of the United Nations) method [37] was used to estimate the irrigation water demand in the study area as follows:

$$\text{Irrigation demand} = ET_c - \text{Effective rainfall} \quad (4)$$

$$ET_c = ET_o * K_c \quad (5)$$

$$\text{Effective rainfall} = \text{Total rainfall} * 70\% \quad (6)$$

Here $ET_c$ is crop ET, $ET_o$ is potential ET, and $K_c$ is the crop coefficient. We considered 70% of total rainfall as effective rainfall for this region (http://www.fao.org/docrep/X5560E/x5560e03.htm, accessed on September 2017).

All varieties of rice and wheat are considered as representative crops and these occupied nearly 76% of the crop area in 2011-2012 [10]. Table 3-1 provides the irrigation schedules of these major crops. Planting dates of crops depend on the land type and potential flooding depth [38]. Here we used an average planting date for each crop disregarding the land classification. $K_c$ was adjusted based on local factors. The variability of $K_c$, along with the irrigation periods for major crops, were taken from a report from the Bangladesh government [38].

Domestic water demand was calculated using an average of 100 lpcd (liter per capita per day) for 1983 and 120 lpcd for 2009-2012 and 2015. Industrial water demand was considered the same as water use in this sector, namely 25% [39] of total water withdrawal for industrial purposes.

**GW Recharge**

Recharge (R) computes water returns to the subsurface and is an important variable when considering sustainable GW management [40]. This study used three different methods to estimate recharge and its variability. A Modified Chaturvedi Formula was applied based on water level fluctuation and rainfall amounts in the Ganga-Yamuna Doab [41]:

$$R = 1.35\,(P-14)^{0.5} \tag{7}$$

where R is net recharge due to precipitation during the year, in inches, and P is annual precipitation, in inches.

This empirical method is applicable to humid and tropical regions where annual rainfall exceeds 40 cm. This study area falls within these characteristics.

Secondly, GW recharge was approximated using the Water Table Fluctuation (WTF) method as follows:

$$R = \Delta S_{G}w = S_y * (dh/dt) = S_y * (\Delta h/\Delta t) \tag{8}$$

where $\Delta S_{GW}$ is change in GW storage, $S_y$ is specific yield, $\Delta h$ is change in head, and $\Delta t$ is the time interval.

GW data for 1968-2014 WY were used to estimate R. $S_y$ information was collected from a map contained in secondary literature [18].

Finally, we used RS observations to assess the changes in GW recharge as follows:

$$R = \Delta GW_{wet} - \Delta GW_{dry} \tag{9}$$

where $\Delta GW_{wet}$ is the change in GW storage at the end of the wet season, in this case October, and $\Delta GW_{dry}$ is the change in GW storage at the end of the dry season, namely May. Equation (9) was used for the same water year (April – March) and equation (1) was used to estimate $\Delta GW$.

Future water availability largely depends on the amount of GW used and the volume available [42]. Recharge provides insight on future GW availability. We determined the sustainability by the ratio of GW withdrawal and recharge.

**Water Quality**

Data for SW (2001-2015) and GW salinity (2012) was collected from BWDB and the Institute of Water and Flood Management, Bangladesh University of Engineering and Technology. The daily data of SW salinity were not continuous. GW arsenic data (1998-99) were from the national database of the Department of Public Health Engineering (DPHE). This database was chosen because of its extensive coverage in the study area. An analysis of this data gave insight to how poor water quality further restricts freshwater availability.

**Statistical Tests**

The Mann-Kendall trend and Sen's slope tests were conducted to observe the changes in SW and GW. The Shapiro-Wilk normality test checked data normality. Recharge methods were compared with Tukey's HSD (honest significant difference) test to evaluate the differences among them.

# RESULTS AND DISCUSSION

## Water Availability

SW availability in this region is highly seasonal and mostly depends on the Ganges River and rainfall. The mean annual rainfall is around 2000 mm with a standard deviation of 270 mm, with 80% of rainfall occurring in the wet season. Dry season rainfall is almost negligible and consequently makes an insignificant contribution to SW. The Farakka barrage drastically reduces dry season flow and has been in operation and diverting upstream Ganges flow since 1975. The authors' previous work [12] showed that the average reduction of low flow in the Ganges River was 49% under the 1976-1988 treaty, 73% in 1989-1996 when there was no treaty, and 52% from 1997-2015 under the second treaty. The condition of the Gorai River, the only major distributary of Ganges, was even worse. The Gorai River carries significant flow towards Sundarbans. The average decrease in low flow was 87%, 99%, and 58% for the three consecutive post-barrage periods wherein the period without a treaty (1989-1996) suffered the most [12]. Jeuland et al. [43] showed a similar dry season low flow condition at Farakka, showing only 6% of total flow from January to May. Several other sources showed similar results [16], [44]–[46].

The climatic pattern is also changing in the study area. Table 3-2 represents the changes in climatic patterns in the pre- and post-barrage periods. In the pre-barrage period, wet season rainfall and temperature showed statistically significant increasing and decreasing trends, respectively. The post-barrage period shows the opposite trend. The decrease of rainfall and the increase of temperature is statistically significant during the

dry season. $ET_a$ is also increasing for both seasons. The post-barrage period demonstrates all the relevant climatic changes conducive to drier conditions.

Clearly climate shifts and the Farakka barrage both affect SW availability. The results from DMC quantifies the proportion of contributing factors on flow change. Thus it is helpful to prioritize the causes that need immediate measures. The DMC curve should be a straight line if there is no change in flow. However, the Pettit test on dry season DMC slope points to 1976 (WY) as a major transition year. This is the same WY when the Farakka barrage began operation. Table 3-3 shows a 186% impact of the Farakka barrage on total changes whereas contributions from dry season rainfall is almost negligible. The transition year for the wet season DMC is 1965 (WY) and anthropogenic factors contribute 180% of total changes. Although the Farakka barrage has no contribution to wet season flow for the Bangladesh part of the Ganges River, there are other dams and barrages upstream of the Farakka barrage [47] that definitely impacts flow reduction.

Low SW availability promotes GW withdrawal for irrigation, as seen after the 1980's. Figure 3-3 compares the 2006-2015 seasonal mean variation of WT with the 1967-1980 pre-GW irrigation period. In some areas changes in the WT are more prominent during the wet season. It indicates that higher GW withdrawal has begun in the post-GW irrigation period, even during the wet season. The northern section of the study area shows the highest change, as well as a higher WT depth. The WT depth is measured in meters (m), PWD which is 0.46 m below the mean sea level. This depth varies from 8 to 12 m, PWD in the northwest part of the study area whereas the coastal region ranges

from 0 to 3 m, PWD. Higher GW withdrawal is lowering WT, as found in 72% of piezometers. The aquifer transmissivity ranges from 500 - 4000 $m^2$/day. The northern side of the area has higher transmissivity and GW withdrawal than the rest of the region. The lowest water level (below ground level) varied from 4 m to 27.5 m in 2012, making it difficult to withdraw GW.

GRACE data is becoming a valuable tool to assess GW availability. $\Delta$TWS showed the water storage (cm equivalent water height) declined over the 14-years' period of 2002-2016. Both the dry and wet seasons show similar declining trends ($\approx$ 1.1 cm equivalent water/year). Figure 3-4 shows the significant changes in the northern part of the study area which matches with in situ measurements.

In 2012 the World Bank reported untapped GW resources in the lower reaches of the Ganges Basin. Shamsudduha et al. [18] reported lower GW withdrawal in the study area compared with the rest of Bangladesh. However, even with the current withdrawal amount, GRACE and in situ observations found a reduction in WT. The impact of the Farakka barrage is inevitable in lowering WT since water diversion reduces SW which in turn results in lower recharge and finally a lower WT [44].

**Water Demand, Withdrawal, and Use**

Irrigation demand is much higher than domestic and industrial demands, specifically 93% of total water demand. Similarly, irrigation was 96% of total water withdrawal. Figure 3-5 shows the water withdrawal from both GW and SW sources for each sector. SW withdrawal was discussed for the year 2011 [12]. This study includes the average water withdrawal conditions for 2009-2012 and 2015. Rainfall and SW flow met

the irrigation demand in the wet season and GW almost entirely met dry season irrigation demand. The bi-modal graph of agricultural demand (Figure 3-5) shows the peak during the pre-monsoon season (March-May) and early post-monsoon season (October). The dry season water withdrawal is higher than demand, indicating unused water in the irrigation sector.

Though the irrigation demand is still higher, irrigation demand along with crop evapotranspiration ($ET_c$) decreased over the last 67 years (1949-2015 WY). This supports Bouchet's [49] hypothesis that rising $ET_a$ supports the decrease of $ET_o$ and consequently the decrease of $ET_c$. All the meteorological stations show higher $ET_c$ than $ET_a$. This can be explained by the urbanization effect [50] as all the BMD stations are in urban areas [51]. Urbanization (or deforestation) increases runoff , leading to a decrease in ET [52]. Similar evidence was found in both the southern [53] and the eastern United States [54]. Moreover, water bodies and soil moisture have large impacts on $ET_a$. The declining trend of $ET_c$ matches with the findings of Murshed et al. (2018) which showed a decrease in agricultural land. Mirza and Hossain [55] also showed falling crop production because of lower water availability.

Domestic demand increased 40% from 1983 to 2011 and was 6% of total water demand in the 2011 WY. The total water withdrawal in this sector is much lower (≈85%) than demand. The poor SW quality discourages people to use it as a primary source of drinking water, hence almost the entire domestic water withdrawal (99.4%) comes from GW sources. Only 45% of this water withdrawal is considered to be actual water use due to the existing inefficient water management.

GW also plays a dominant role in the industrial sector which comprises 1% of the total water demand. SW withdrawal is almost half of GW in this sector. The agriculture-dominated area has 9516 rice mills, 408 steel industries, 298 garnet factories, 44 jute mills, 17 textile mills, 13 aluminum mills, and 5 sugar industries, along with few minor industries [10].

**Freshwater Sustainability**

A drastic reduction in the Ganges' flow makes SW vulnerable to salinity intrusion. It is a key indicator pointing towards SW sustainability issues in areas bordered by the ocean. This study found SW salinity up to 17 ppt in May 2014 (Figure 3-6a) in the Sundarbans area, which is beyond the acceptable limit of 15 ppt for the Sundari (Heritiera fomes) trees [56]. These species occupy the majority of the Sundarbans Forest. Because of this higher salinity trend, Mukhopadhyay et al. [57] forecasted a 17% reduction of the Sundarbans Mangrove Forest by the year 2105. Murshed et al. [12] also noted an increasing rate (0.5-0.9 ppt/year on average) in SW salinity from 2001-2015. GW salinity is also affected by the severity and expansion of SW salinity. The seasonal comparison maps of GW salinity (Figure 3-6c and 3-6d) show a more severe impact in the dry season than in the wet season. The coastal regions of the study area showed GW salinity up to 19 ppt during the dry season in 2012 (Figure 3-6c). A salinity intrusion pattern is making both SW and GW sources unsustainable.

Arsenic is another threat to sustainable GW use. The blue and yellow colored portions in Figure 3-6b are safe for drinking water purposes according to the World Health Organization and the Bangladesh Government, respectively. GW from the red

zones contains arsenic levels of more than 0.05 mg/l which is not suitable for human consumption.

Again, recharge is a critical aspect in measuring GW sustainability. The three different methods used provide three different ranges of recharge (Figure 3-7). RS data showed the highest recharge (Equation 9) whereas the WTF method (Equation 8) showed the lowest. Tukey's HSD test (Table 3-4) shows a statistically significant difference between these methods. The uncertainty range shows a broad spectrum of recharge. Other literature shows similar wide-ranging recharge values. The results of Kirby et al. [58] are similar to the Empirical (Chaturvedi) method (Equation 7). Recharge values from RS observations are analogous to Shamsudduha [18]. Again, estimated recharge using the WTF method is similar to MPO [35], [59] and Karim [60]. $S_y$ values used in the WTF method were collected from a map in secondary sources and can be regarded as a source of uncertainty.

These broad-spectrum recharge values were compared with GW withdrawal. Figure 3-8 depicts the ratio of recharge versus total GW withdrawal. A ratio less than one is considered to be unsustainable. The in situ withdrawal amount was compared with the recharge values calculated from the Empirical and WTF methods and was shown to be unsustainable. RS observations show lower water withdrawal (Equation 3) than in situ observation, but still indicate an unsustainable condition. Although actual water use is lower than water withdrawal (Figure 3-5), the recharge trend for a significant part of the study area is declining. Figure 3-9 shows the recharge trend (using the Empirical method) which indicates unsuitable GW conditions. These results support the declining WT trend.

# CONCLUSIONS

This study identifies the major causes behind water scarcity in the Bangladesh part of the Ganges Delta. It emphasizes both quantity and quality aspects to address the shortage of fresh water.

The amount of fresh SW is decreasing. Upstream water diversion due to the Farakka barrage during the dry season is the major contributor to this calamity. In addition, statistically significant increases in temperature and $ET_a$ are also contributing to water shortages. The increasing trend of $ET_a$ and decreasing trend of $ET_c$ point towards the reduction of agricultural land and the increasing of water bodies. Waterlogged conditions [12], [61] may contribute to higher $ET_a$. Decreasing quantities of fresh SW also affect the water quality of the coastal region. Salinity has become a significant concern, especially during the dry season.

Increasing SW salinity is also amplifying GW salinity. Saline water is contaminating aquifers where a major portion is already contaminated with arsenic. RS observations show a statistically significant decreasing trend of total water storage anomalies. In situ WT observations yielded similar findings. In addition, the recharge values show a broad range of uncertainty. Comparing these recharge values with GW withdrawal depicts an unsustainable trend of GW availability.

Freshwater scarcity needs to be addressed regarding both quantity and quality. Large quantities of poor-quality water fail to meet the needs of human beings, the environment, and the ecosystem. This study area is an example of how freshwater deficits impact water quality and subsequently damage the environment and ecosystem. The

information that has been presented can help formulate better water management plans which enable the sustainable use of freshwater resources.

## ACKNOWLEDGMENTS

This work was funded by the Utah Water Research Laboratory of Utah State University. Travel support for field work and a data purchase fund was provided by the International Water Management Institute, Sri Lanka. The authors are also grateful to the Institute of Water and Flood Management, Bangladesh University of Engineering and Technology and Bangladesh's Department of Public Health Engineering for their data support.

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Table 3-1. Irrigation schedule of major crops.

| Crop Type | Total Irrigation Days | Starting Time | Irrigation |
|---|---|---|---|
| B. Aus (Rice) | 110 | 15-Apr | Supplementary |
| HYV. Aus (Rice) | 110 | 15-Apr | Primary |
| B. Aman (Rice) | 110 | 22-Mar | Supplementary |
| L.T. Aman | 120 | 20-Aug | Supplementary |
| HYV Aman | 110 | 22-Jul | Supplementary |
| L. Boro (Rice) | 110 | 10-Dec | Primary |
| HYV. Boro (Rice) | 120 | 15-Jan | Primary |
| HYV Wheat | 110 | 30-Nov | Primary |

Table 3-2. Changes in climatic patterns in the pre- and post-barrage periods.

| Period | Climate Parameter | Mann-Kendall Trend Test | | Sen's slope (Unit) |
|---|---|---|---|---|
| | | 2-sided p-value | Statistic | |
| Pre-barrage | Dry season rainfall | 0.83 | -11 | -0.31 (mm/year) |
| | Dry season ET | 0.21 | -61 | -1.42 (mm/year) |
| | Dry season temperature | 0.90 | -5 | 0 (°C/year) |
| | Wet season rainfall | *0.027* | 107 | 14.77 (mm/year) |
| | Wet season ET | 0.56 | 29 | 0.43 (mm/year) |
| | Wet season temperature | *0.0086* | -127 | -0.015 (°C/year) |
| Post-barrage | Dry season rainfall | *0.016* | -200 | -4.79 (mm/year) |
| | Dry season ET | *< 2.22e-16* | 565 | 4.3 (mm/year) |
| | Dry season temperature | *0.00018* | 234 | 0 (°C/year) |
| | Wet season rainfall | 0.33 | -81 | -2.92 (mm/year) |
| | Wet season ET | *< 2.22e-16* | 529 | 2.68 (mm/year) |
| | Wet season temperature | 0.44 | 59 | 0 (°C/year) |

Italicized numbers show statistically significance.

Table 3-3. The effects of rainfall and anthropogenic factors on Flow at “SW90 “of Ganges River (downstream of Farakka Barrage).

| Period | Transition Year | Observed Mean Value (m3/s) | | Predicted Mean Value (m3/s) | Total Change | | Impact of Rainfall | | Impact of Anthropogenic Factors | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Before Transition Year | After Transition Year | After Transition Year | m3/s | % | m3/s | % | m3/s | % |
| Dry Season | 1976 | 3557 | 2291 | 4649 | 1266 | 36 | 1092 | -86 | 2358 | 186 |
| Wet Season | 1965 | 25957 | 21968 | 29164 | 3989 | 15 | 3208 | -80 | 7196 | 180 |

Table 3-4. Tukey's HSD test between the empirical, WTF, and RS recharge methods.

| Recharge Method | Difference in Observed Means | Lower End Point of Interval | Upper End Point of Interval | p-value after Adjustment for Multiple Comparisons |
|---|---|---|---|---|
| RS-Emirical | 77 | 40 | 115 | 3.39E-05 |
| WTF-Empirical | -97 | -135 | -60 | 6.00E-07 |
| WTF-RS | -175 | -212 | -138 | 0.00E+00 |

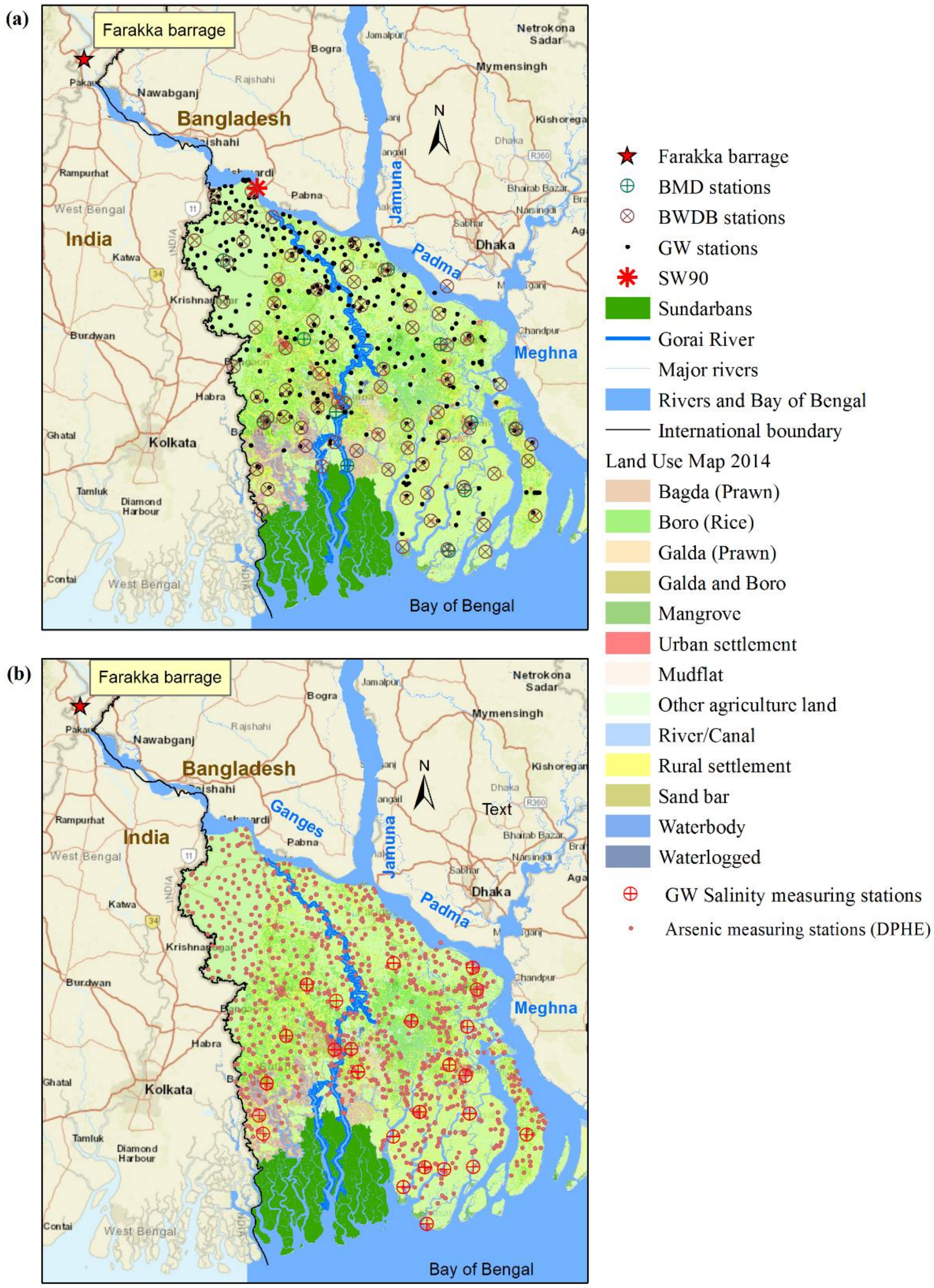


Figure 3-1. Physical description of the Ganges delta of Bangladesh and surrounding areas showing a) hydro-meteorological and b) salinity and arsenic measuring stations used in this study.

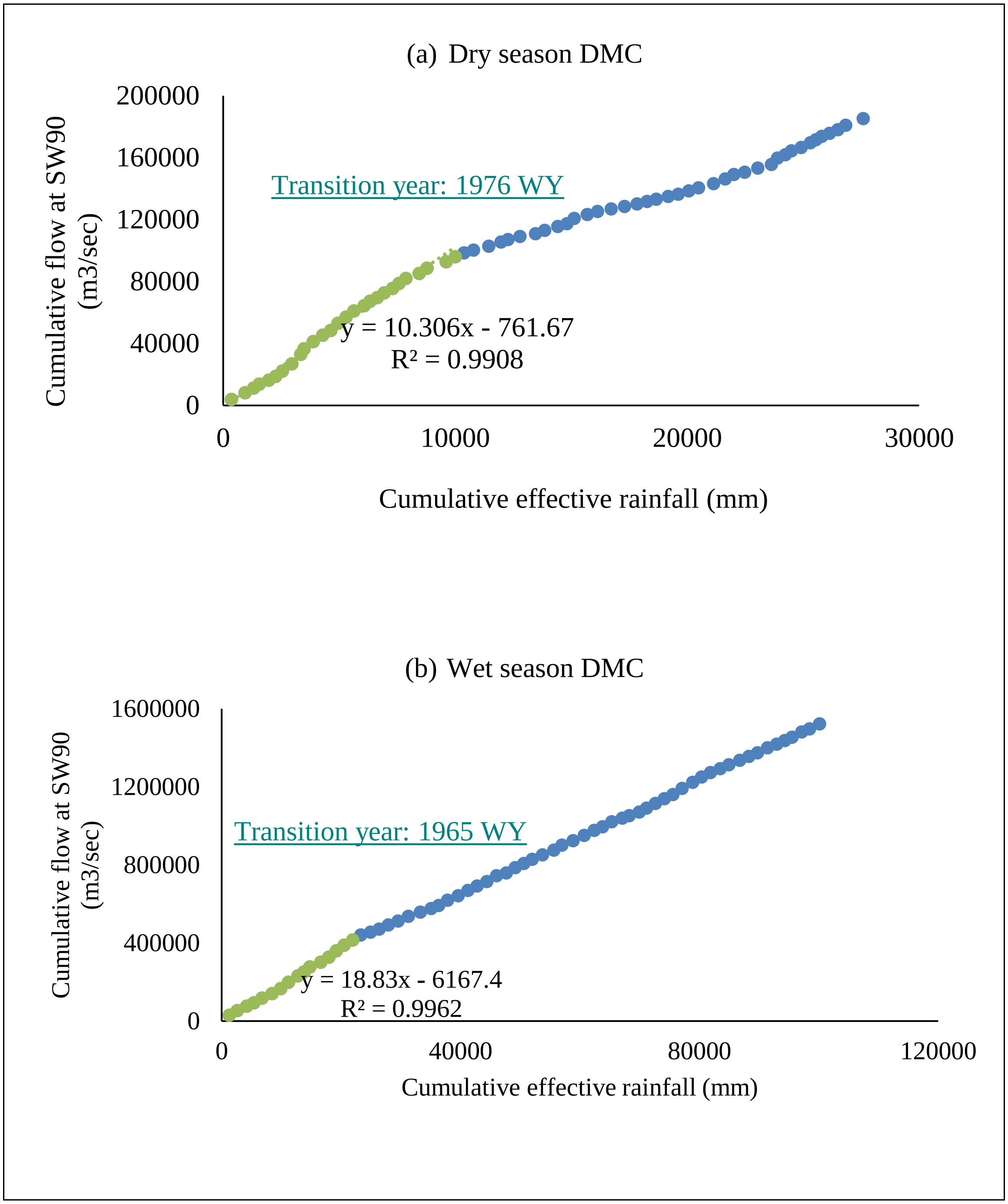


Figure 3-2. Seasonal Double Mass Curves of cumulative effective rainfall versus cumulative flow at SW 90 of the Ganges River. Green and blue points show the curves before and after the transition years, respectively. The linear regression equation is for the DMC curve before the transition year.

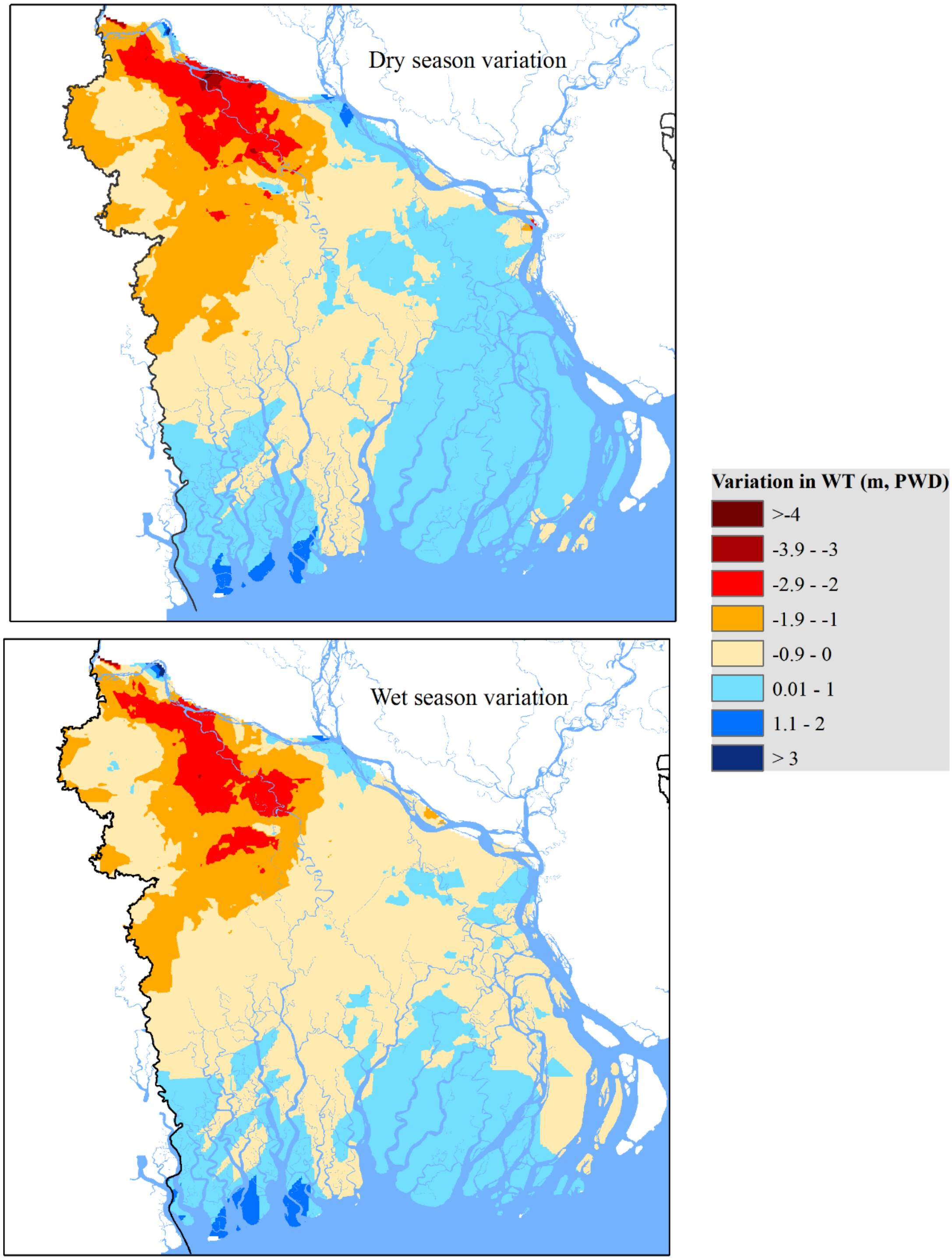


Figure 3-3. Seasonal water table variation in m, PWD showing the mean variation of the 2006-2015 average from the pre-GW irrigation (1967-1980) average. Note: PWD (m) is mean sea level – 0.46 m.

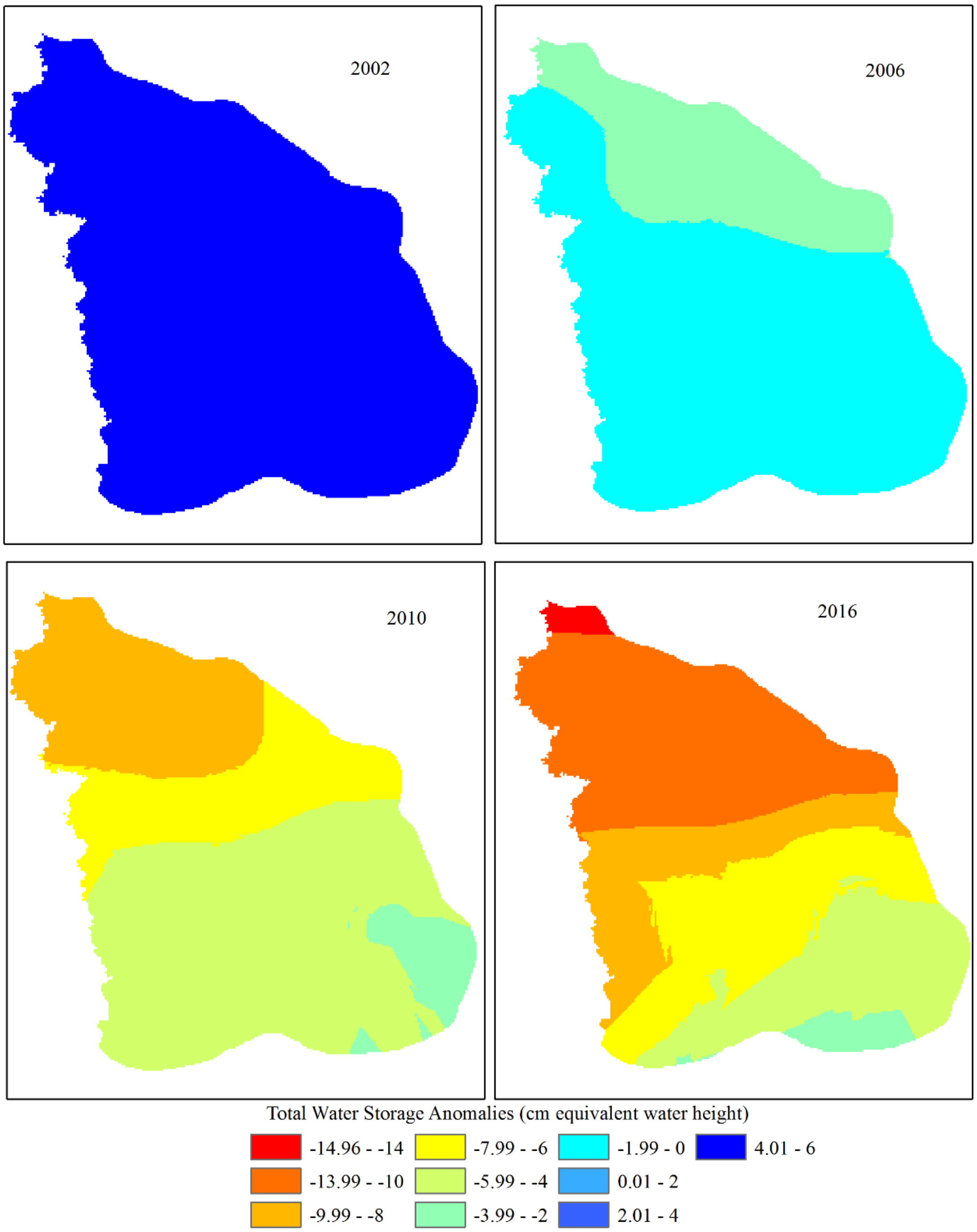


Figure 3-4. Total annual water storage anomalies (cm equivalent of water height) from the GRACE satellite mission. Note: the year 2002 does not show any variation as GRACE started measuring anomalies from that time.

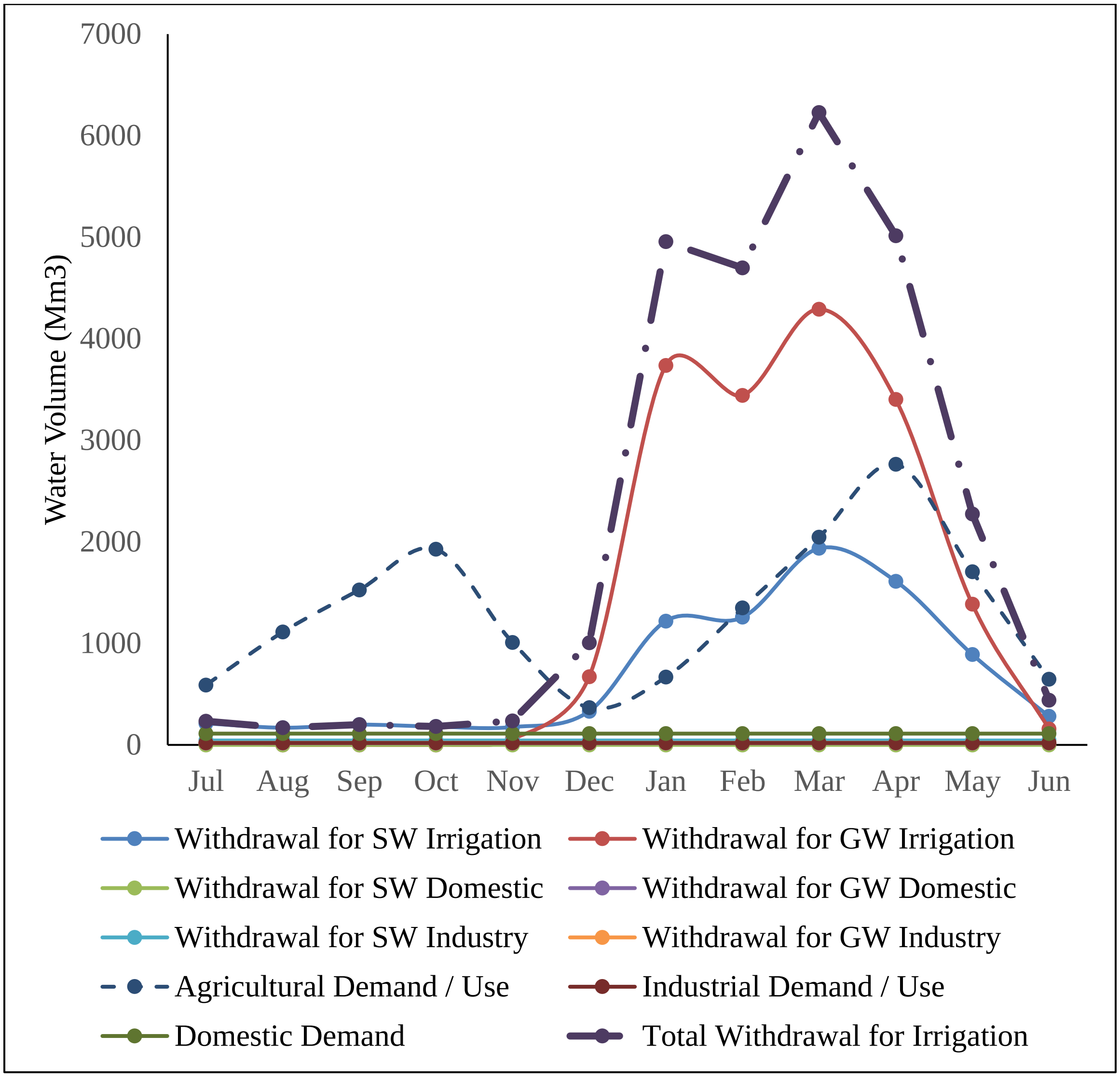


Figure 3-5. Five year average of (2009-2012, 2015) water withdrawal, demand, and use of GW and SW.

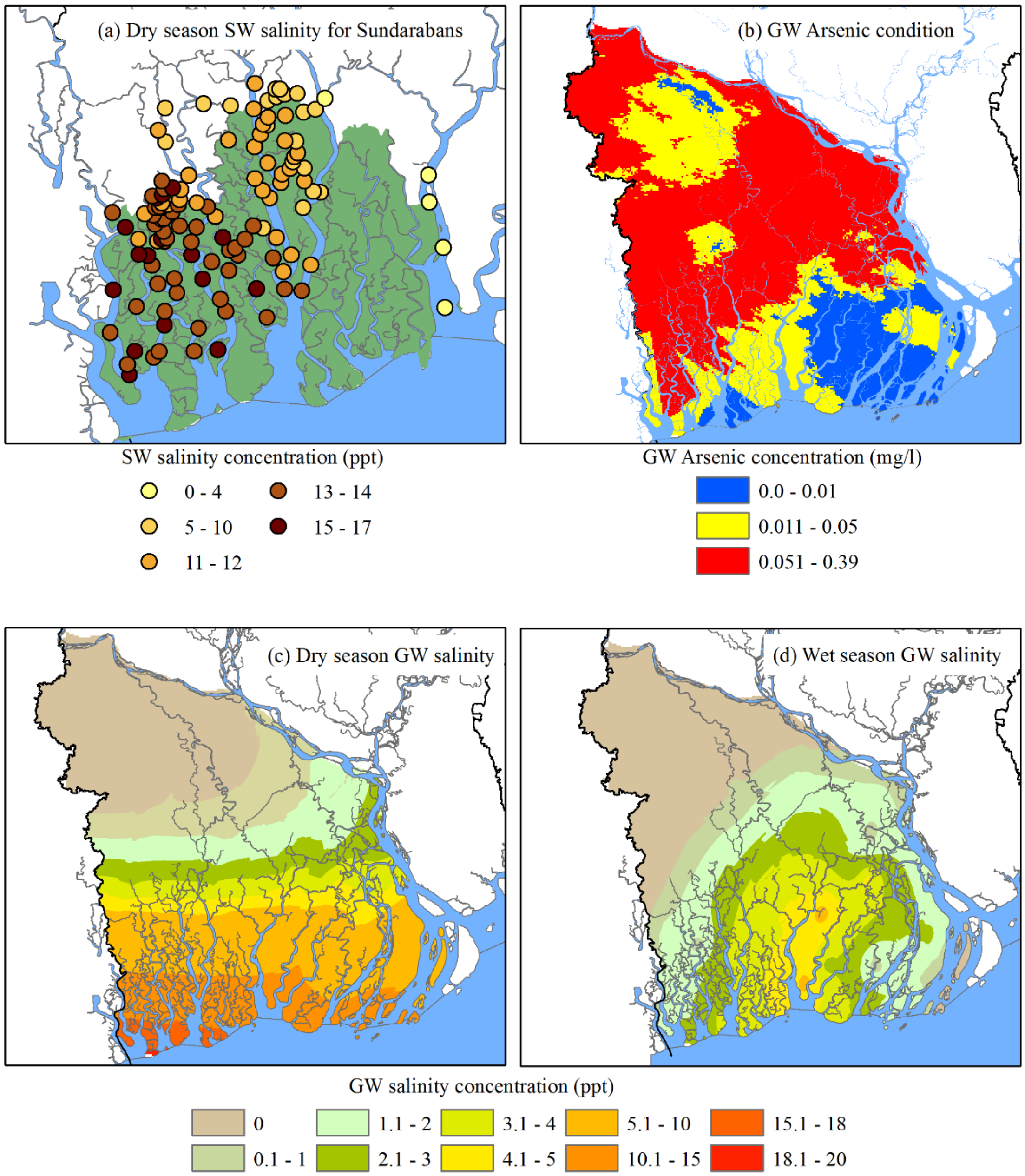


Figure 3-6. (a) Dry season SW salinity in May 2014 for Bangladesh part of Sundarbans, (b) 1998-99 GW arsenic contamination, (c) 2012 dry season GW salinity, and (d) 2012 wet season GW salinity.

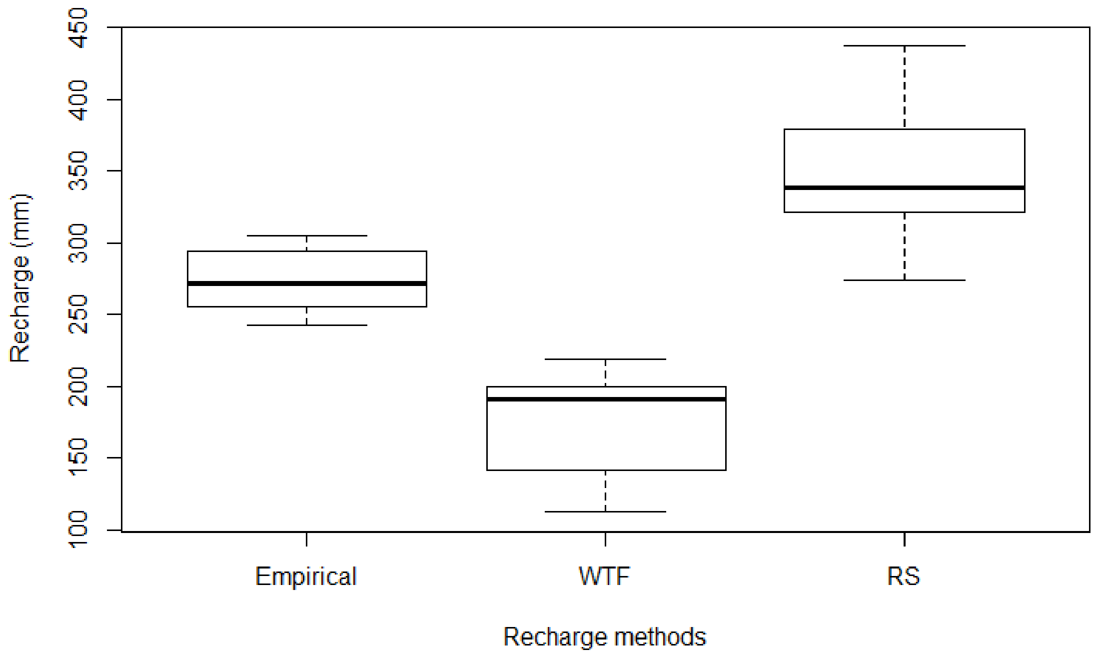


Figure 3-7. Recharge variation between the empirical, WTF, and RS methods.

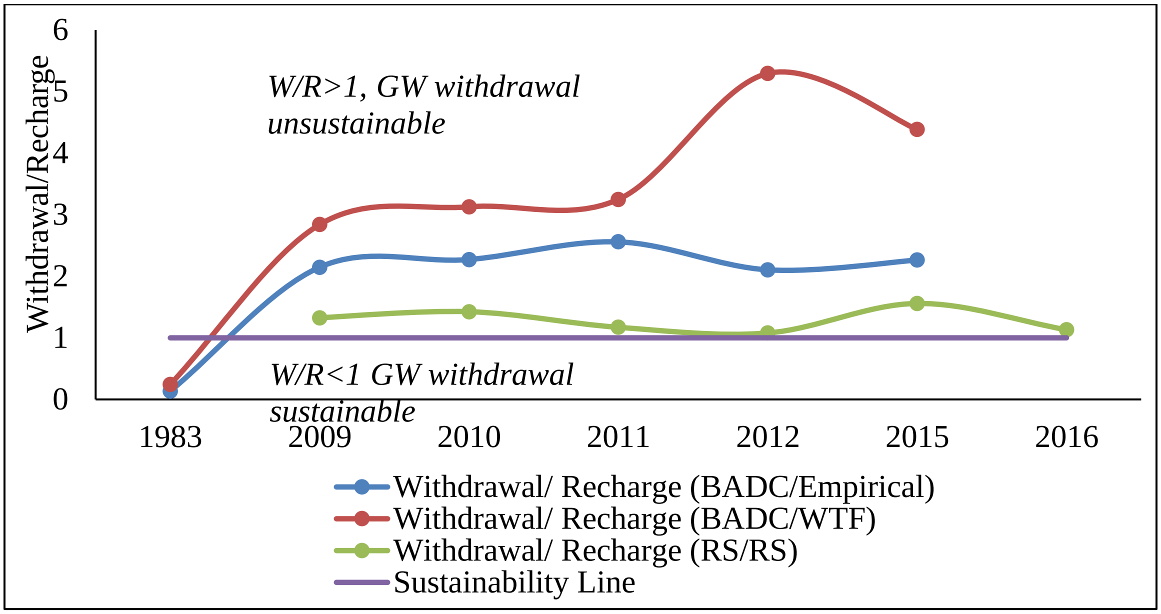


Figure 3-8. GW sustainability considering withdrawal to recharge ratio.

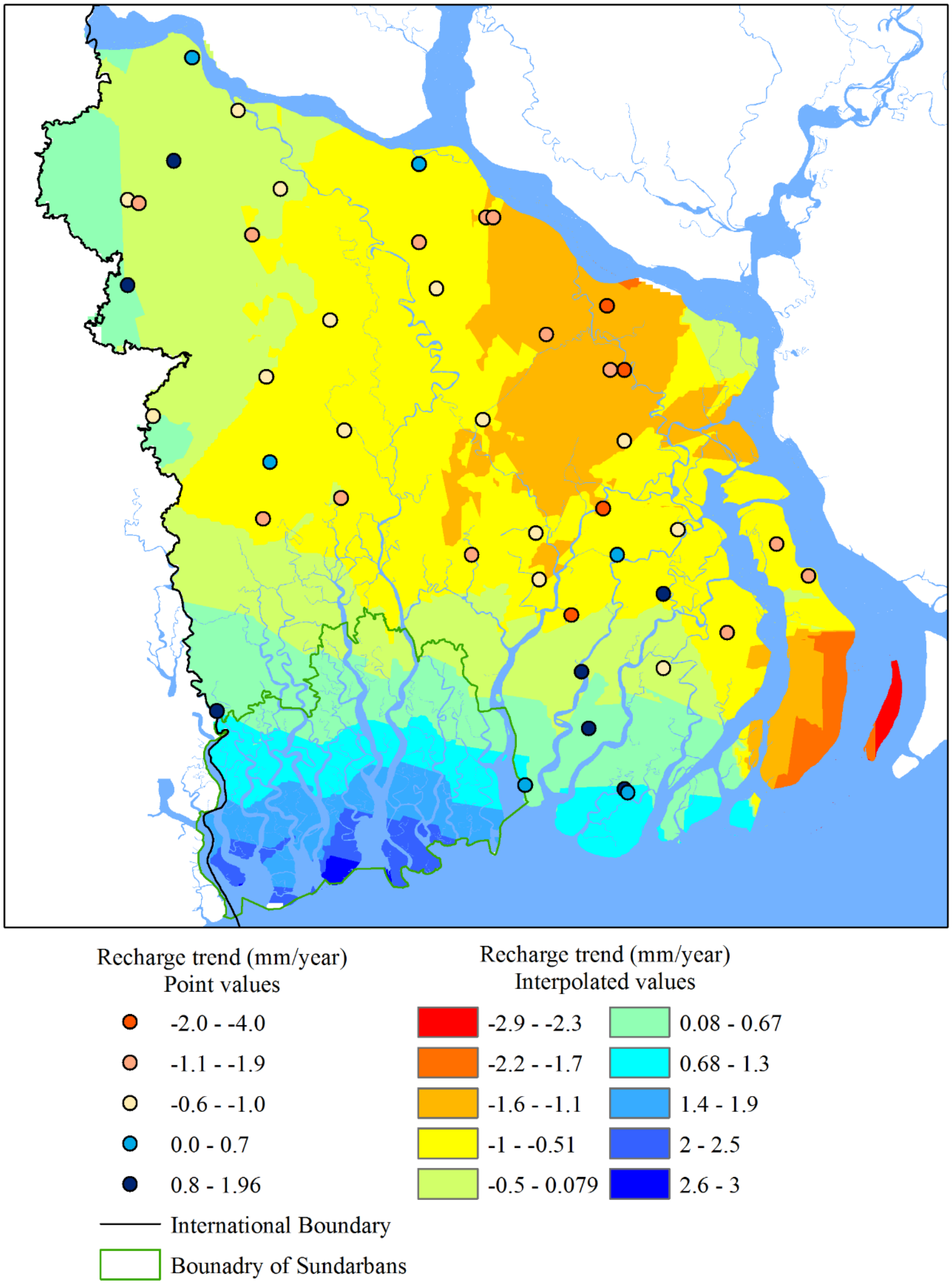


Figure 3-9. Recharge trends in the post-GW irrigation period (1981-2015).

# CHAPTER 4

## EFFECTS OF HYDRO-CLIMATIC CONDITIONS ON AGRICULTURAL WATER DEMAND IN THE GANGES DELTA OF BANGLADESH[3]


## ABSTRACT

Understanding the climate change effects on agricultural water demand is crucial for the Ganges Delta of Bangladesh, which is an agriculture-dominated region. Evidence shows a decrease in agricultural land and loss of soil fertility in the region due to water scarcity, floods, droughts, and salinity intrusion problems. As such, the purpose of this study is to understand potential impacts on future agricultural water demand under climate change. We used projected climate data (2020-2100) from three regional climate models along with their eight driving global climate models. Moderate and high carbon emission scenarios (RCP 4.5 and 8.5) of the Coupled Model Intercomparison Project Phase 5 were used to assess the relevant changes on climatic parameters, water loss, crop water requirement, irrigation demand, and freshwater availability. The random forest algorithm was used to predict future land cover data and was incorporated into a complementary relationship model to estimate actual evapotranspiration. Crop water requirement was estimated and compared with freshwater availability to assess agricultural sustainability. High uncertainty was found among different climate model scenarios. A mean increase of 2 to 3°C temperature during the dry season is expected. Rainfall showed fluctuation over time rather than a continuous increase or decrease.


[3] Murshed, S.B., Kim, H., and Kaluarachchi, J.J., submitted to Agricultural Water Management

Although we found the possibility of decreased wet season rainfall up to 500 mm, opposite scenarios are also possible. The results suggest wide uncertainty regarding rainfall. Irrigation demand may increase anywhere from 18% to 60% from the historical (2001-2015) mean. Quantifying uncertainty is essential to developing adaptation plans to combat climate change effects. We proposed making an allowance at the 95$^{th}$ percentile of the maximum upper limit of expected irrigation demand considering the seasonal variation of water availability. The findings of this study are helpful in developing economically feasible agricultural water management plans.

## INTRODUCTION

Managing agricultural water demand is challenging in many parts of the world due to high demand on freshwater resources, water scarcity, and degradation of water quality (FAO, 2012; Gruère et al., 2018; Mancosu et al., 2015). The agricultural sector accounts 92% of all water consumption globally (Hoekstra et al., 2012). The water usage in this sector is often inefficient and sometimes contributes to water pollution (Gruère et al., 2018). Similar concerns are applicable to the Ganges Delta of Bangladesh, one of the most fertile regions of the world (van der Most et al., 2009). The Ganges Delta region is 42,000 km$^2$ with a population of more than 30 million (BBS, 2013). Agricultural land occupies 70% of the total land area (BBS, 2013) excluding 5800 km$^2$ of mangrove forest which is 60% of Sundarbans. As the world's largest mangrove forest, Sundarbans adds great ecological and economic value to this delta area (FAO, 1994; Sadik, 2009). The mangrove forest buffers coastal agricultural land from cyclones, storm surges, and coastal erosions (CEGIS, 2007; Mukhopadhyay et al., 2015; Ronnbaack, 1999). The region's

economy is highly dependent on agriculture with 46% of livelihoods coming from small farms and 28% from agriculture-related labor, for a total of 74% (Ministry of Agriculture and FAO, 2013). Irrigations consume 96% of total water withdrawal, of which 68% is groundwater (GW) and 31% is surface water (SW) (Murshed and Kaluarachchi, 2018). The existing withdrawal and recharge patterns of GW indicate an unsustainable withdrawal condition (Murshed and Kaluarachchi, 2018). Further, climate and human-induced hydrological changes make this deltaic area susceptible to the loss of agricultural land (Murshed et al., 2019).

Local climatic conditions have a significant influence on freshwater availability, which in turn affects irrigation demand. High inter-annual variation of freshwater availability is a defining trait of the hydrologic system of the Ganges Delta of Bangladesh. A common climatic phenomenon in this sub-tropical region, heavy monsoon rainfall from June to October contrasts starkly with the dry season, from November to May. The study area is heading towards extreme climatic conditions with increasing temperature and evapotranspiration trends (Murshed et al., 2019). High-intensity rainfall with short duration is also becoming more frequent (Murshed et al., 2019, 2013).

Since 1975, dry season water diversion at the Farakka barrage has reduced flow of the Ganges River, resulting in severe freshwater scarcity during the dry season in the delta region. This region does not have much control over incoming streamflow since it is in the downstream portion of the Ganges River Basin (Figure 4-1). Since the delta is flat, at the current sea level tidal effects spread up to 200 km upstream (Dasgupta et al., 2016). This reduced flow degrades both surface and groundwater, changes morphology, hinders navigation, aggravates salinity intrusion, and poses health hazards (Wolf, 1998). Given

the region's dependence on agriculture, salinity is a major concern. High salinity leads to a loss of soil fertility and reducted crop production. The World Bank (Dasgupta et al., 2014) found a 15.6% decrease in rice yields when soil salinity exceeds 2.56 ppt. The maximum value of soil salinity in the region ranges from 7.2 to 19.2 ppt (SRDI, 2017) which has a severe negative impact on crop production. The area for cultivating major varieties of rice (B. Aus and B. Aman) is decreasing (SRDI, 2017). The problem is compounded by the low market price for rice given its increasingly poor quality (Dasgupta et al., 2014).

Climate change can also have a substantial impact on agricultural water demand (FAO, 2012). Projected irrigation demand under climate change is expected to change based on emission scenarios, variations in temperature, ET and rainfall, crop types, crop area, and forest cover, along with many other considerations (Gondim et al., 2012; Savé et al., 2012; Woznicki et al., 2015). Crop physiological processes largely depend on temperature (Boonwichai et al., 2018). With a projected temperature increase, Boonwichai et al. (2018) found an increase in crop water use and a decrease in rice yield and crop water productivity. Climate change constrains the availability of freshwater and poses a serious threat to irrigation (Woznicki et al., 2015). Combined with expectations that the region will be warmer in the future (Fahad et al., 2018; Hasan et al., 2017), along with the rise in sea level (Brown et al., 2018; Pethick and Orford, 2013), threats from coastal floods, cyclones, and storm surges become even more concerning (Jisan et al., 2018). Such risks are common to Delta areas because of anthropogenic climate change (Ghosh et al., 2019). Developing countries are more susceptible to climate change because of geographic location (Harrington et al., 2016) and environmental dependency

for livelihoods (Brown et al., 2018), food, and other basic necessities.

Quantifying uncertainty is an additional issue in climate change studies (Webster and Sokolov, 1998), especially when addressing the science-policy interface (Curry, 2018). Researchers (Greve et al., 2018; Greve and Seneviratne, 2015) have found substantial uncertainty in the climatic impact on the hydrological cycle and regional water availability. More than 50% of uncertainty arises from the choice of climate model (Greve et al., 2018). One of the key factors linked with uncertainty is the regional climate change signals which are affected by synoptic and mesoscale processes that occur on large spatial scales (Giorgi et al., 2009). This critical issue can mostly be resolved if we consider climate models as possible scenario generators rather than future projection machines (Curry, 2018).

Considering regional challenges, we focus on the hydro-climatic effects on future agricultural water demand in this century, specifically from 2021 to 2100, by addressing climate change and uncertainty. The driving factor of this study is understanding ET loss since the terrestrial hydroclimate is greatly influenced by ET processes (Berg and Sheffield, 2019) that can lead to forecasting freshwater availability (Padrón et al., 2019) and irrigation demand (Gondim et al., 2012; Goodarzi et al., 2019). We used the representative concentration pathways (RCP) of moderate (RCP 4.5) and extreme (RCP 8.5) scenarios under the Coupled Model Intercomparison Project Phase 5 (CMIP5). The Asian monsoon climate is better captured by CMIP5 (Hasan et al., 2017). In addition, CMIP5 also projects changing patterns of future ET under global warming (Berg and Sheffield, 2019).

Several studies (Ara et al., 2017; CCC, 2009; Hossain and Paul, 2019; Islam et al.,

2019) showed the impact of climate variability on irrigation water requirements, agricultural production, rice yield, and so forth in this region. A few recent studies (Hossain and Paul, 2019; Mondal et al., 2019; Saha and Barmon, 2015) also focused on adaptation practices in the agricultural sector under climate change. This study addressed long-term impacts and uncertainty under climate change on agricultural water demand in a quantitative manner for combating climate change impacts in the agricultural sector. Uniquely, this study predicts land cover data for 2021 to 2100 using a normalized difference vegetation index (NDVI). We used this information in the computation of actual ET (ETa) to understand total water loss. Freshwater availability (FWA) was estimated considering this water loss and rainfall, and finally, we compared FWA and irrigation demand so as to understand future water needs in the irrigation sector. We predicted a range of possible outcomes at given probability levels. Another key objective of this study is to transform the climate change information from regional-scale to local-level to make the end results useful for policymakers striving to develop hydro-economically feasible water management options to sustain long-term agriculture.

## METHODS

### Observed and Climate Model Data

Irrigation demand was computed using ETa and the crop water requirement (ETc). We used five climatic parameters, namely rainfall, maximum and minimum temperature, relative humidity, and wind speed to estimate ETa and ETc. Observed in situ meteorological data from 1949 to 2015 were collected from 11 stations of the Bangladesh Meteorological Department (BMD) as shown in Figure 4-1. We used three

regional climate models (RCMs), the REMO, RCA4, and RegCM4, based on the availability of data from the Coordinated Regional Downscaling Experiment (CORDEX). CORDEX was initiated by the Task Force on Regional Climate Downscaling to facilitate impact-oriented works (Giorgi et al., 2009). The spatial resolution of these data is 0.44° (≈ 50 km). Three RCMs, along with their driving global climate models (GCMs), were used in this study:

RCA4-CNRM-CERFACS-CNRM-CM5

RCA4-ICHEC-EC-EARTH

RCA4-MPI-M-MPI-ESM-LR

REMO-MPI-M-MPI-ESM-LR

RegCM4-CNRM-CERFACS-CNRM-CM5

RegCM4-CSIRO-QCCCE-CSIRO

RegCM4- MPI-M-MPI-ESM-MR

RegCM4-NOAA-GFDL-GFDL-ESM2M

RCA4 and REMO have data until 2100 whereas RegCM4 has data until 2085. RCM data were extracted corresponding to the 11 locations of BMD stations for better comparison with BMD and RCMs. Although RCMs provide higher resolution data than GCMs, they still possess some systematic biases (Maraun, 2016; Themeßl et al., 2012), especially for rainfall (Gudmundsson et al., 2012). Therefore, climate model data for the historical period (1961-2000) were used for bias correction with BMD data. The quantile

mapping bias corrections procedure (Themeßl et al., 2012) was chosen since it does not modify trends (Maraun, 2016) and can capture the extreme events due to anthropogenic climate change (Jeon et al., 2015).

We used Taylor diagrams (Taylor, 2001) to represent the similarities and differences of bias-corrected climate model variables with observed data. It is a powerful tool to view the statistical summary of correlation and standard deviation of different data patterns (Fahad et al., 2018; Taylor, 2001). This study found the bias-corrected RCM and GCM values better represent the observed BMD data as shown in Figure 4-2. Another important observation is that bias-corrected GCMs under each RCM were closely positioned with each other. Therefore we used the mean daily values of all GCMs for each RCM and all analyses were performed based on these RCMs. We consider all outcomes from these RCMs to cogitate the uncertainties and relative possibilities of future climate change.

**Land Cover Data**

This study used NDVI values to represent land cover data which were in turn incorporated to estimate total water loss (equivalent to ETa). NDVI data (2001-2014) from Moderate Resolution Imaging Spectroradiometer (MODIS) Collection 6 land products of 250m resolution were used in this study (downloaded from http://daac.ornl.gov/MODIS/modis.shtml in February 2019). We extracted the NDVI area by centering each BMD station (Suzuki et al., 2001). We mostly focused on NDVI from agricultural lands as the focus of the study is agricultural water demand. We used a regression type of random forest (RF) algorithm (Biau and Scornet, 2015; Breiman,

2001), ensembles based machine learning approach, to predict future NDVI (Turk et al., 2017). Five historical climatic parameters, namely rainfall, maximum and minimum temperature, relative humidity, and wind speed, were used as predictor variables for training the model. The trained model then predicted the NDVI values at each BMD station using the same climatic variables from selected RCMs under RCP 4.5 and RCP 8.5 scenarios. We used 201decision trees to tune the model because out-of-bag error (OOB) does not show any improvement beyond this number. The OOB scores range from 0.002 to 0.00086, which indicates a good estimate of future NDVI. R packages, *RandomForest* and *caret*, were used to build the RF model.

**Estimation of ETa and Freshwater Availability**

Given its dependency, land use patterns influence the climate system (van Vuuren et al., 2011) and thus influence ET. Kim and Kaluarachhi (2017) improved the modified complementary relationship of Anayah and Kaluarachchi (2012) by incorporating NDVI and used 60 Eddy Covariance Ameriflux sites in the USA as validation. We used the same method and applied local correction factors proposed by Kim and Kaluarachchi (2017) using latent heat flux from the Yucheng (YCS) site of Asiaflux. This Asiaflux site was chosen based on its similar cropping pattern as the study area. The available data period for YCS is 2003-2005. A recent study by Khatun et al. (2016) found the highest daily ET value of 7 mm for Mymensingh, an Asiaflux site near the study area. Due to data restrictions, this study was unable to use Mymensingh flux data.

Below are the model equations relevant to ET calculations. The modified complementary relationship or the modified Granger and Gray (GG) method (Anayah and Kaluarachchi, 2012) is described by:

$$ET_{GG} = \frac{2G}{G+1} ETW \quad (1)$$

$$G = \frac{ET}{ETP} \quad (2)$$

Where ETW is a wet environment ET that would occur under a saturated soil-plant system. ETP is potential ET. G in Equation (2) can change after incorporating NDVI data (Kim and Kaluarachchi, 2017).

$$ET_{GG\text{-}NDVI} = \frac{2G_{new}}{G_{new}+1} ETW \quad (3)$$

$$\text{where} \quad G_{new} = 1 + \frac{P}{ETP} - \left[1 + \left(\frac{P}{ETP}\right)^{\omega}\right]^{\frac{1}{\omega}} \quad (4)$$

P is rainfall (mm/day) and $\omega$ is linearly correlated with the long-term average annual vegetation cover which is represented here by NDVI.

The adjusted $ET_{GG\text{-}NDVI}$ method (Kim and Kaluarachchi, 2017) is described by:

$$\text{Adjusted } ET_{GG\text{-}NDVI} = ET_{GG\text{-}NDVI} \ \alpha \ e^{\beta G_{new}} \quad (5)$$

Using 60 Ameriflux sites, Homin and Kaluarachchi (2018) developed a nonlinear correction function to describe parameters $\alpha = 0.7895$ and $\beta = 0.9655$.

For this study we adjusted Equation (5) as follows:

$$ET_{GG\text{-}NDVI} = ET_{GG\text{-}NDVI}\ \alpha\ e^{\beta G_{new}} + \gamma \qquad (6)$$

using data from the Yucheng Site in China and found that

$a = 0.8446$, $\beta = 0.1942$, and $\gamma = 0.6979$.

We compared the daily ET values from 2003 to 2005 with additional sites of similar cropping patterns. ET in rice fields in the Phillippines was found within the range of 3.6 to 4.52 mm/day (Carmelita et al., 2011) whereas the Narmada River Basin in India found that ET varies from 4.08 to 7.18 mm/day (Kundu et al., 2018). $ET_{GG\text{-}NDVI}$ values from Equation (6) are within this combined range and $R^2$ is 0.893. These results show that the derived equation represents the actual condition fairly well. Hereafter, total water loss ($ET_{GG\text{-}NDVI}$) is denoted ETa.

We deducted daily ETa (mm) from daily rainfall (mm) to estimate available water. The multi-decadal mean of this available water can be treated as mean runoff and is usually represented as a measure of renewable freshwater sources (Gudmundsson et al., 2017). Hence, freshwater availability (FWA) was computed by using the multi-decadal mean (Padrón et al., 2019) of this available water.

$$FWA = \text{multi-decadal mean } (P - ET_a) \qquad (7a)$$

$$FWA_{2021\text{-}2050} = \text{multi-decadal mean } (P - ET_a) \text{ from } 2021\text{-}2050 \qquad (7b)$$

$$FWA_{2051\text{-}2080} = \text{multi-decadal mean } (P - ET_a) \text{ from } 2051\text{-}2080 \qquad (7c)$$

$$FWA_{2081\text{-}2100} = \text{multi-decadal mean } (P - ET_a) \text{ from } 2081\text{-}2100 \qquad (7d)$$

**Estimation of Crop ET and Irrigation Demand**

Reference ET (ETo) was computed using the Penman-Monteith method (Allen et al., 2006):

$$ET_O = \frac{0.408\,\Delta_{ASCE}\,(R_n - G_{ASCE}) + \gamma\frac{900U(e_s - e_a)}{T_{avg}+273}}{\Delta_{ASCE} + \gamma\,(1+0.34U)} \qquad (8)$$

Where ETo is in mm day$^{-1}$, Rn is net radiation at the crop surface [MJ m$^{-2}$ day$^{-1}$], $G_{ASCE}$ is soil heat flux density [MJ m$^{-2}$ day$^{-1}$], $T_{avg}$ is the mean daily air temperature at 2 m height [°C], U is the wind speed at 2 m height [m s$^{-1}$], $e_s$ is saturation vapour pressure [kPa], $e_a$ is actual vapour pressure [kPa], ($e_s$ – $e_a$) is the saturation vapour pressure deficit [kPa], $\Delta_{ASCE}$ is the slope vapour pressure curve [kPa °C$^{-1}$], and γ is the psychrometric constant [kPa °C$^{-1}$].

Crop coefficient ($K_c$) data were gathered from a Bangladesh Government report (MPO, 1987) and multiplied with ETo to obtain ETc. ETc was also considered as the crop water requirement. Irrigation demand was computed by deducting effective daily rainfall from ETc. Here, effective rainfall is rainfall which actually contributes to fulfilling crop water requirements (http://www.fao.org/docrep/X5560E/x5560e03.htm, accessed in September, 2017). Since water availability during dry and wet seasons varies drastically, estimates of ET and FWA were performed on a seasonal basis defining the water year (WY) as April to March. Unless otherwise noted, ETa, ETc, irrigation demand

and FWA were expressed for each RCM. For example, ETa calculated using the RCA4 model is stated as RCA4-ETa.

### Interdependency of Climatic Variables, Irrigation Demand, and FWA

Correlation among different climatic parameters increases understanding of the linkage among variables. It is also helpful to recognize the causes behind the changes in freshwater availability. We used non-parametric Kendall's tau correlation coefficients (Arndt et al., 1999; Chok, 2010) to understand the inter-dependency of five parameters, namely maximum and minimum temperature, rainfall, ETa, ETc, and irrigation demand.

## RESULTS AND DISCUSSIONS

### Changes in Climate Variables

Projections of climate variables have high uncertainty due to the forcing scenarios (e.g., greenhouse gas concentrations, aerosols, solar radiation, etc.) of climate models (Baumberger et al., 2017). Probability density functions (PDFs) of these variables quantifies uncertainty (Loucks et al., 2005; Webster and Sokolov, 1998). Figure 4-3 shows the expected value of three climatic variables, specifically rainfall and the maximum and minimum temperatures, for 2021 to 2100. Most scenarios show a rise in temperature, especially for RCP 8.5 which presents the extreme $CO_2$ emission scenario (van Vuuren et al., 2011). PDFs of temperature also indicate higher uncertainty for RCP 8.5. RCA4 and REMO show the maximum mean temperature increases from 2°C to 3°C for the dry season while RegCM4 predicts a marginal decrease of 0.5°C. Wet season

mean temperature showed an increase between 1°C and 3°C which is alarming for a low-lying coastal area such as the Ganges Delta of Bangladesh. As per an IPCC prediction (IPCC, 2018), an increase of temperature of 1.5 °C can lead to extremely hot conditions in most inhabited regions.

Increased temperature may lead to surplus or deficit rainfall depending on location (IPCC, 2018). REMO and RegCM4 predict a decrease in mean rainfall (≈ 500 mm) for the wet season. Existing historical data (1949-2015) shows that 80% of rainfall occurs during the wet season (Murshed and Kaluarachchi, 2018). Decreasing wet season rainfall coupled with increasing temperatures indicate a drier weather pattern. RegCM4 found increasing dry season rainfall to be 2.5 to 3.8 times current rainfall. It may indicate a change in future seasonal patterns. Another remarkable observation in Figure 4-3 is that REMO shows an increase in the mean rainfall for the wet season and vice versa for the dry season which may lead to a drier dry season and a wetter wet season. This could lead to more wet season floods and greater water scarcity and drought during the dry season. The uncertainty range for rainfall varies significantly. There is a possibility of changes in seasonality, decreased rainfall, or, to a lesser extent, the possibility of increased wet season rainfall.

Seasonal uncertainty of climatic variables is shown in Figure 4-4 for maximum and minimum seasonal RCMs' values for RCP 4.5 and RCP 8.5 emission scenarios. These results show that RegCM4 is adding more variability to rainfall and temperature.

Unlike temperature, which mostly shows an increase in mean temperature from the current (2001-2015) average, rainfall shows a fluctuation pattern rather than a continuous increase or decrease. In fact, rainfall does not show much temporal variation from 2021 to 2100. Another key difference between predicted rainfall and temperature is that changes in rainfall are similar for both RCP 4.5 and RCP 8.5 scenarios. On the other hand, temperature with RCP 8.5 shows a clear rising trend from RCP 4.5, especially after 2050 (Figure 4-4). Given the uncertainty, the results show that careful planning for agricultural water management is essential in the region.

**Predicted NDVI**

The NDVI values are very similar (0.47 to 0.5) throughout 2001-2012 as shown in Figure 4-5. Though 2013 and 2014 show slightly higher NDVI values (0.52), the predicted NDVI does not show much variation in this century irrespective of emission scenarios. RCP 8.5 predicts increasing croplands, grasslands, and decreasing forest vegetation cover while RCP 4.5 depicts the opposite (van Vuuren et al., 2011). The major crops are mostly rice with some wheat, sugarcane, jute, and some spices (BBS, 2013). These crops have shorter plant lives and a lower cover degree which may not be captured in NDVI matrices (Olsen et al., 2015).

**Predicted Water Loss and Irrigation Demand**

ET is an important indicator of water loss and its measurement is necessary for water resources management. This study attempts to quantify the variability of ET. We estimated ETa and ETc to compute actual water loss and crop water requirements,

respectively. We first examined the PDFs of ETa and ETc shown in Figure 4-6. We found high variability in predicted ETa and ETc, depending on the RCM. Although most scenarios show an increase in dry season ETa and ETc, RegCM4 shows the opposite, a mean wet season increase of 100 mm for ETa and 300 mm for ETc. Figure 4-6 also shows a decrease in mean ETa for the wet season with RCA4 and REMO. However, RegCM4-ETa showed an increasing trend where the wet season could increase more than the dry season (≈ 120 mm). The broad variation of irrigation demand PDFs point to higher uncertainty, suggesting careful consideration is required in future irrigation planning.

The uncertainty plots of ETa, ETc, and irrigation demand are shown in Figure 4-7. The combined maximum and minimum values of RCA4, REMO and RegCM4 until 2085 were considered. Data from the last 15 years (2085-2100) show only the combination of RCA4 and REMO as RegCM4 data is not available after 2085. Here we find two similar fluctuation patterns for multi-model mean values. One is from 2021 to 2085, and the other from 2086 to 2100. These multi-model mean values do not show much temporal variation for both emission scenarios. However, there are noticeable differences among the RCMs' spread, i.e., between the maximum upper and minimum lower limit. Ryan et al. (2019) found similar findings for multi-decadal land water availability.

For planning purposes, we considered the 95$^{th}$ percentile of maximum upper limits and minimum lower limits of ETa, ETc, and irrigation demand as shown in Table 4-1. Dry season ETa and ETc show intensification from the historical mean (2001-2015).

Though similar changes for the wet season maximum upper limit were found, a marginal decrease was shown in the wet season minimum lower limit. Hence, total water loss and crop water requirements can be higher in most cases. Moreover, the RCP 8.5 emission scenario shows a greater rise in ET than in the RCP 4.5 emission scenario, indicating more water loss with extreme emission scenarios. This leads to an increase in future irrigation demand. Change in dry season irrigation demand is higher than in the wet season. Again, the RCP 8.5 scenario shows higher crop water needs than RCP 4.5.

Finally, the use of the $95^{th}$ percentile of the maximum upper limits of irrigation demand for future planning purposes was suggested. These values were selected, combining both RCP scenarios. The percent increase from the current irrigation demand is higher in the wet season (75%) than the dry season (36%) as shown in Table 4-2. Ryan et al. (2019) argued that the percent of water loss would be higher in the wet season given greater water availability. Hence, the percentage change of dry season irrigation can be lower despite needing more water for irrigation.

**Correlation and Dependency Among Variables**

The interrelationship of climatic variables is not linearly correlated. The seasonal Kendall’s tau correlation curves in Figures 4-8 to 4-10 show a positive correlation between irrigation demand and ETc. These two parameters also positively correlated with temperature in 75% of the cases. Obviously, irrigation demand and rainfall have a negative correlation. Most model results showed an increase in irrigation demand from 2021-2100, except the RCA4 wet season and RegCM4 dry season, which is supported by

actual increasing rainfall. Under the different models, both positive and negative correlations were found between ETa and ETc, rainfall and temperature, temperature and ETa.

Total water loss (ETa) and crop water requirement (ETc) may or may not have a linear correlation as they are calculated considering different parameters. ETa may increase due to an increase in runoff due to increased urbanization (Anayah and Kaluarachchi, 2012). ETc entirely depends on cropping patterns and crop areas. If increased urbanization decreases agricultural land, which is true in many cases, ETc can decrease despite increasing ETa. On the other hand, ETa and ETc may both increase with a rise of temperature up to a certain level.

Baldocchi et al. (2019) discussed two different perspectives on changes in evaporation. Warming may increase evaporation if we consider the thermodynamic and physiological perspective, but the opposite condition (warming decreases evaporation) may occur if we use the meteorological perspective (Baldocchi et al., 2019). Recent research by Berg and Sheffield (2019) found a significant contrast between transpiration and soil evaporation in the tropics. In that case, an increase in soil evaporation influences the increase of ETa while a decrease in transpiration contributes to decreasing ETc. Increased ETa may lower ocean temperature due to the rise in ocean heat storage controlled by salinity-driven mechanisms (Leggett and Ball, 2019). This salinity-driven mechanisms may also influence the Ganges Delta of Bangladesh, a coastal area facing salinity intrusion problems (Murshed and Kaluarachchi, 2018). Rainfall and temperature

may have a linear or nonlinear correlation, depending on changes in the heat balance (Zhao and Khalil, 1993).

The interrelationship among variables can also be explained by box plots (Figures 4-11, 4-12 and 4-13) considering four time frame for each RCM. The future analysis period (2021-2100) was divided into four segments: 2021-2040, 2041-2060, 2061-2080, and 2081-2100. Although there was an increase in temperature changes over the period, deviations in ETa, ETc, and irrigation demand showed values both higher and lower than the historical mean (2001-2015) under different models. The last three parameters largely depend on rainfall. Table 4-3 shows the mean changes in irrigation demand. Usually, the extreme scenario (RCP 8.5) shows higher needs in irrigation demand. It may differ if rainfall decreases more in RCP 4.5 than RCP 8.5. This is supported by 2021-2040 of the REMO dry season, 2041-2060 in the RCA4 dry season, the REMO wet season, and all time frames of RegCM4. Thus a decrease in irrigation demand is accompanied by an increase in rainfall and vice versa.

## CONCLUSIONS

Agriculture is the most vital sector of freshwater use in the Ganges Delta of Bangladesh, given a rural economy that has prevailed for decades. This region is affected by severe floods and droughts on an ongoing basis with changes in climate patterns. Most studies (Baten et al., 2019; Brammer, 2016; Rahman and Lateh, 2016; Rahman et al., 2017; Rakib et al., 2019) have focused on salinity and ongoing floods and droughts in the region. Our current study is fulfilling the need to assess the long-term climate change effects and corresponding water needs. This study describes how climate change in this

century is imposing significant uncertainty on climatic parameters, water loss, crop water requirement, irrigation demand, and freshwater availability. This was demonstrated using RCA4, REMO, and RegCM4 regional climate models and two emission scenarios, RCP 4.5 and RCP 8.5.

Mean irrigation demand may increase within a range of 18% to 60% from the historical mean, bearing in mind the extreme upper limit. This study used a novel approach to estimate ETa using a random forest algorithm to predict future land cover (NDVI) and incorporated these values in the estimation of total water loss. Knowing this total water loss is helpful in assessing freshwater availability, a considerable portion of which is allocated for irrigation. We found that correlation among climate variables does not always show a particular relationship and this lack of a clear correlation in turn broadens the uncertainty range. Given these results, addressing uncertainty is vital in developing future water management plans. We proposed using the 95$^{th}$ percentile of the maximum upper limit of future irrigation demand and suggested considering the seasonal values in future decision makings, policy development, infrastructure design, water-sharing treaties, and so forth. Quantitatively, the dry season requires more irrigation water. Results showed that in future additional water may be needed up to 75% and 35% of the historical mean for the wet and dry seasons, respectively. In essence, the wet season can lose more water compared to the dry season. Another critical issue is in-stream water needs, which require additional work to understand salinity intrusion in this delta region. Climate change mitigation and adaptation are necessary to deal with these serious climate change impacts.

# ACKNOWLEDGMENTS

This work was funded by the Utah Water Research Laboratory of Utah State University. Travel support for field work and a data purchase fund was provided by the International Water Management Institute, Sri Lanka.

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Table 4-1. 95$^{th}$ percentile extreme values of the changes in actual evapotranspiration (ETa), Crop evapotranspiration (ETc) and irrigation demand from 2001-2015 mean.

| Variable | Season | RCP Scenario | 95$^{th}$ Percentile Upper Limit | 95$^{th}$ Percentile Lower Limit |
|---|---|---|---|---|
| ETa (mm) | Dry | 4.5 | 153 | 44 |
| | | 8.5 | 216 | 63 |
| | Wet | 4.5 | 190 | -38 |
| | | 8.5 | 231 | -28 |
| ETc (mm) | Dry | 4.5 | 427 | 243 |
| | | 8.5 | 572 | 315 |
| | Wet | 4.5 | 295 | -28 |
| | | 8.5 | 335 | -34 |
| Irrigation Demand (mm) | Dry | 4.5 | 554 | 218 |
| | | 8.5 | 651 | 313 |
| | Wet | 4.5 | 517 | 71 |
| | | 8.5 | 520 | 45 |

ETa: actual evapotranspiration, ETc: crop evapotranspiration, RCP: representative concentration pathways

Table 4-2. Results of irrigation demand compared to the historical (2001-2015) mean.

| Irrigation Demand | Dry Season (mm/year) | Wet Season (mm/year) |
|---|---|---|
| Current Demand (2001-2015) | 1805 | 693 |
| Change in Demand | 651 (+36%) | 520 (+75%) |
| Future Demand | 2456 | 1213 |

Table 4-3. Percent change of mean irrigation demand from historical data (2001-2015).

| Model | 2021-2040 | | 2041-2060 | | 2061-2080 | | 2081-2100 | |
|---|---|---|---|---|---|---|---|---|
| Emission Scenario | 4.5 | 8.5 | 4.5 | 8.5 | 4.5 | 8.5 | 4.5 | 8.5 |
| RCA4 (dry) | +18 | +22 | +25* | +22* | +20 | +24 | +23 | +25 |
| RCA4** (wet) | -3 | -8 | -3 | -10 | -4 | -16 | -3 | -20 |
| REMO (dry) | +15 | +12 | +18 | +18 | +12 | +22 | +12 | +20 |
| REMO (wet) | +26 | +26 | +37* | +27 | +36 | +40 | +25 | +37 |
| RegCM4 *** (dry) | -26 | -28 | -31 | -30 | -28 | -36 | | |
| RegCM4 (wet) | +55 (P: -38) | +45 (P: -30) | +60 (P: -38) | +50 (P: -30) | +55 (P: -30) | +55 (P: -30) | | |

P: rainfall

* The predicted rainfall decreased in RCP 4.5 more than RCP 8.5 during 2041-2060. Consequently, RCP 4.5 shows a greater increase in irrigation demand than RCP 8.5.

** RCA4-wet season shows a decrease in irrigation demand because this model projects an increase in wet season rainfall.

*** RegCM4-dry season shows a decrease in irrigation demand as this model predicts an increase of 2.5 to 3.8 times the dry season rainfall.

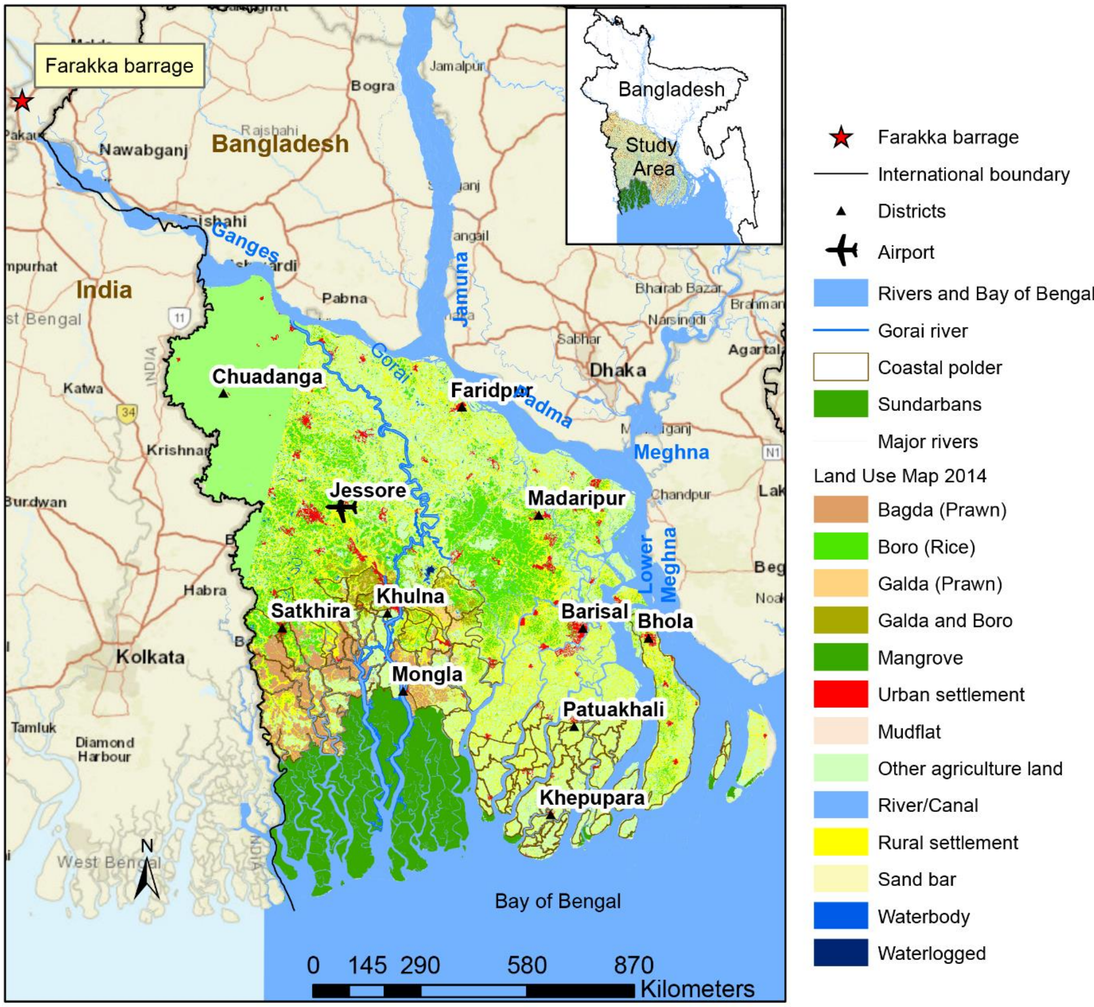


Figure 4-1. Physical layout and land use map of the Ganges Delta region.

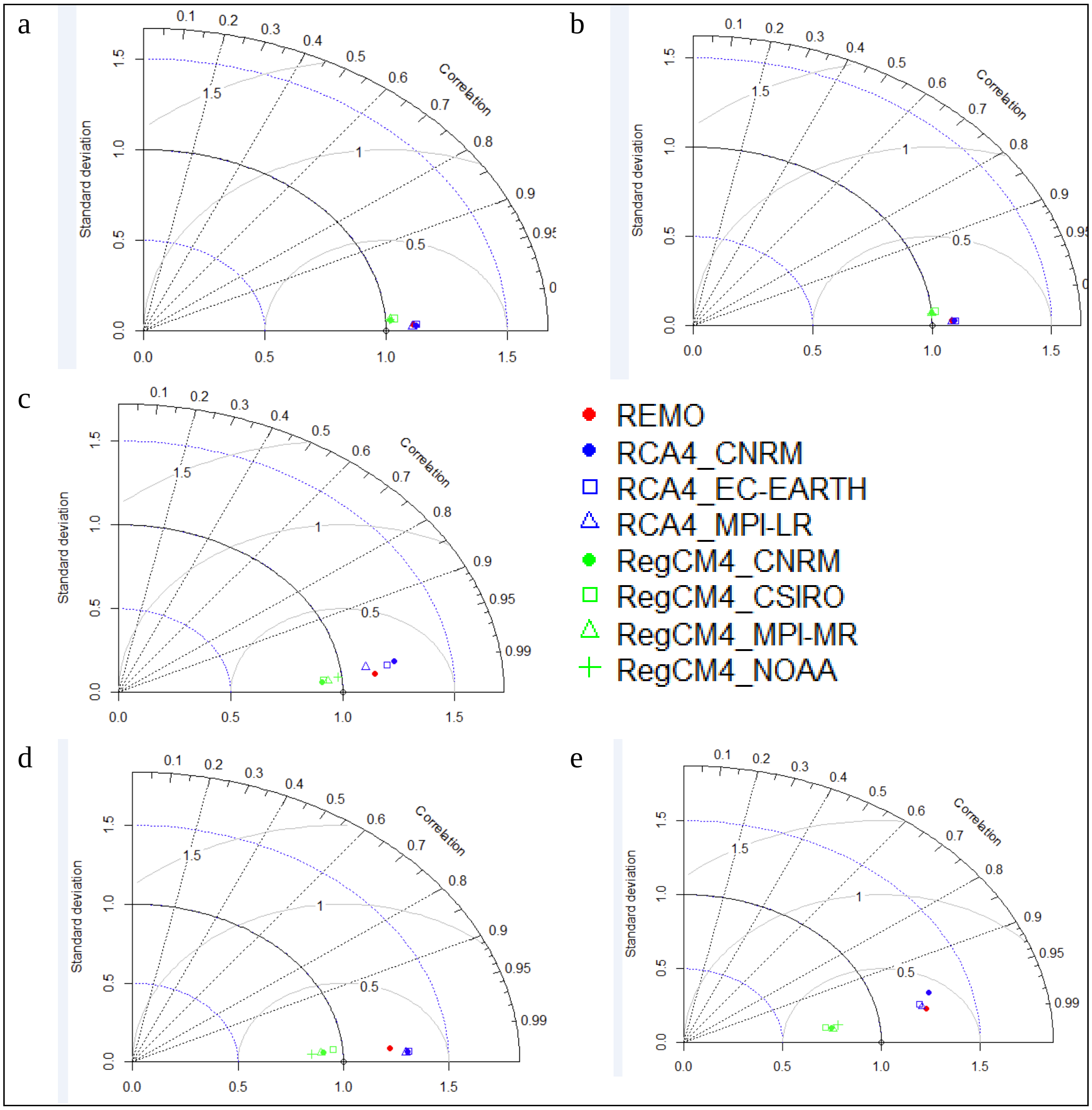


Figure 4-2. Taylor diagrams for bias-corrected a) maximum temperature, b) minimum temperature, c) rainfall, d) relative humidity, and e) wind speed.

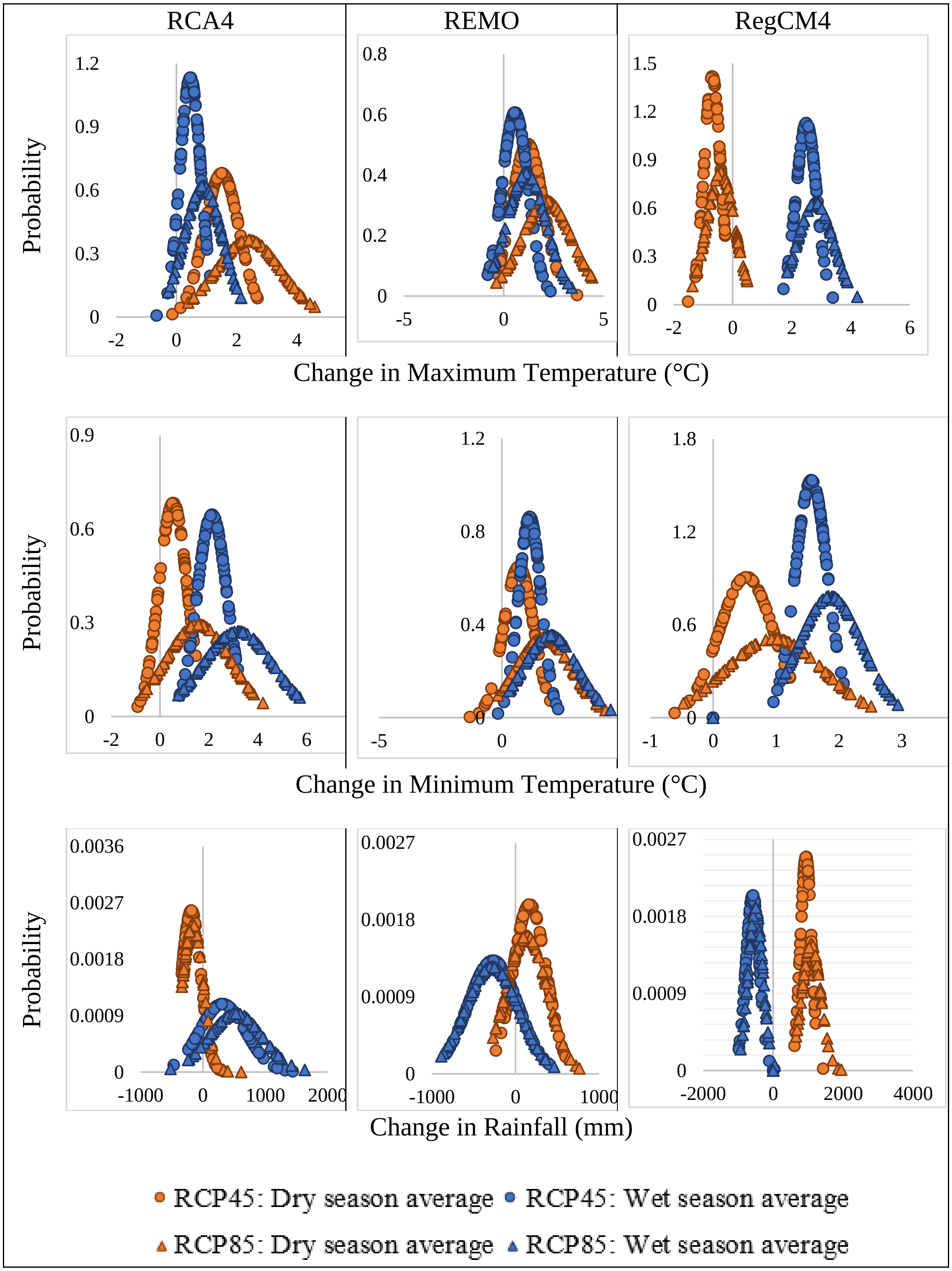


Figure 4-3. Probability Distribution Functions (PDFs) of climatic variables.

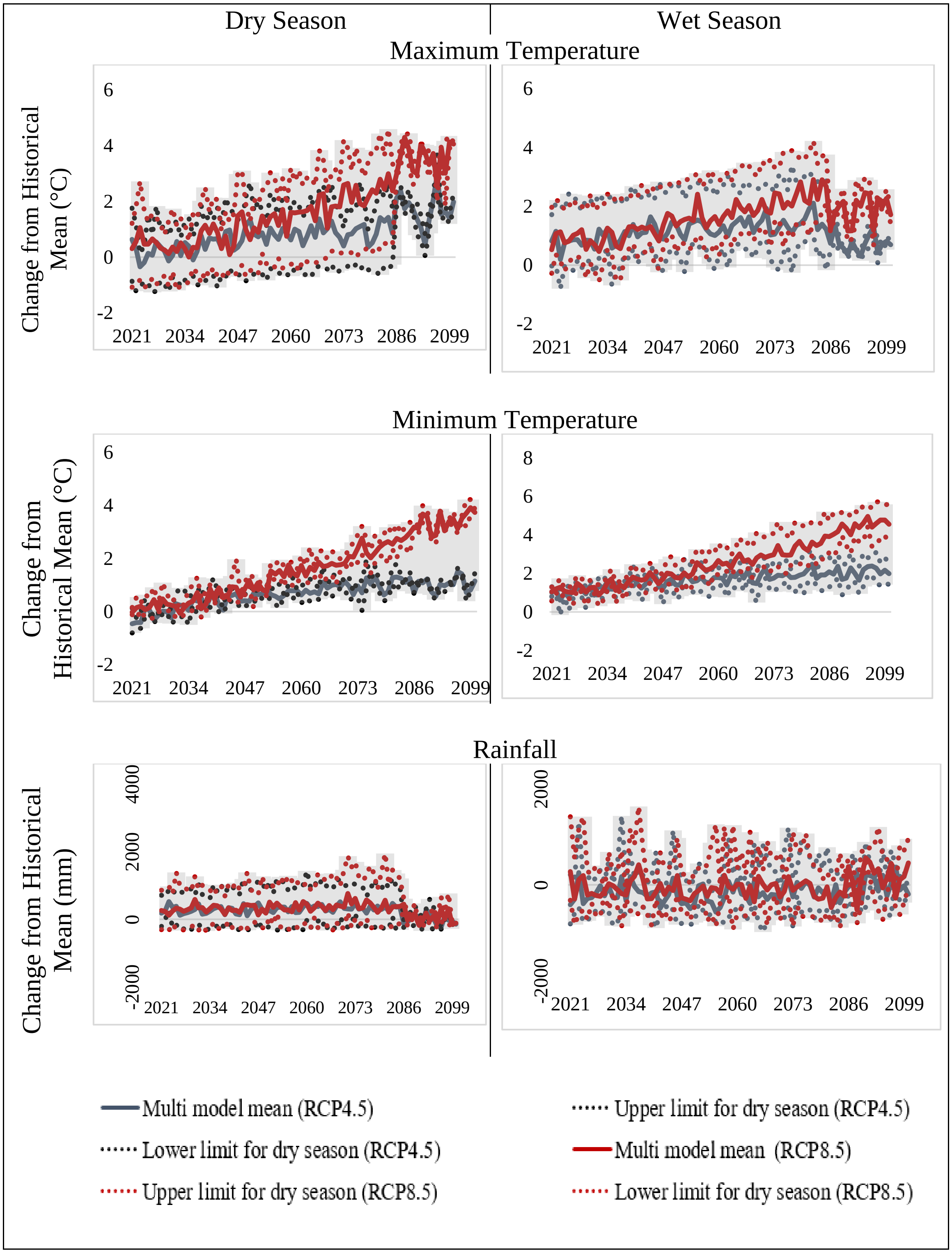


Figure 4-4. Uncertainty plots of climatic variables.

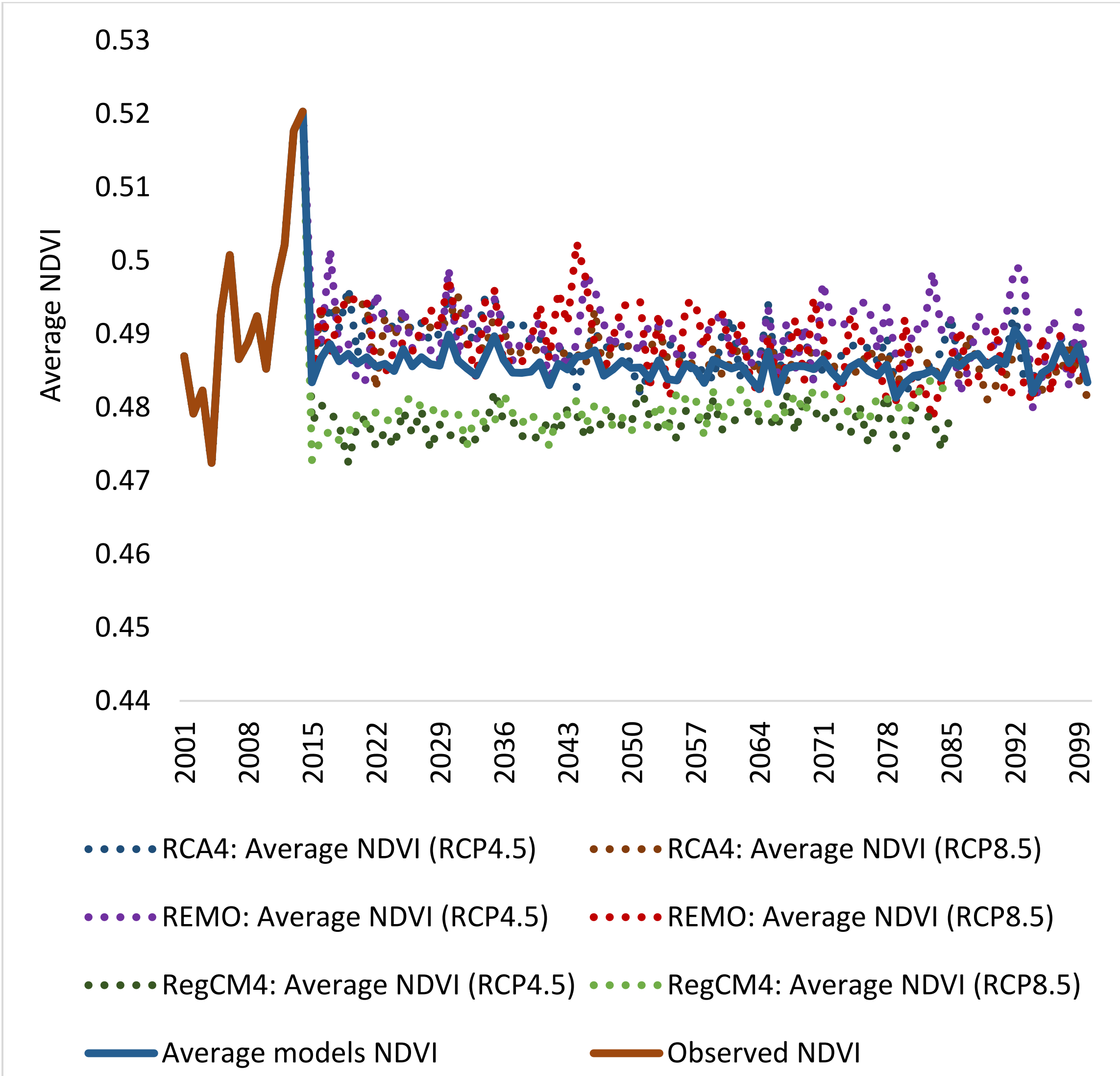


Figure 4-5. Observed NDVI (2001-2014) and predicted NDVI (2015-2100).

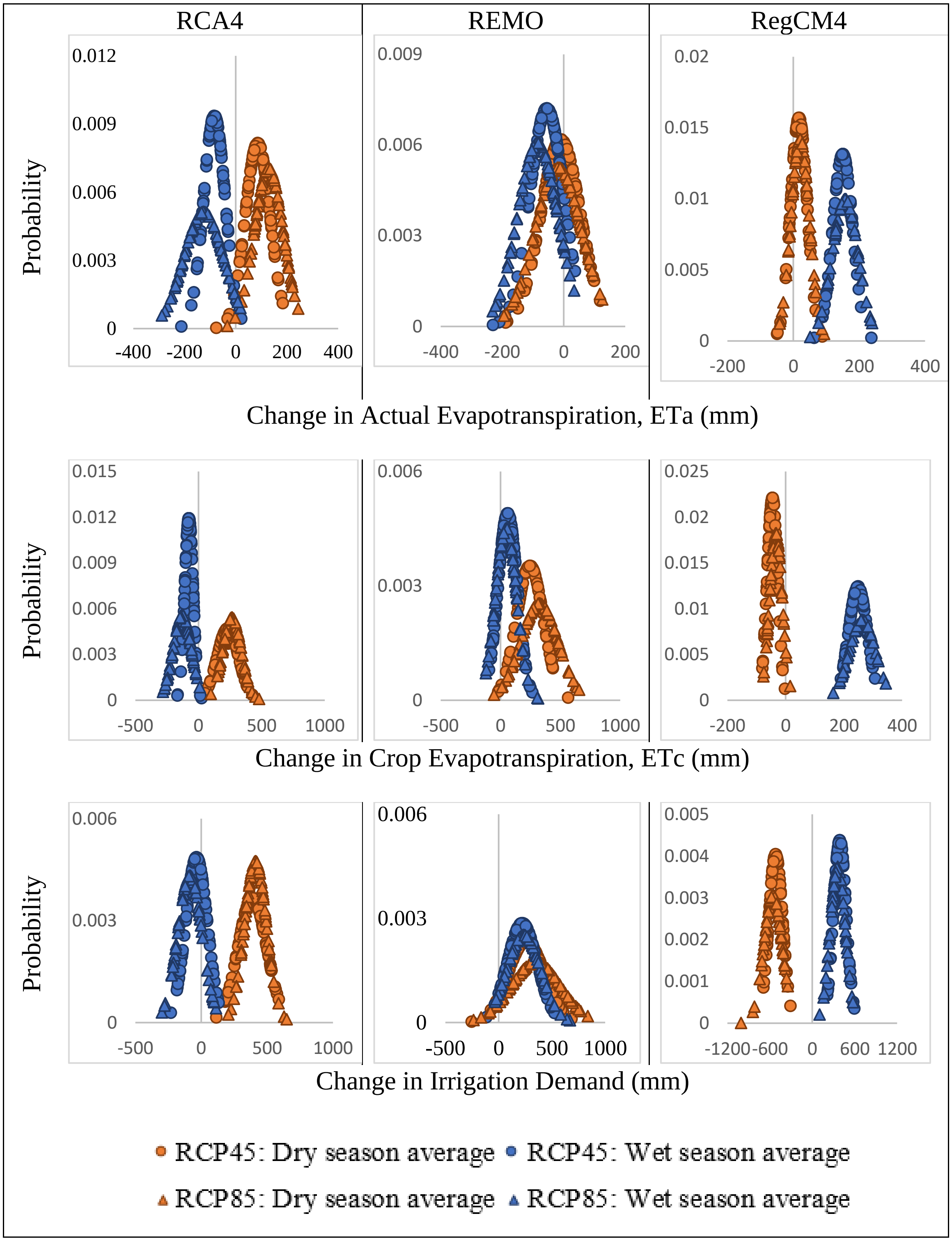


Figure 4-6. Probability Distribution Functions (PDFs) of actual evapotranspiration (ETa), crop evapotranspiration (ETc), and irrigation demand.

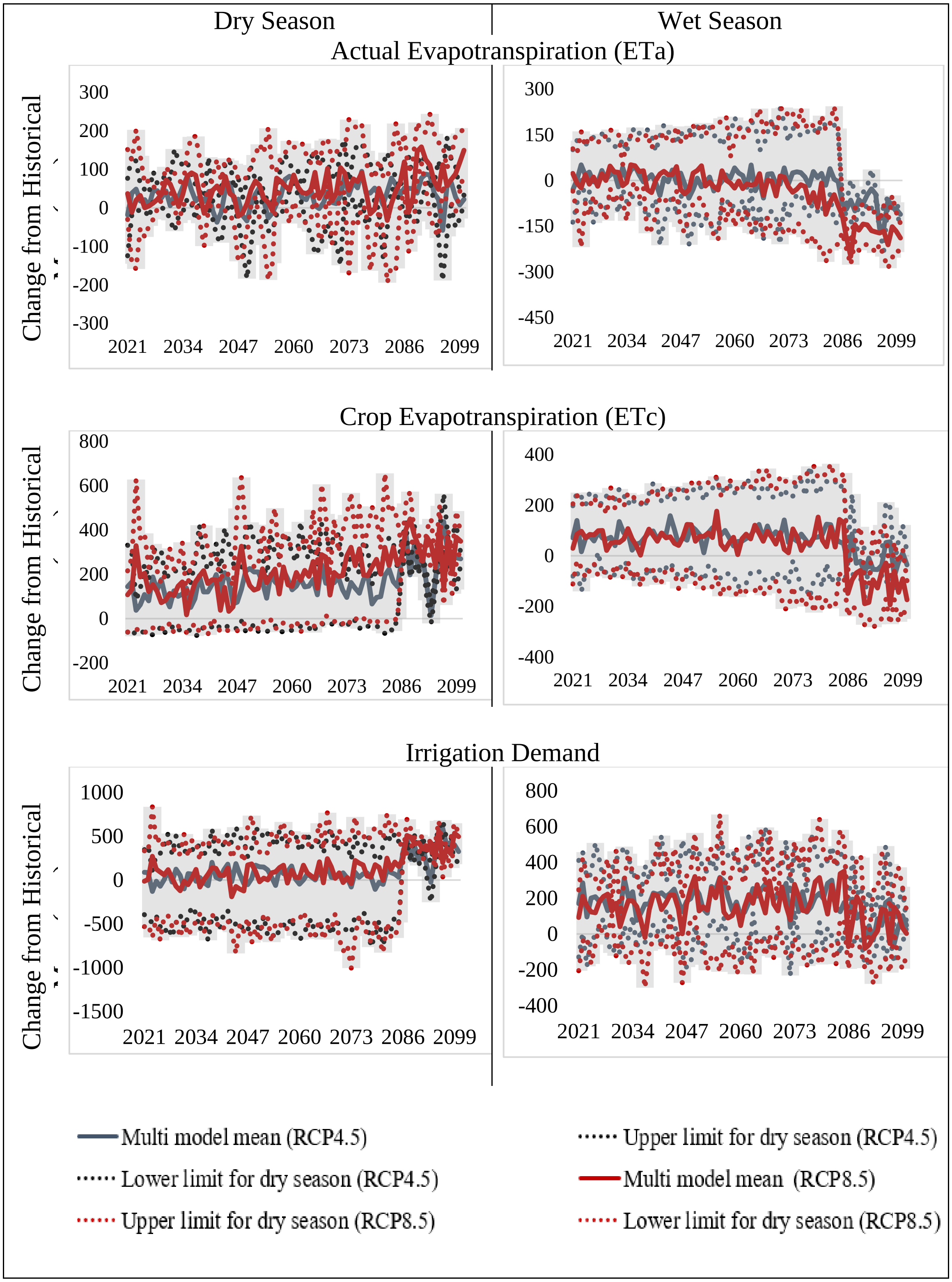


Figure 4-7. Uncertainty plots of actual evapotranspiration (ETa), crop evapotranspiration (ETc), and irrigation demand.

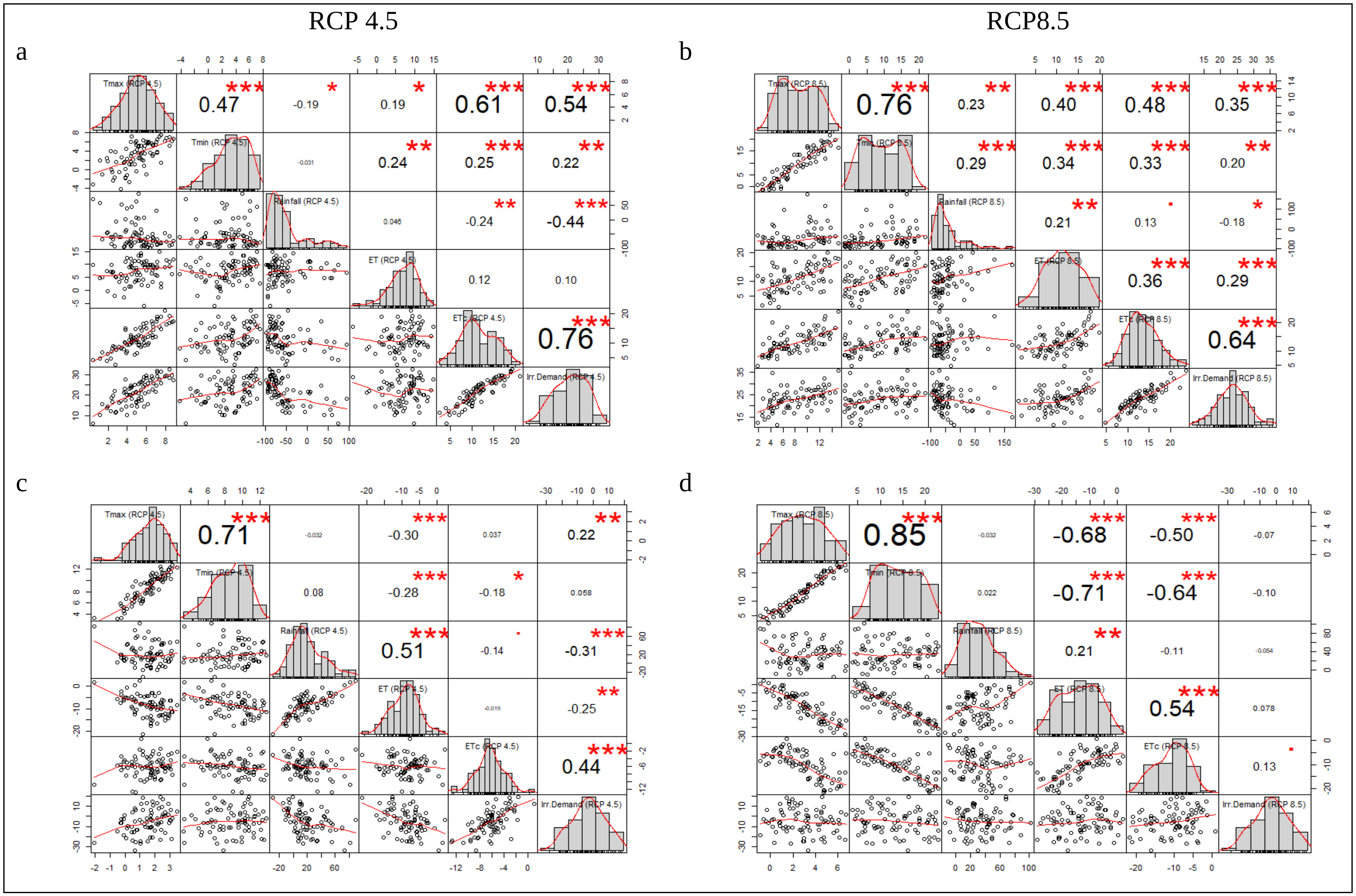


Figure 4-8. Kendall’s tau correlation matrices among different variables for the RCA4 model; (a) and (b) for the dry season, and (c) and (d) for the wet season with p-values 1, · 0.05, *0.01, **0.001, and ***0.

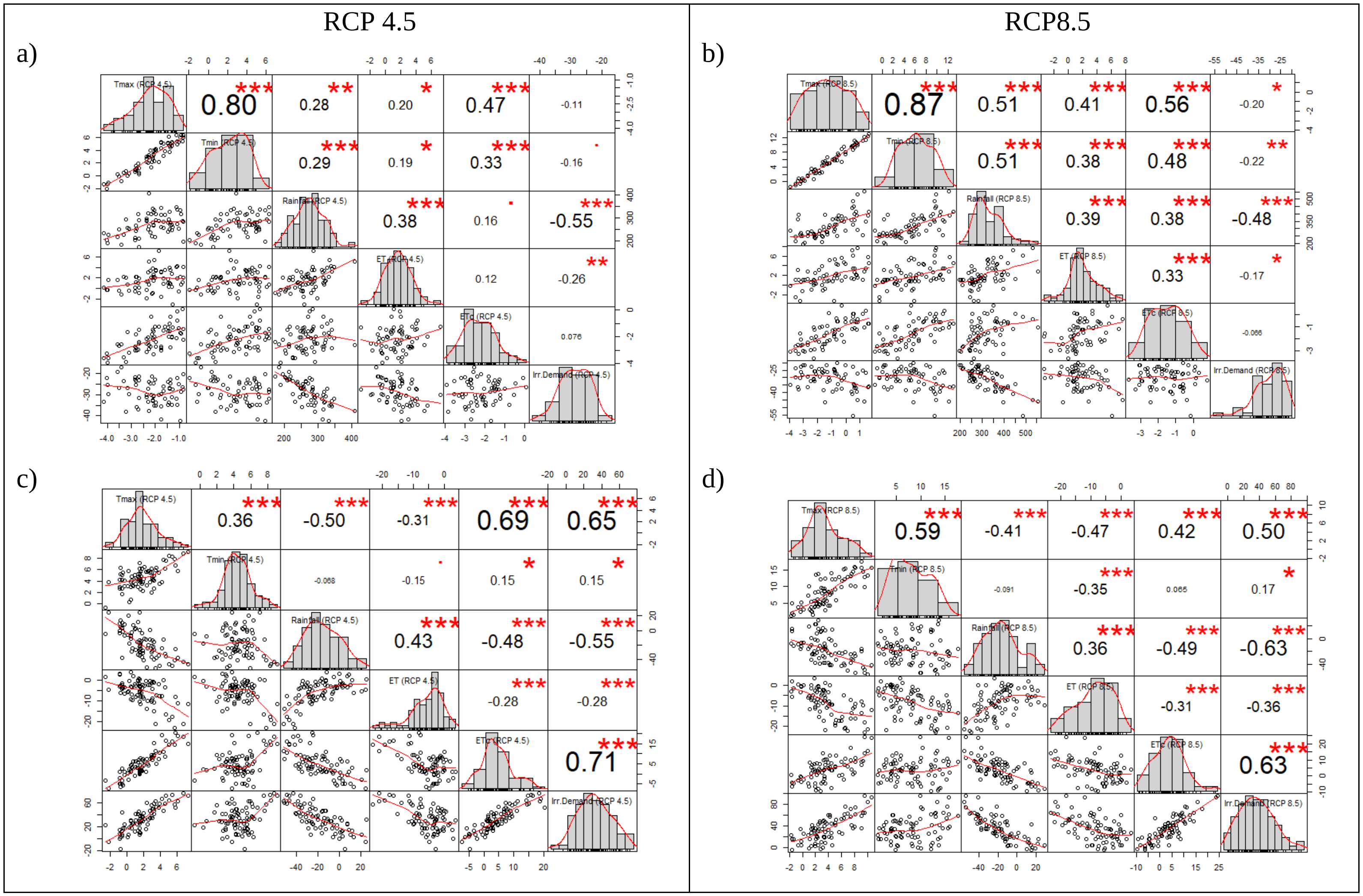


Figure 4-9. Kendall's tau correlation matrix among different variables for the REMO model; (a) and (b) for the dry season, and (c) and (d) for the wet season with p-values 1, · 0.05, *0.01, **0.001, and ***0.

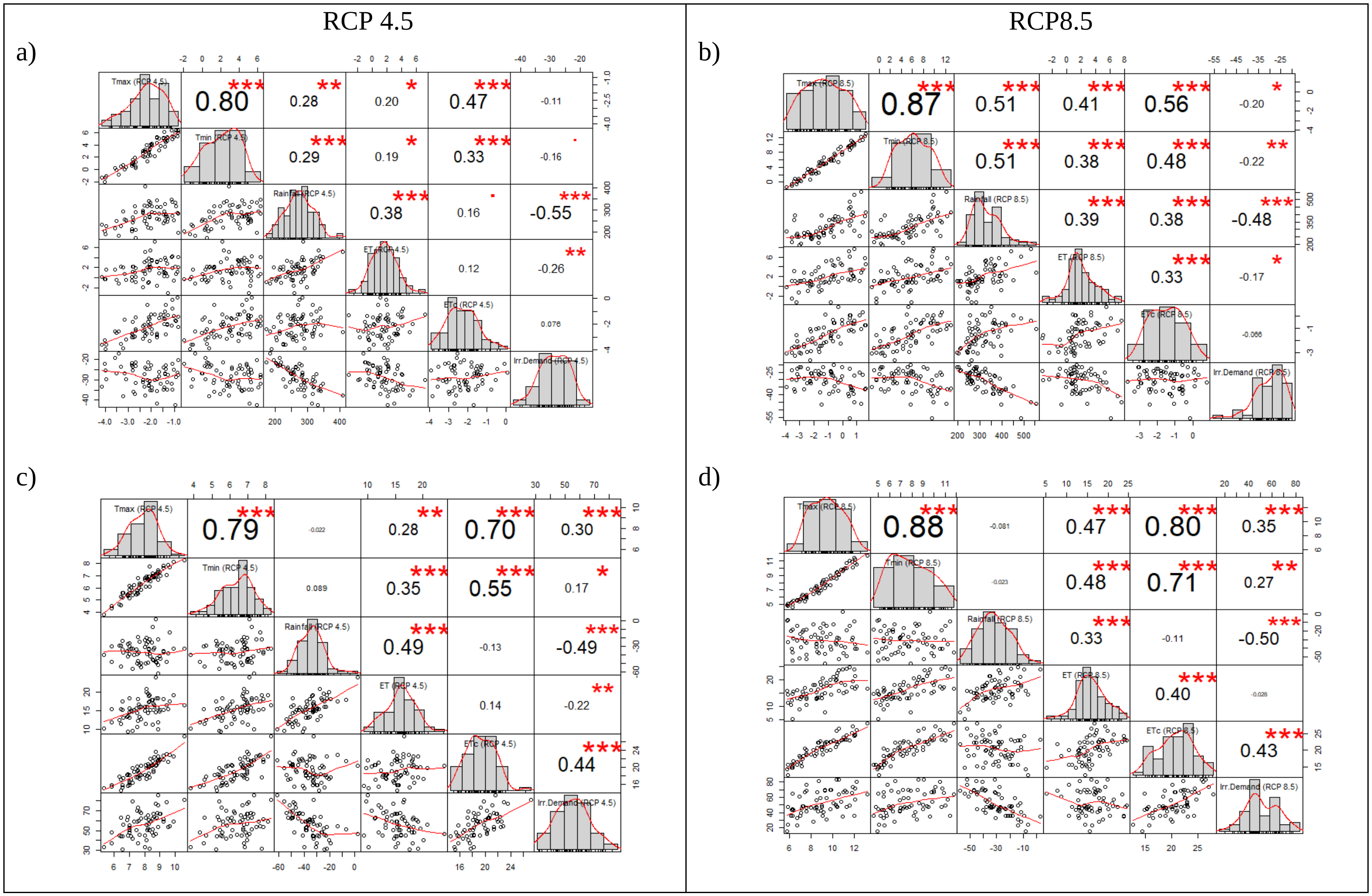


Figure 4-10. Kendall's tau correlation matrix among different variables for the RegCM4 model; (a) and (b) for the dry season, and (c) and (d) for the wet season with p-values 1, ⋅ 0.05, *0.01, **0.001, and ***0.

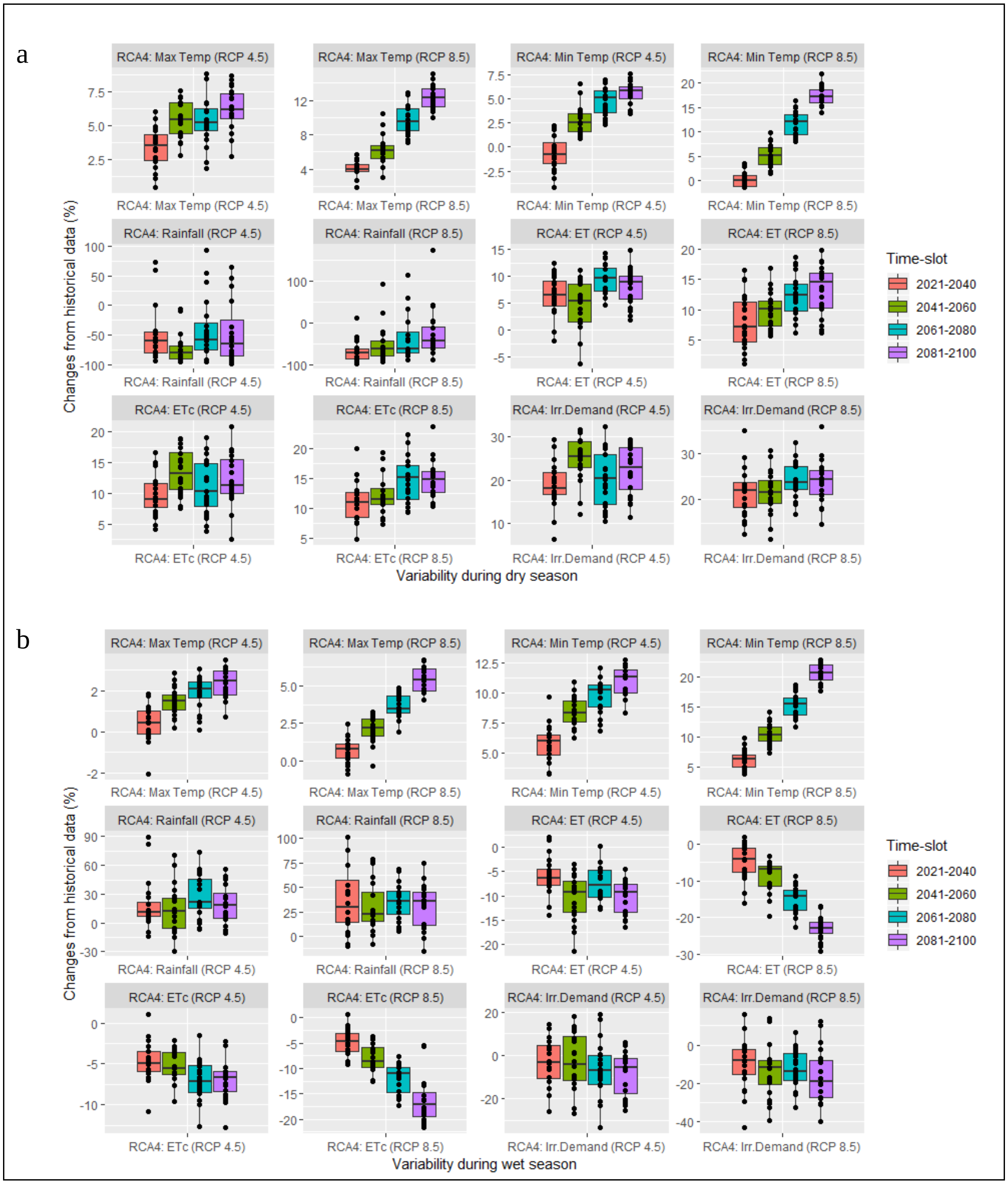


Figure 4-11. Seasonal variation of temperature, rainfall, actual evapotranspiration (ETa), crop evapotranspiration (ETc), and irrigation demand for the RCA4 model considering RCP 4.5 and RCP 8.5 scenarios.

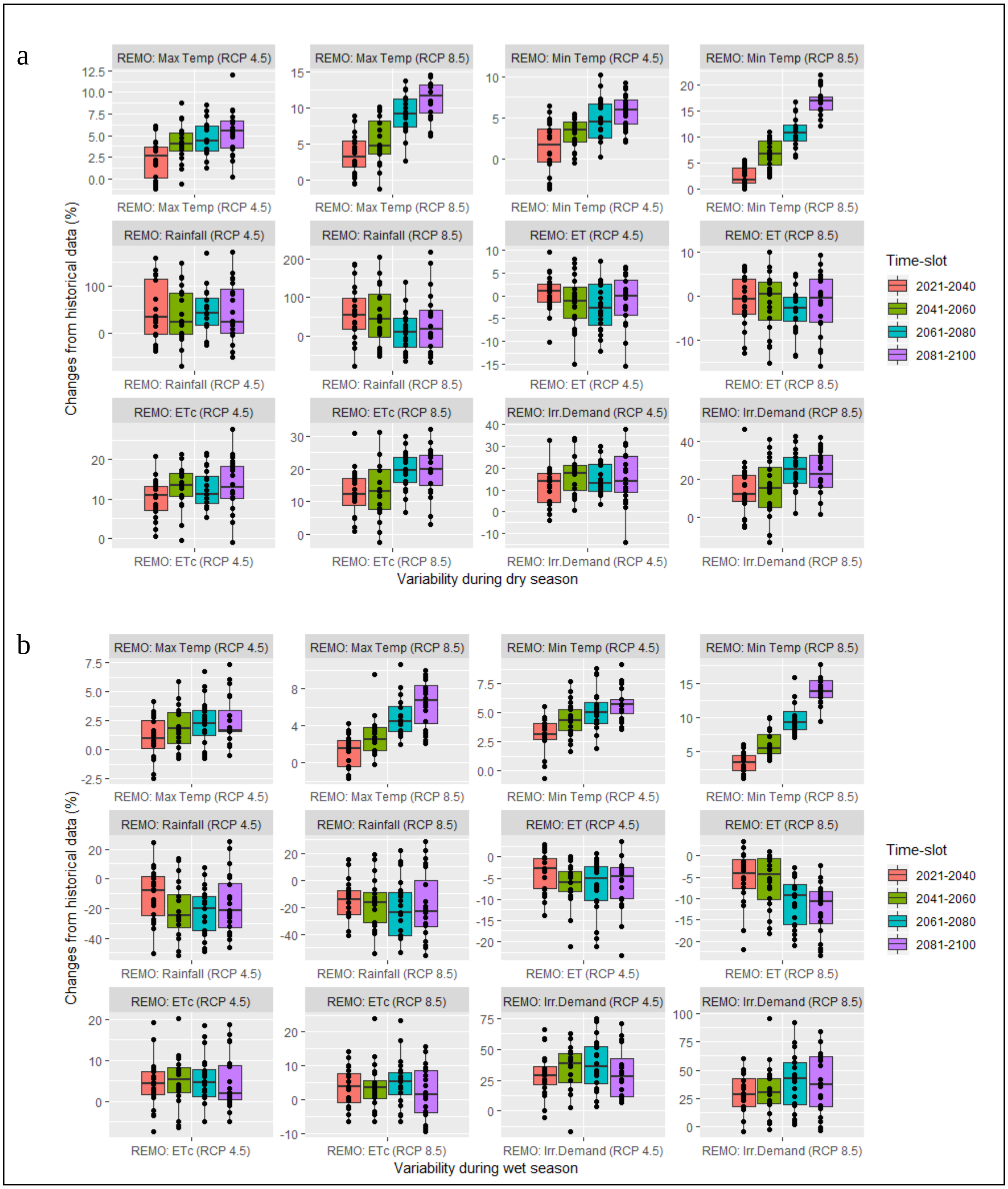


Figure 4-12. Seasonal variation of temperature, rainfall, actual evapotranspiration (ETa), crop evapotranspiration (ETc), and irrigation demand for the REMO model considering RCP 4.5 and RCP 8.5 scenarios.

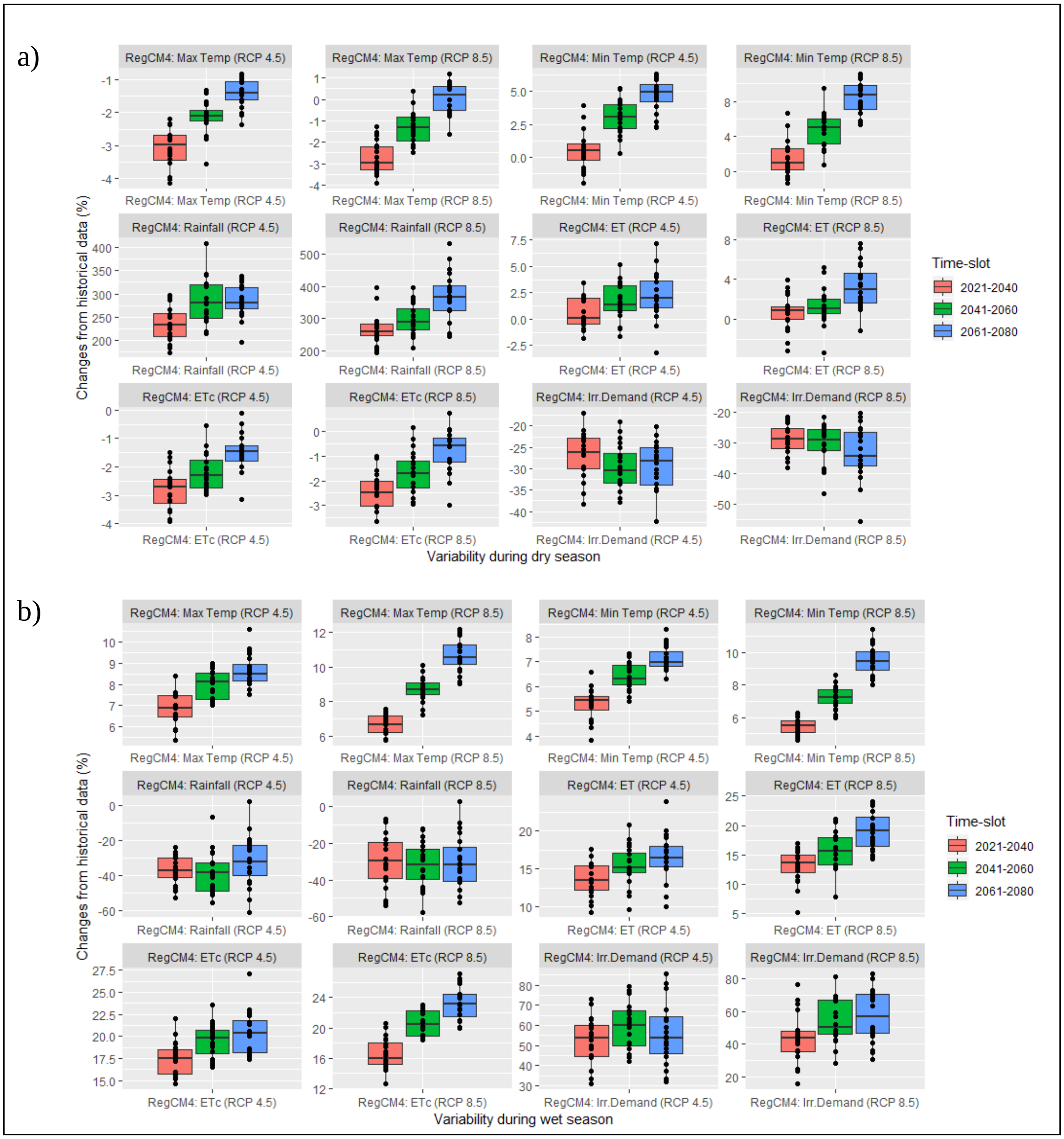


Figure 4-13. Seasonal variation of temperature, rainfall, actual evapotranspiration (ETa), crop evapotranspiration (ETc), and irrigation demand for the RegCM4 model considering RCP 4.5 and RCP 8.5 scenarios.

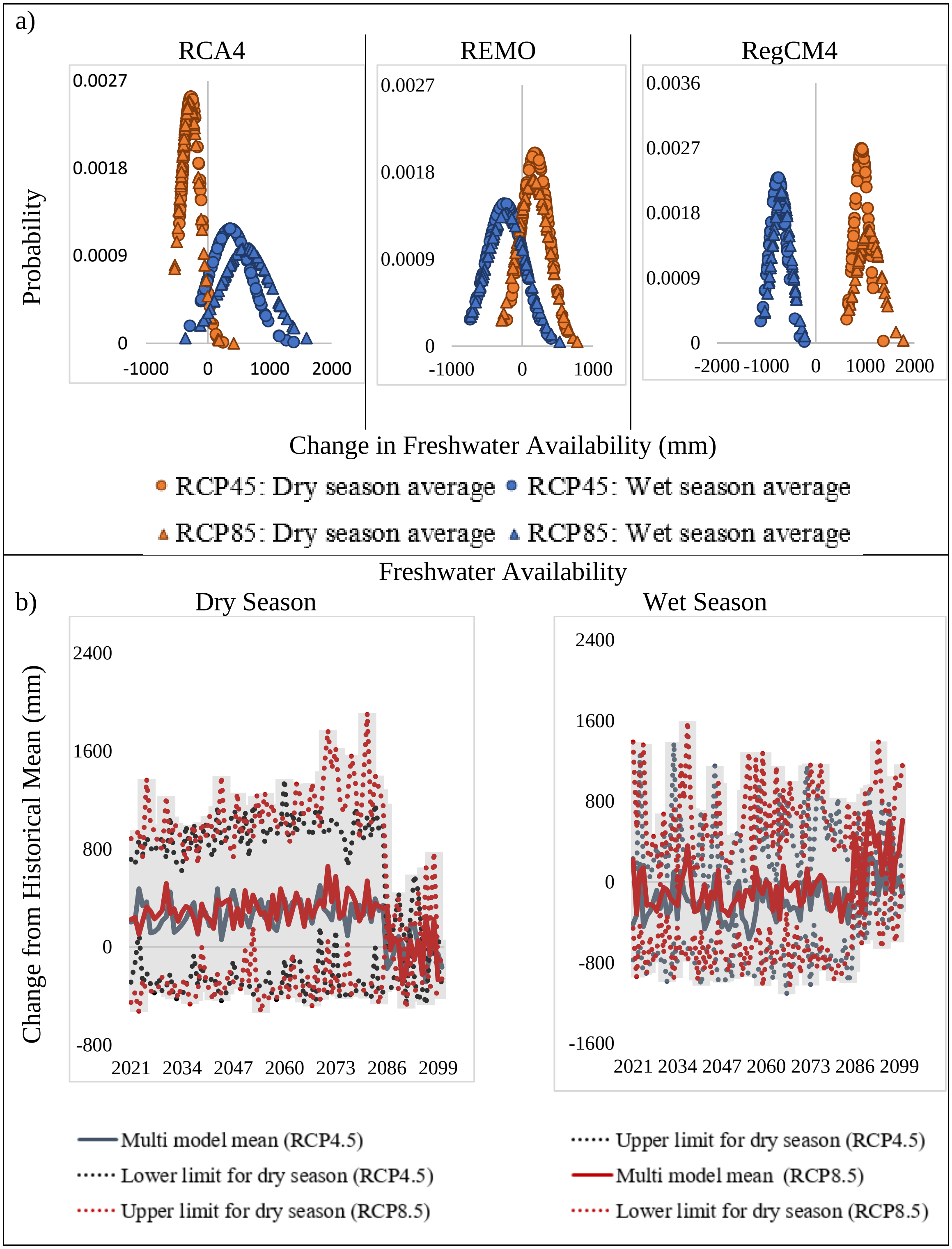


Figure 4-14. Plots showing the probability density function of freshwater availability in (a) and the uncertainty of freshwater availability for regional climate models in (b).

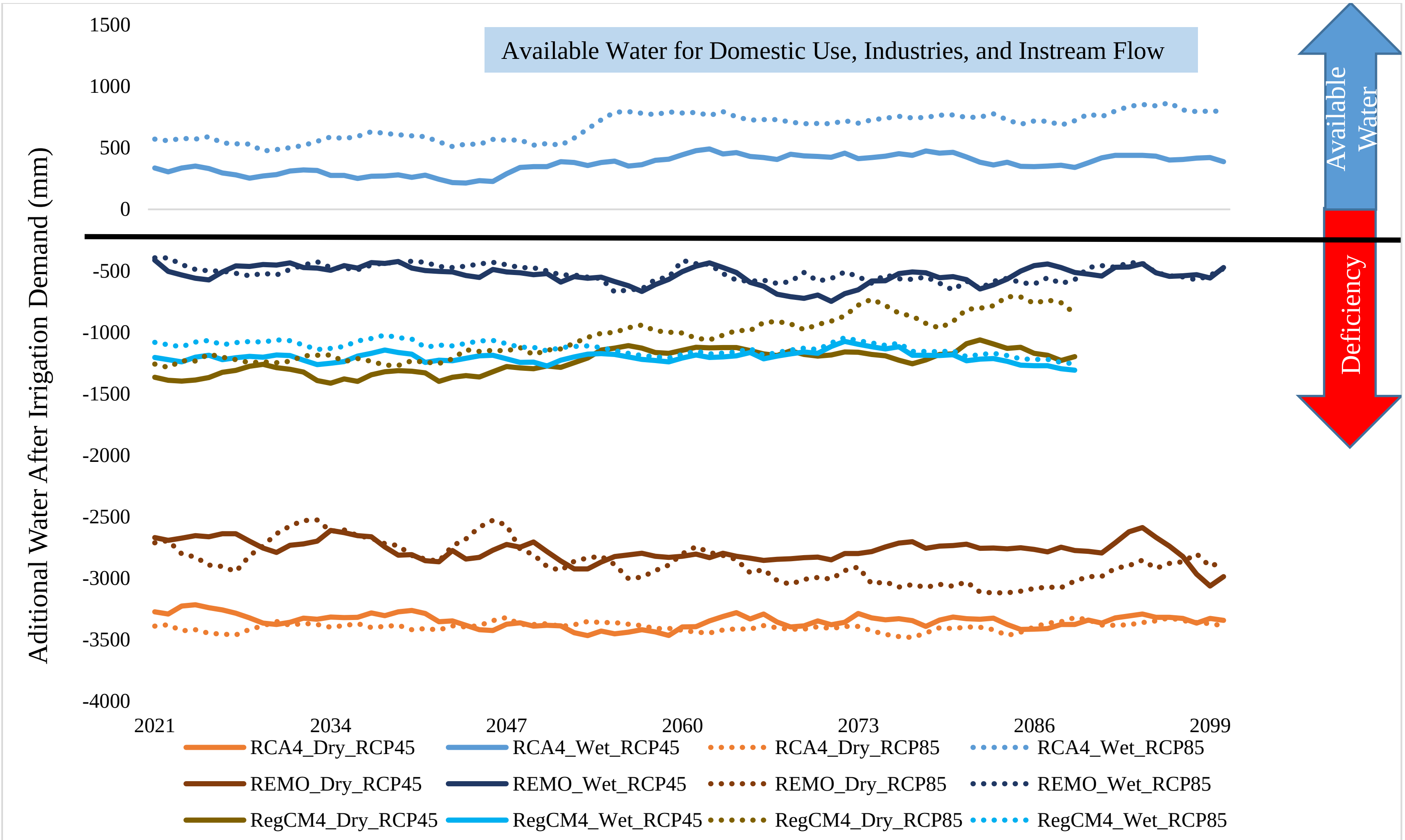


Figure 4-15. Climatic impact on freshwater availability (FWA) after fulfilling the irrigation requirement. Here, FWA is the multi-decadal mean of [(Rainfall-Evapotranspiration) - irrigation demand].

# CHAPTER 5

# SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

## Summary and Conclusions

This dissertation is a case study focusing on the causes of freshwater scarcity in the Ganges Delta of Bangladesh. It is a transboundary rural river basin, located downstream part of the Ganges river. The Ganges Delta is facing water scarcity concerns due to the presence of upstream dams and barrages diverting water. Having knowledge on the existing hydrological conditions and developing possible future scenarios for better water resources management are important to sustain rural livelihood. Understanding the importance of agriculture-driven living in the region is crucial in this assessment. This study summarizes the key concerns necessary to address freshwater scarcity and to sustain agriculture productivity.

Chapter 2 identified the key reasons behind the current changes in surface water hydrology and corresponding impacts on water resources. Human interventions, mainly Farakka Barrage, plays a dominant role in changing the hydrologic features of this region. This barrage not only diverts upstream water but also obstructs sediment flow during the dry season, inducing severe freshwater scarcity and excessive sedimentation problems.  Reduced upstream flow triggers salinity intrusion, loss of agricultural land, and forcing people to migrate from the region. Floods, the common natural disaster in this region, mostly occur due to the drainage congestion rather than overflowing of river water. Though human-induced changes have a severe hydrological impact, climate

variability also poses threats to freshwater availability. Low dry season rainfall, increasing trends of consecutive wet and dry days, cooling and heating degree days, and extreme hot days along with rising temperature and actual evapotranspiration (ETa) pointed the fact that the study area is heading towards an extreme climatic condition. This chapter mostly focused on understanding the existing background information necessary for future water management plans.

Given the devastating changes on surface water hydrology, Chapter 3 addressed interdependency, availability, and accessibility of surface water and groundwater. This study used both in-situ and GRACE data to understand the changes in groundwater. Water demand and withdrawal for agriculture, domestic, and industry sectors were analyzed using field-based data. Low surface water availability causes higher groundwater withdrawal, which is higher than the recharge rate, consequently heading towards an unsustainable condition. These findings help to understand the adequacy of freshwater to meet the primary demand of agriculture, domestic, and industrial sectors. Freshwater availability is under severe constraints considering both quantity and quality aspects.

Chapter 4 predicted the future agricultural water demand considering moderate and extreme carbon emission scenarios. Three regional climate models, along with eight driving global climate models, provided a broad range of uncertainty of future water availability. ETa was measured with high accuracy to understand the total water loss. The previous study by Kim and Kaluarachchi (2017) used existing land cover data into a modified complementary relationship model (Anayah and Kaluarachchi, 2012) and found satisfactory ETa distribution for the USA. This study included climate change

information with the complementary relationship ET model proposed by Kim and Kaluarachchi (2017). Further corrections were made by applying local correction factors to comply with the Ganges Delta of Bangladesh. Addressing uncertainty is another key issue discussed in this chapter, which is an integral part of climate change studies and essential for future water management plans.

The contributions from this dissertation are listed below –

- This study provided information on the key areas which require immediate attention to deal with freshwater scarcity.
- It revealed the causes of ongoing floods, droughts, and water scarcity.
- Freshwater availability was measured considering water supply and demands, seasonal variability, sustainability, and relevant constraints for water security. This study addressed both water quality and quantity of surface and groundwater.
- Climate change information was transformed from regional-scale to local-level (Ganges Delta of Bangladesh).
- Climate change projections were used in the random forest algorithm to predict future land cover data and were incorporated into ETa estimation method. It gives more accurate data on total water loss.
- Agricultural water demand was computed using different climate models and assessed the probable water consumption scenarios.
- The uncertainties were quantified to incorporate it into future water management plans.

This dissertation deals with the practical concerns of freshwater availability for a downstream river basin under a complex geopolitical framework. It quantifies the location and time-specific needs, which are essential to developing appropriate measures. The water-sharing treaty at Farakka Barrage is likely to be renewed in 2027. This study expects to contribute to possible solutions for meeting water requirements at the lower end of the Ganges Delta. Moreover, it can lead to regional integration because the water-relevant problems have similar consequences on both India and Bangladesh parts of Sundarbans. Future economic growth will largely depend on the application of these potential measures. This macro-level study can be helpful for policymakers to disburse funds to the most needed sectors to sustain agriculture.

**Recommendations**

- Quantity, Quality, and timing of available water are the most critical concerns for any water management project
- The basin-wide management approach is needed to deal with freshwater scarcity
- Availability and constraints of both surface and groundwater should be considered
- Climate change is inevitable, and quantifying uncertainties helps to design sustainable solutions.
- Minimizing salinity intrusion, salinity leaching, promoting saline tolerant crops, and irrigation efficiency are some of the urgent issues that need to be considered for agriculture sustainability.
- Although the findings are based on the Ganges Delta of Bangladesh, the solution approaches apply to any delta area.

- Climate Change Impact on Freshwater Availability (FWA)
- The projected climate change at a local level has a noticeable effect on FWA, as shown in Figure 4-14a. REMO and RegCM4 show a mean increase in dry season FWA and a greater increase (≈ 500 mm) for RegCM4 which may be attributed to higher dry season rainfall. Though wet season rainfall is more elevated than in the dry season, a decrease in mean rainfall, along with a reduction in mean ETa, contributes to a reduction in wet season FWA. RCA4 shows the opposite seasonal condition for FWA, namely the reduction of the mean wet season and vice versa. Although the multi-model mean values do not show much temporal variation until 2085, the difference between extreme upper and lower limits is significant (Figure 4-14b), pointing to higher uncertainty in FWA. This is supported by recent studies (Greve et al., 2018; Greve and Seneviratne, 2015), which show climate change can increase the uncertainty range for water availability. It is to be noted that the multi-model mean variation after 2085 does not include data from the RegCM4 model.
- We also investigated additional water availability after satisfying the irrigation demand, which is the largest water use sector (Murshed and Kaluarachchi, 2018) in the lower end of the Ganges Delta. We used a five year moving average of additional water availability to assess whether there is enough water for domestic, industry, and in-stream use. Figure 4-15 shows a serious deficit of water availability for users. Only the RCA4 wet season showed a surplus to fulfill domestic, industry, and in-stream requirements and was higher for RCP 8.5. There are not many differences between the RCP scenarios when considering

these water deficit conditions. This situation highlights the fact that there is an urgent need for increasing irrigation efficiency using various approaches such as changing cropping patterns, shifting planting dates, and effectively organizing water sharing among different stakeholders. Moreover, salinity intrusion can increase in this delta region if we fail to meet the instream water requirement.

**Future works**

- Develop cost-effective mechanisms which will help to minimize freshwater scarcity and therefore sustain agriculture activities.
- Analyze climate indices to understand the extreme climatic patterns considering climate change projections.
- Incorporate salinity into ETa estimation to increase its accuracy, especially for delta areas having salinity intrusion problems.

# APPENDICES

# Appendix A: Permission to Reprint an Article

from: **Sonia Murshed** <sonia.murshed@aggiemail.usu.edu>
to: Homin KIM <kimhomin83@gmail.com>
date: Nov 10, 2019, 12:40 PM
subject: Permission to reprint a manuscript

Hello Homin,

Hope you are doing fine.

Our article, Effects of Hydro-Climatic Conditions on Agricultural Water Demand in The Ganges Delta of Bangladesh, in which you are a coauthor, is one of my PhD dissertation chapters. As per USU guidelines, I would like to ask for your permission to reprint it as a chapter in my dissertation. This permission request along with your response will appear as an appendix in my dissertation.

Regards,
Sonia Binte Murshed

from: **Homin Kim** <kimhomin83@gmail.com>
to: Sonia Murshed <sonia.murshed@aggiemail.usu.edu>
date: Nov 11, 2019, 6:23 PM
subject: Re: Permission to reprint a manuscript

Dear Sonia,

I hope you are well too. Here is my note for you.

This is my formal permission in accordance with USU guideline to reprint the article 'Effects of Hydro-Climatic Conditions on Agricultural Water Demand in The Ganges Delta of Bangladesh' as a chapter of your dissertation.

Regards,

Homin Kim

## Appendix B: Curriculum Vitae

**SONIA BINTE MURSHED**

PhD candidate, June 2019
Department of Civil and Environmental Engineering
Utah State University
4100 Old Main Hill, Logan, UT 84322-4100, USA
Email: sonia.murshed@aggiemail.usu.edu, soniamurshed@gmail.com

### EDUCATION

**PhD (Fall, 2014 - present),** Department of Civil and Environmental Engineering, Utah State University
Dissertation title: Hydro-Climatic Changes and Corresponding Impacts on Agricultural Water Demand in The Ganges Delta of Bangladesh
Advisor: Dr. Kaluarachchi, Jagath J.

**M.Sc. (September 2008)** in Water Resources Development, Bangladesh University of Engineering and Technology
Thesis title: Management of Conflicts between Irrigation and Fisheries in Siapagla FCD (Flood Control and Drainage) Project
Advisor: Dr. Khan, Shah Alam

**B.Sc. (November 2004)** in Civil Engineering, Bangladesh University of Engineering and Technology
Thesis title: The Effect of Sand Bed Depth on Filter Media of Slow Sand Filter
Advisor: Dr. Ahmed, Farooque

### PROFESSIONAL EXPERIENCE

**Graduate Assistant** (August, 2014-July, 2019), Department of Civil and Environmental Engineering, Utah State University, Logan, Utah, USA

**Assistant Professor** (October 10, 2012 to present, on study leave from July 2014 for pursuing PhD), Institute of Water and Flood Management, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh

**Lecturer** (June 30, 2009 to October 09, 2012), Institute of Water and Flood Management, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh

**Executive Engineer** (December 2005 - December 2006), HARB Trade International Limited, Dhaka, Bangladesh

**Co-ordination Engineer** (January 2005 - August 2005), Nagar Design & Developments Ltd. Dhaka, Bangladesh

## AWARDS

**Travel and Data Purchase Grant** for Ph.D. work provided by the International Water Management Institute, Sri Lanka under the research project "The Gangetic Aquifer Management for Ecosystem Services," 2014-2015

**Best Paper Award for Young Professionals**: International Conference on Water Resources Policy in South Asia, December 17-20, 2008, Colombo, Sri Lanka

**SAWA (South Asian Water) Fellowship**: Awarded by Crossing Boundaries (CB) Project, funded by Dutch Government., IWFM, BUET for Oct 2006- Apr 2008.

**Technical Scholarship**: Awarded by BUET for 1998-2004.

## RESEARCH INTERESTS

Hydrology, Eco-hydrology, Integrated Water Resources Management, Hydro-climatology, Transboundary water conflicts

## RESEARCH PROJECTS

**Increasing the Resilience of Agricultural and Aquaculture Systems in the Coastal Areas of the Ganges Delta** [Component G4: Assessment of Impact of Anticipated External Drivers on Water Resources of Coastal Zone] (June 2011- June 2014, was involved after November 2012)
Investigators: Shah Alam Khan, AKM Saiful Islam and Sonia Binte Murshed
Worked as: Co-Investigator (CI)
Organization: CGIAR-CPWF

**Review of Warning System for Climatic Disasters in Bangladesh** (June 2011- August 2013)
Investigators: Sonia Binte Murshed, Shah Alam Khan and AKM Saiful Islam
Worked as: Principal Investigator (PI)
Organization: Ministry of Environment and Forestry, Dhaka, Bangladesh

**High-resolution Regional Climate Change Information for Bangladesh to inform Impacts Assessments, Vulnerability indicators and Adaptation Policies** (July 2011-December 2012)
Investigators: Akm Saiful Islam, M. Asad Hussain, Sonia Binte Murshed
Worked as: Co-Investigator (CI)
Organization: IWFM, BUET, Dhaka, Bangladesh and Met Office, UK

**Impact of Climate Change on Rainfall Intensity in Bangladesh** (November 2010-December,2012)
Investigators: AKM Saiful Islam, Sonia Binte Murshed and Shah Alam Khan
Worked as: Co-Investigator (CI)
Organization: IWFM, BUET, Dhaka, Bangladesh

## PUBLICATION:

**Journal**:

Murshed, S. B., Kim, H. and Kaluarachchi, J. J. (2019) "Effects of Hydro-Climatic Conditions on Agricultural Water Demand in the Ganges Delta of Bangladesh, Agricultural Water Management, Under Review.

Murshed, S. B., Rahman, M. R. and Kaluarachchi, J. J. (2019) "Changes in Hydrology of the Ganges Delta of Bangladesh and Corresponding Impacts on Water Resources," Journal of the American Water Resources Association, JAWRA featured Collection: Climate Change Solutions.

Murshed, S. B. and Kaluarachchi, J. J. (2018) "Scarcity of Fresh Water Resources in the Ganges Delta of Bangladesh," Water Security, volumes 4-5, pp 8-18, Science Direct. https://doi.org/10.1016/j.wasec.2018.11.002

Nowreen S, Murshed S.B., Islam A.S, Bhaskaran B, Hasan MA (2014), "Changes of Rainfall Extremes around the Haor Basin Areas of Bangladesh using Multi-member Ensemble RCM," Theoretical and Applied Climatology 119 (1-2), Springer, Pages 363-377; doi:10.1007/s00704- 014-1101-7.

Nowreen,S., Murshed, S.B., Islam, A.S., Hasan, M.A. and Sarker, T.K. (2012), "An indicator of Climate Change in the South West Region of Bangladesh", The International Journal of Climate Change: Impacts and Responses" Volume 4, Issue 3, Pages 47-60, 2012, (ISSN: 1835-7156).

Murshed, S.B., and Khan, M.S. (2009), "Water Use Conflict between Agriculture and Fisheries in a Selected Water Resources Development Project in Bangladesh". SAWAS 1 (2):159-183, 2009, Volume 1, Issue 2

**Proceedings:**

Murshed, S.B., Nowreen, S., Islam, A.S., Hasan, M.A. and Sarker, T.K., "Change of Extreme Precipitation Indices for the Eight Hydrological Regions of Bangladesh" International Conference on Climate Change Impact and Adaptation (I3CIA-2013), Nov 14-16, 2013, DUET, Gazipur, Bangladesh

Nowreen,S., Murshed, S.B., Islam, A.S., Bhaskaran, B., "Change of Future Climate Extremes for the Haor Basin Area of Bangladesh." Proceedings of the 4th International Conference on Water and Flood Management (ICWFM 2013), 4-5 October 2013, BUET, Dhaka, Bangladesh Volume 2, pp. 545 -556, BUET, (ISBN: 978-984-33-2298-2).

Murshed, S.B., Islam, A.S. and Khan, M.S. (2011) "Impact of Climate Change on Rainfall Intensity in Bangladesh." Proceedings of the 3rd International Conference on Water and Flood Management (ICWFM 2011), 8-10 January 2011, Dhaka, Bangladesh, Volume 2, pp.881-890 (ISBN: 978-984-33-2298-2).

Islam, A.S., Bhaskaran, B., Arifin, S., Murshed, S.B., Mukharjee, N. and Hossain, B.M.T. (2011) "Domain Size Experiment using PRECIS Regional Climate Model for Bangladesh." Proceedings of the 3rd International Conference on Water and Flood Management (ICWFM 2011), 8-10 January 2011, Dhaka, Bangladesh, Vol.-2, pp. 891-898 (ISBN: 978-984-33-2298-2).

**Presentations:**

Murshed, S. B. and Kaluarachchi, J. J. (2019) "Climate impacts on Drought in the Ganges Delta in Bangladesh", 2019 UCOWR Annual Conference, June 11 -13, 2019, Snowbird, Salt Lake City, Utah, USA. (Oral)

Murshed, S. B., Kim, H. and Kaluarachchi, J. J. (2019) "Evapotranspiration under Climate Change in the Ganges Delta of Bangladesh", 2019 Spring Runoff Conference: Water Challenges in the West, March 26, 2019, Utah State University, Logan, Utah, USA. (Poster)

Murshed, S. B. and Kaluarachchi, J. J. (2018) "Climate Impacts on Agricultural Water Demand in the Ganges Delta of Bangladesh", 2018 AGU Fall Meeting, December 10 -14, 2018, Washington DC, USA. (Poster)

Murshed, S. B. and Kaluarachchi, J. J. (2018) "Linkage of Hydro-Climatological Variables to Flood and Drought in the Ganges Delta of Bangladesh," The Student Research Symposium April 12, 2018, Utah State University, Logan, USA. (Poster)

Murshed, S. B. and Kaluarachchi, J. J. (2018) "Groundwater Sustainability in the Ganges Delta of Bangladesh," 2018 Spring Runoff Conference: Monitoring and Managing Water for All, March 27, 2018, Utah State University, Logan, Utah, USA. (Poster)

Murshed, S. B. and Kaluarachchi, J. J. (2017) "Scarcity of freshwater resources in the Ganges Delta of Bangladesh", 2017 AGU Fall Meeting, December 11 -15, 2017, New Orleans, Louisiana, USA. (Poster)

Murshed, S. B. and Kaluarachchi, J. J. (2017) “Vulnerability of Fresh Water Resources in the Ganges Delta of Bangladesh”, 2017 AWRA Summer Specialty Conference, Climate Change Solutions: Collaborative Science, Policy and Planning for Sustainable Water Management, June 25-28, 2017, Sheraton Tysons Hotel, Tysons, VA, USA. (Oral)

Murshed, S. B. and Kaluarachchi, J. J. (2017) “Instream Water Availability in the Sundarbans Mangrove Ecosystem of Bangladesh”, Spring Runoff Conference: Data-driven water management for an uncertain future, March 28-29, 2017, Utah State University, Logan, Utah, USA. (Poster)

Murshed, S.B., Khan, M.S.A. and Islam, A.S. (2012) “Adaptation Strategies of Urban Drainage System in Dhaka City” International Conference on Climate Adaptation, May 29-31, 2012, University of Arizona, Arizona, USA. (Oral)

Murshed, S.B. and Khan, M.S.A. (2008), "Water Use Conflict between Agriculture and Fisheries in a Selected Water Resources Development Project in Bangladesh” International Conference on Water Resources Policy in South Asia, December 17-20, Colombo, Sri Lanka. (Achieved best paper award for young professionals). (Oral)

**Book:**

Murshed, S.B., and Khan, M.S.A. (2008), “Water Use Conflict between Agriculture and Fisheries in Bangladesh”, LAP LAMBERT Academic Publishing, Germany, 2013, pages 148 (ISBN-13:978-3-659-43821-9).

## SELECTED PROFESSIONAL WORKSHOP/ SEMINAR / TRAINING:

Workshop on **Pangeo: Scalable Geoscience Tools in Python—Xarray, Dask, and Jupyter** at 2018 AGU Fall meeting
Date: Dec 12, 2018
Venue: Grand Hyatt, Washington DC, USA

Workshop on **Multitemporal Supervised Classification Using Google Earth Engine** at 2018 AGU Fall meeting
Date: Dec 10, 2018
Venue: Grand Hyatt, Washington DC, USA

Workshop on **Satellite: Using Python and modern tools for research and analysis of satellite data products** at 2018 AGU Fall meeting
Date: Dec 9, 2018
Venue: Grand Hyatt, Washington DC, USA

Workshop on **Informed Risk Management** (Using GoldSim to Support Integrated Water Resources Management) at 2017 AWRA Summer Specialty Conference

Date: June 25, 2017
Venue: Sheraton Tysons Hotel, VA, USA

Knowledge Sharing Seminar on "**Water and Waste: Excreta Does Matter**" organized by Centre for Science and Environment and Bangladesh Institute of Planners
Date: September 4, 2013
Venue: Planners' Tower, Dhaka

Bangladesh country level dialogue meeting on "**Transnational Policy Dialogue for Improved Water Governance of Brahmaputra River**" organized by Centre for Science and Environment and Bangladesh Institute of Planners
Date: 21 August, 2013
Venue: IWFM, BUET, Dhaka

Training Program on "**Space Technology for Flood Hazard Mapping, Flood Forecast and Rapid Mapping in Bangladesh**" Jointly organized by Department of Disaster Management (DDM) and UN-SPIDER Beijing Office in collaboration with SPARRSO and Comprehensive Disaster Management Programme (CDMP II) Date: May 12-16, 2013
Venue: Computer Lab (Level 4), SPARRSO, Agargaon, Dhaka,
Bangladesh

Training Workshop on "**Urban Drainage Modeling for Coastal Towns of Bangladesh Considering Climate Change**"
Date: April 19-21, 2013
Venue: IWFM, BUET

Final workshop on "**High-resolution Regional Climate Change Information for Bangladesh to inform Impacts Assessments, Vulnerability indicators and Adaptation Policies**"
Organized by IWFM, BUET and Met office, United Kingdom with financial support from the Department for International Development (DFID) of the UK
Date: January 27, 2013
Venue: IWFM, BUET

**Adaptation to Changing Water Resources Availability in Northern India with respect to Himalayan Glacier Retreat and Changing Monsoon Pattern**
HighNoon Spring School of Collaborative project of EU
Organized by Indian Institute of Technology (IITD), Delhi, India
Date: April 2-6, 2012
Venue: Premises of IITD

**Triangulation Workshop for Selection and Prioritization of External Drivers of Change on Water Resources of the Coastal Zone**
Organized by Institute of Water Modelling (IWM), Dhaka, Bangladesh and Partners of

Project G4 (Assessment of the Impact of Anticipated External Drivers of Change on Water Resources of the Coastal Zone)
Date: March 20, 2012
Venue: BRAC Centre Inn, 75 Mohakhali, Dhaka-1212, Bangladesh

Stakeholder Workshop on "**High-resolution Regional Climate Change Information for Bangladesh to inform Impacts Assessments, Vulnerability indicators and Adaptation Policies.**"
Organized by IWFM, BUET and Met office, United Kingdom with financial support from the Department for International Development (DFID) of the UK
Date: March 8, 2012
Venue: IWFM, BUET

**Statistical Downscaling Model (SDSM)** Workshop
Jointly organized by Loughborough University, BRAC University and British Council
Date: October 26-27, 2011
Venue: BRAC University, Dhaka, Bangladesh

**Space-based Information for Disaster Preparedness and Risk Assessment**
Jointly organized by CDMP II, DMRD, MoFDM and ICIMOD
Date: April 09-13, 2011
Venue: Bangladesh Computer Council, Agargaon, Dhaka

**Flood Hazard Mapping and Socioeconomic Vulnerability**
Organized by Institute of Water and Flood Management (IWFM) of Bangladesh University of Engineering and Technology, (BUET) and The International Centre for Integrated Mountain Development, ICIMOD in association with Southampton University, United Kingdom and Centre for Geoinformatics, Z_GIS, University of Salzburg, Austria.
Date: April 27 - May 1, 2010
Venue: BRAC-CDM, Gazipur Dhaka

Training Workshop on **"Regional Climate Modeling using PRECIS.**"
Organized by Climate Change Study Cell (CCSC) of Bangladesh University of Engineering and Technology (BUET) and Met Office, United Kingdom with financial support from the Department for International Development (DFID) of the UK
Date: February 14 -18, 2010
Venue: IWFM, BUET

Regional Workshop on **"Climate Change and Water Resources: IWRM as a Tool to Cope with Changing Condition of the Climate System"**
Organized by CapNet South Asia in association with CapNet global
Date: January 10 -14, 2010
Venue: BRAC-CDM, Gazipur Dhaka