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Climate Change and It's Impact on Ground Water Resources in Northwest Banglades

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Climate Change and It's Impact on Ground Water Resources in Northwest Bangladesh

M. Phil Thesis

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A THESIS

Submitted to the Department of Applied Physics and Electronic Engineering Faculty of Engineering of the University of Rajshahi for the degree of Master of Philosophy (M.Phil)

By

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May, 2011

Dedicated to my elder Brother

Whose Blessing comes to me from heart......

Declaration

I hereby declare that this thesis entitled "Climate Change and It's Impact on Ground Water Resources in Northwest Bangladesh" is embodied my original research work prepared for the degree of Master of philosophy at the Department of Applied Physics and Electronic Engineering , Faculty of Engineering, University of Rajshahi. This work contains no material, which has been accepted for the award of any other degree or diploma in any University. To the best of my knowledge and belief, this thesis contains no material previous published by another person, except where due acknowledgement has been made in the text.

(Md. Moshiur Rahman)

Date: May 2011

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ফলিত পদার্থ বিজ্ঞান ও ইলেকট্রনিক
ইঞ্জিনিয়ারিং বিভাগ
রাজশাহী বিশ্ববিদ্যালয়
রাজশাহী-৬২০৫

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CERTIFICATE

This is to certify that Md. Moshiur Rahman, has carried out a research work entitled *"Climate Change and It's Impact on Ground Water Resources in Northwest Bangladesh"* for the fulfillment of the degree of Master of Philosophy (M. Phil). He has worked under our joint guidance and supervision and has fulfilled the requirements for the submission of this thesis. The results presented in this thesis have not been submitted in part or full to any other University or Institute for award of any degree/diploma.

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ABSTRACT

Northwest region of Bangladesh is one of the most water stressed region of the country. All the rivers and cannels of the area dry up during the dry season and make the people completely dependent on groundwater. Cultivation of dry season rice which is the lifeline of the livelihood in the most part of the region completely relies of groundwater supply. Scarcity of groundwater for irrigation during the recent years has hampered the agricultural production in the area. Prolonged absence of groundwater within the operating range of shallow tube-wells during the dry season is a growing concern in the area. It is anticipated that climate change will aggravate the situation in near future. A study has been carried out in the present research to identify the causes of groundwater scarcity, estimate the groundwater demand, project the future climate, and to assess the impacts of climate change on groundwater scarcity in the northwest districts of Bangladesh. Long-term groundwater hydrographs are analyzed and correlated with standardized precipitation index to identify the probable causes of groundwater scarcity in the region. Climate models are run with IPCC B2 SRES scenario to project the future change of climate in the region. The projected climatic parameters are then used to estimate the change in irrigation demand in the context of climate change. Finally, the impacts of changing irrigation demand on groundwater level are assessed. The study revealed that recurrent droughts, rapid expansion of groundwater based irrigation and cross-boundary anthropogenic interventions are the main causes of groundwater scarcity in the area. The climate models project an average increase of temperature and rainfall in the region. This will cause an increase of water requirement for land preparation, evapotranspiration and effective precipitation during irrigation period. However, there will be no appreciable change in overall irrigation water requirement as the irrigation period will be substantially shortened by the increased temperature. The study revealed that the climate change will cause an increase in daily use of water for irrigation in the end of this century. As groundwater is the main source of irrigation, higher abstraction rate of groundwater for irrigation will cause a negative impact on groundwater level which in

turn will negatively affect the prevailing situation of groundwater scarcity in the area during the dry season.

Climate Change and It's Impact on Ground Water Resources in Northwest Bangladesh

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LIST OF SYMBOLS AND ELABORATIONS

ASTER	Advanced Space-borne Thermal Emission and Reflection Radiometer.
BADC	Bangladesh Agricultural Development Corporation.
BBS	Bangladesh Bureau of Statistics.
BMD	Bangladesh Meteorological Department.
BMDA	Barind Multi-purpose Development Authorities.
BWDB	Bangladesh Water Development Board.
CCSAP	Climate Change Strategy and Action Plan.
CD	Cumulative Deficit.
GIS	Geographical Information System.
GCM	General Circulation Models.
HYV	High-Yield Variety.
IPCC	Intergovernmental Panel for Climate Change.
LAI	Leaf Area Index.
MAGICC	Models for the Assessment of Greenhouse-gas Induced Climate Change.
MHC	Moisture Holding Capacity.
MPO	Master Planning Organization.
OECD	Organization for Economic Co-operation and Development.
P	Precipitation.
PE	Potential Evapotranspiration.
RMSE	Root Mean Squared Error.
SPI	Standardized Precipitation Index.

SRDI	Soil Research Development Institute.
ST	Soil Moisture Storage.
SWIR	Short Wave InfraRed.
TIR	Thermal InfraRed.
UNDP	United Nation Development Program.
WRPO	Water Resources Planning Organization.

Chapter- 1

INTRODUCTION

1.1 Introduction

Groundwater is the main source of irrigation in the northwest districts of Bangladesh. About seventy-five percent water for irrigation in the region comes from groundwater (Bari and Anwar, 2000). According to a recent BADC survey (Bangladesh Agricultural Development Corporation, 2002); the contribution of surface water and groundwater sources to the total irrigated agriculture has been changed drastically in the last two decades in Bangladesh. The contribution of groundwater has increased from 41% in 1982-83 to 75% in 2001-2002 and the surface water use has been declined from 59% to less than 25% over the same period. The ratio of groundwater to surface water use is much higher in northwestern districts of Bangladesh compared to other parts of the country. Cross-country anthropogenic activities especially withdrawal of huge amount of water from the Indian part of River Ganges caused a severe negative impact on water resources and eco-systems in the region. All the rivers and cannels of the area dry out during the dry season and make the people completely depended on groundwater. The area is also highly prone to droughts because of high rainfall variability (Paul, 1998; Shahid, 2008; Shahid and Behrawan, 2008). Groundwater becomes the only source of water during drought period in the region. The national water policy of Bangladesh government also encouraged groundwater development for irrigation both in the public and the private sectors (International Engineering Company, 1964; MPO 1987, 1991; WRPO, 2004). Government poverty alleviation program through the introduction of special groundwater-based irrigation project in the area named as Barind Multi-purpose Development Authorities (BMDA) has accelerated the use of groundwater.

After the introduction of BMDA in 1986, six thousand deep tube wells are installed in the area. In addition to that 65, 815 shallow tube wells are also installed in private sectors by the year of 2000 for the exploitation of groundwater for irrigation. Number of shallow and deep tube-wells used for irrigation in Bangladesh during the time period of 1983-2000 is shown Figure1.1. The figure shows a rapid increase of shallow tube-wells or higher use of groundwater from shallow aquifers in the country from 1995.

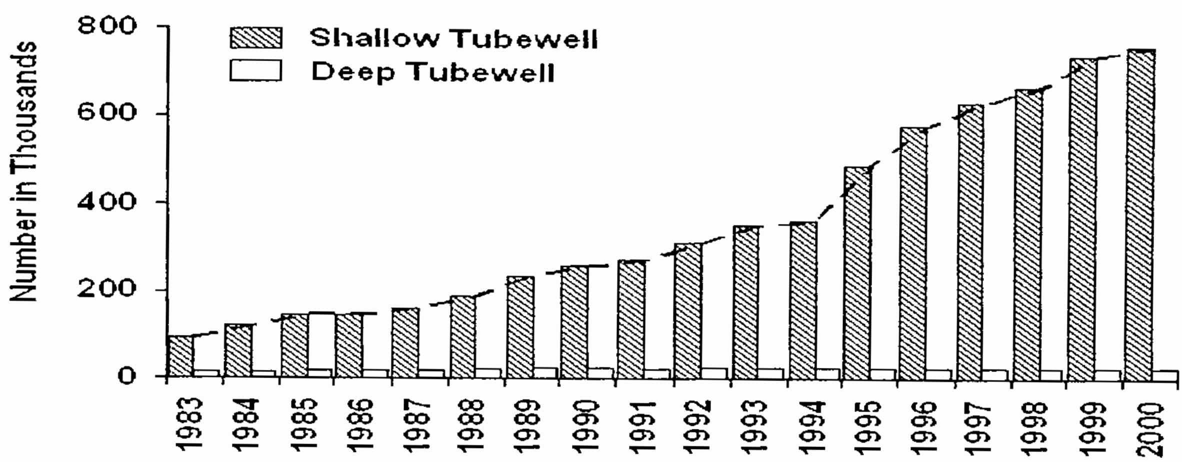


Fig 1.1: Number of shallow and deep tube-wells used for irrigation in Bangladesh during the time period of 1983-2000.

Most of the hydro-geologists working in the area believe that the geology of the area does not support for large-scale exploitation of groundwater (Shwets et al., 1995; Jahan and Ahmed, 1997; Islam and Kanungoe, 2005). According to Jahan and Ahmed (1997), groundwater level, direction of flow and fluctuation pattern show the general trend of groundwater outflow towards the major rivers, streams and low-lying areas at the end of rainy as well as during dry season. Shwets et al (1995) suggested that fast discharge of groundwater towards the rivers of Gangetic influenced area results scarcity of both surface and groundwater by declining of water table and ceasing the groundwater withdrawal operations for the domestic and agricultural utilization in bigger scale. Consequently, huge exploration of groundwater after introduction of BMDA has caused a number of side effects in the area which has become a matter of concern in the recent years. BMDA took necessary initiatives to ensure annual withdrawal less than the annual recharge to keep the groundwater level in position. They have estimated groundwater recharge in the area at least one-third of the annual rainfall and that is 500 mm per year (Asaduzzaman and Rushton, 2006). Islam and Kanungoe (2005) estimated the long-term annual average recharge of 152.7 mm to the groundwater reservoir using water balance study and aquifer simulation modeling. A government report (Government of Bangladesh, 2002) suggests that recharge to groundwater in the northwest part varies from 210 mm to 445 mm. However, exploitation of groundwater in the area is going on the basis of one-third rainfall recharge hypothesis of BMDA which is beyond the sustainable yield.

According to BMDA (2003), over 15 million seedlings were planted in the area to increase the floral biodiversity. It has been claimed that huge plantations have increased the rainfall in the area. They also demand that the water level data collected regularly in different parts of the area shows no sign of long-term declination of water table (Faisal et al., 2005).

It contradicts with the survey reports by other departments of government. It is believed that rainfall in the area has been decreased in the recent years (Banglapedia, 2003). A report of Bangladesh government (Government of Bangladesh, 2002) mentioned that with ever increasing ground water extraction for irrigation in the northwest districts during the dry season in recent years and no increase in rainfall in that period, the ground water level falls to the extent of not getting fully replenished in the recharge season causing overdraft. Another report of BADC (2005) mentioned that the groundwater-based irrigation system in the area has reached a critical phase with croplands in many places going out of the reach of shallow-level aquifer due to fast depleting groundwater table. The recently published groundwater zoning map shows that a record high of 60 percent irrigated croplands in Naogaon and 10 percent in Rajshahi and C'Nawabganj districts have become critical for shallow tube-well operation (BADC, 2005). The major side-effect that has been found in the area is prolonged and recurrent occurrence of groundwater droughts or absence of groundwater above the expected level. The problem is becoming progressively more acute with the growth of population, extension of agricultural lands and climate change.

Bangladesh is one of the most vulnerable countries in the world to climate change (IPCC, 2007). Hydrologic changes are the most significant potential impacts of global climate change in Bangladesh. A study on climate change vulnerability based on certainty of impact, timing, severity of impacts and importance of the sector, ranked water resources as the greatest concern due to climate change in Bangladesh (OECD, 2003). Northwest part of Bangladesh is one of the most vulnerable regions of Bangladesh to climate change in respect of water resources. The impacts of more variable precipitation and extreme weather events are already felt in the region.

Delayed monsoon, more variation in inter-annual rainfall, extreme temperature events such as record breaking severe hot and cold spells indicate a change of climate in the region.

It has been predicted that due to climate change, there will be a steady increase in temperature, decrease in winter rainfall and increase in monsoon rainfall in Bangladesh (IPCC, 2007). Decreasing rainfall in dry season with higher evapotranspiration due to temperature rise will demand higher amount of water for irrigation. At the same time the higher temperature will change the crop physiology and shorten the crop growth period. This will reduce the irrigation days. These contradictory phenomena will change the total irrigation water demand. As agriculture is the main sector of water use in northwest Bangladesh, estimation of the agricultural water demand in the changing environment is essential for long-term water resources development and planning in the area.

Groundwater occurs in the sub-surface of the earth and is not affected by climate change as the surface water. Impact of climate change will be propagated to groundwater through surface water-groundwater interaction. Changes in precipitation and surface water resources will have a direct impact on groundwater recharge and groundwater level. On the other hand changes in the demand of water due to climate change will cause an indirect impact on groundwater resources. As it has been already mentioned that about 75% of irrigation water in the study area comes from groundwater, a change in irrigation water demand due to climate change will have huge impact of groundwater in the study area. Groundwater in the northwest part of Bangladesh is already in stress. Climate change may make the situation more severe. A study of climate change impact on groundwater resources is therefore essential of sustainable groundwater resources management in the northwest part of Bangladesh.

1.2 Objectives of the Research

The major objective of the present research is to model groundwater scarcity, to identify the causes of groundwater scarcity and to assess the possible impacts of climate change groundwater scarcity. Hydrological processes are dynamic phenomena, which change over time and space. Geographical Information System (GIS) maintains the spatial location of data collection point and provides tools to relate the data contained through a relational database. Therefore, one of the basic objectives of the present research is to use GIS for the effective analysis of spatially distributed hydro-meteorological data and modeling. The details of the objectives are given below:

1. Study of the spatial distribution of groundwater demand.
2. Study of the spatial distribution of groundwater scarcities.
3. Analysis of long-term groundwater hydrographs, rainfall time series and groundwater flow regimes to identify the causes of groundwater scarcity.
4. Study of the spatio-temporal variability of the climate in and around the study area,

5. Modelling of the possible changes in rainfall and temperature using regional climate models,
6. Study of the impacts of climate change on water demand, and
7. Study possible impacts of climate change of groundwater resources in the region.

1.3 Study Area

1.3.1 Geography

The study area comprises three northwest districts of Bangladesh viz. Rajshahi, Naogaon and C'Nawabganj. The location of the study area in Bangladesh is shown in Figure 1.2. Geographically, the area extends from 24°08'N to 25°13'N latitude and from 88°01'E to 89°10'E longitude, and covers approximately 7587 km^2. The study area comprises eighty-two Upazillas (sub-districts). Total population of the area is 6.1 million, of which more than 80% people live in rural area and directly or indirectly depend on agriculture. The density of population is almost 804 persons per square kilometer. The topographic map of the study area is shown in Figure 1.3. The topography of the area is mainly flat with an average elevation of 25 m above the mean sea level. There is a mild surface gradient towards southeast.

The northwest region of Bangladesh is comparatively backward, less developed and more poverty-stricken compared to other parts of Bangladesh. The area is mostly non-industrialized. The economy of the area is completely agriculture based. About 74.82% land of the study area is used for agriculture among which 31% land is used for single cropping, 56% for double cropping and 13% land is used for triple cropping.

Cultivation in 59% land in the area is under irrigation and almost 85% of the irrigation water comes from groundwater.

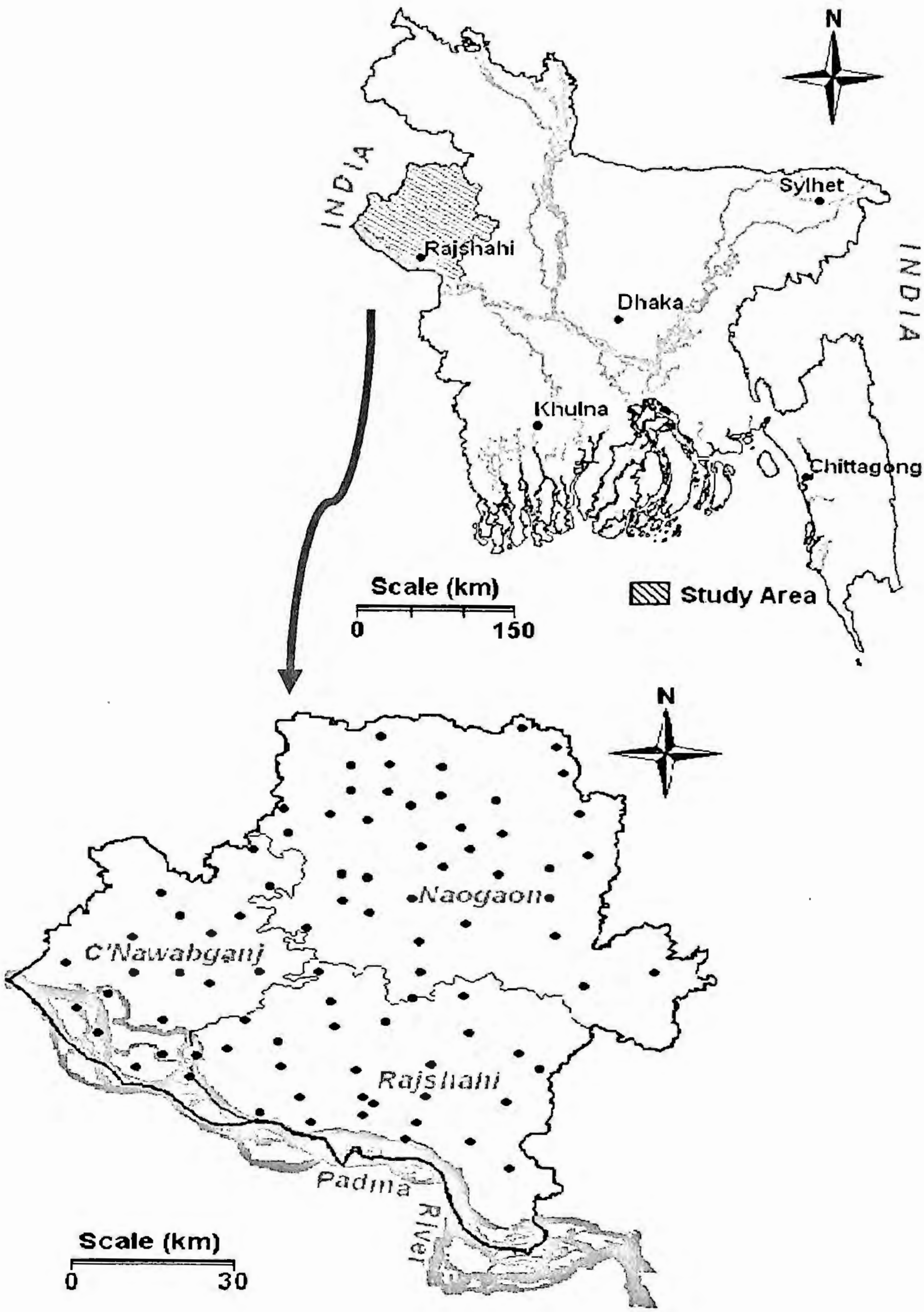


Fig 1.2: Location of the study area in Bangladesh

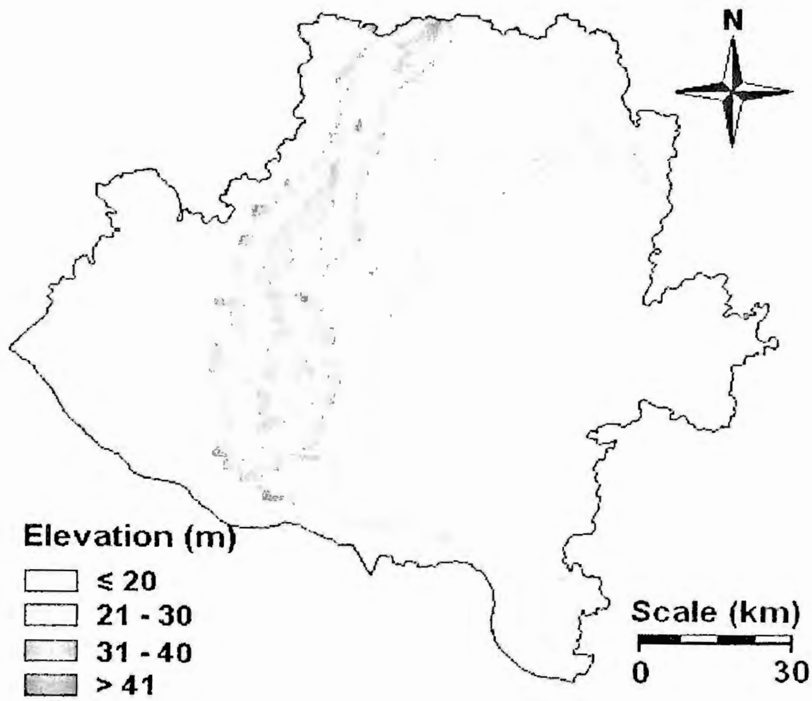


Fig 1.3: Topographic of the study area.

1.3.2 Geology

The northwest portion of Bangladesh is situated over the Indian platform. Physiologically, this area could be divided into Barind Track, Atrai flood plane, Little Jamuna flood plain, Mahananda flood plain and Ganges flood plain.

The surface geology in a major part of the area comprises of uplifted terraces of Pleistocene sediments called Barind Tracts which are more strongly weathered than the surrounding alluvium. The Barind Tract was formed by the deposition of sediments carried by the river Padma and tributaries in the Pleistocene age (Morgan and McIntyre, 1959). In the areas with alluvial, the Barind Tract sediments can be found at depths of the order of 150–200 m or more. The geological map of the area is shown in Figure 1.4.

There are several boreholes in the area drilled by Bangladesh Water Development Board (BWDB) and Bangladesh Agricultural Development Corporation (BADC) for testing the aquifer, irrigation and water supply.

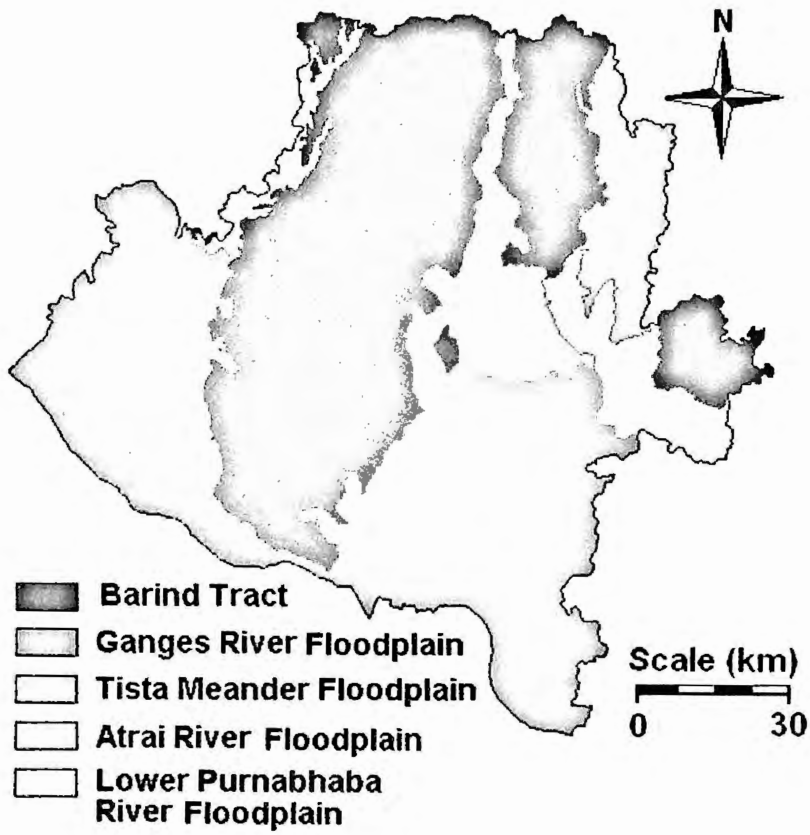
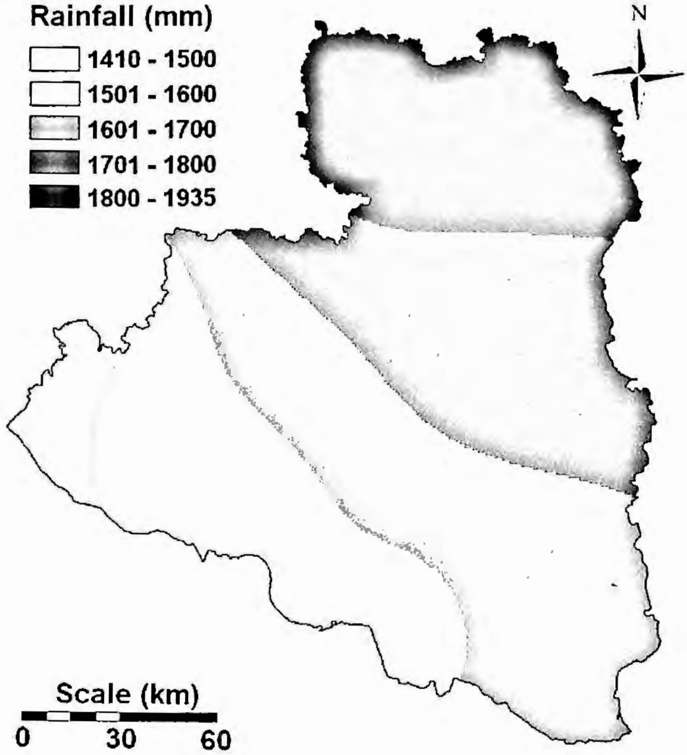


Fig 1.4: Geology of the study area.

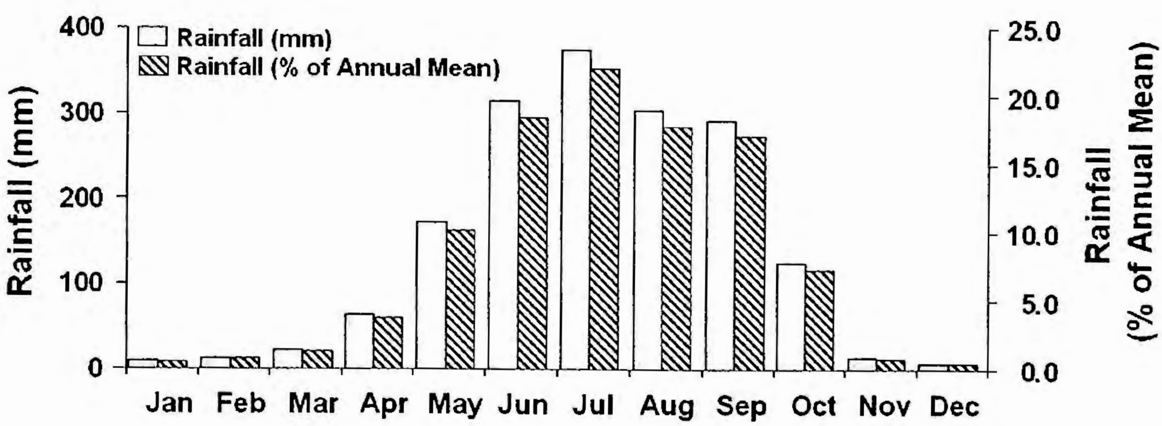
The boring shows that the formation of the top soil of Barind area which is reddish in color is mostly clay though silt and fine sands are encountered in some places. It contains an excess of iron and lime and is deficient in silicon matter. When dry, this soil becomes very hard and in wet season it is slippery rather than soft. The formation of clay and silt underlain by fine, medium and coarse sand (Khan, 1991). The soil of flood plain area shows a pattern of friable silty loam or silty clay loam, they are comparatively rich in calcium, magnesium and potassium.

1.3.3 Climate and Environment

Climatically, the study area belongs to dry humid zone with annual average rainfall vary between 1400 to 1650 mm, among which almost 83% rainfall occur in monsoon (June to October). Spatial distribution of rainfall in and around the study area is shown in Figure 1.5(a). Four distinct seasons can be recognized in the area from climatic point of view: (i) the dry winter season from December to February, (ii) the pre-monsoon hot summer from March to May, (iii) the rainy monsoon from June to September, and (iv) the post-monsoon season which lasts from October to November (Rashid, 1991). The seasonal distribution of rainfall in the study area is shown in Figure 1.5 (b). The figure shows that almost 92.7% rainfalls occur during May to October. Less than 6% rainfall occurs during the irrigation period of dry season *Boro* rice field (January to April). Rainfall in the area varies widely from year to year. For example, the rainfall recorded at Rajshahi in 1997 was 2,062 mm, but in 1992 it was 798 mm only. Annual variability of non-monsoonal and monsoonal



(a)



(b)

Fig 1.5: (a) Spatial distribution of rainfall; (b) monthly distribution of rainfall in the study area.

rainfall in the area are shown in Figure 1.6(a) and (b) respectively. The figures show that non-monsoonal rainfall varies more than 50% and monsoonal rainfall varies more than 20% in the study area. Average temperature in the region ranges from 25 to 35^0C in the hottest season and 9 to 15^0C in the coolest season. In summer, some of the hottest days experience a temperature of about 42^0C or even more. In winter it falls to about 5^0C. So the region experiences extremes that are clearly in contrast to the climatic condition of the rest of the country (Banglapedia, 2003).

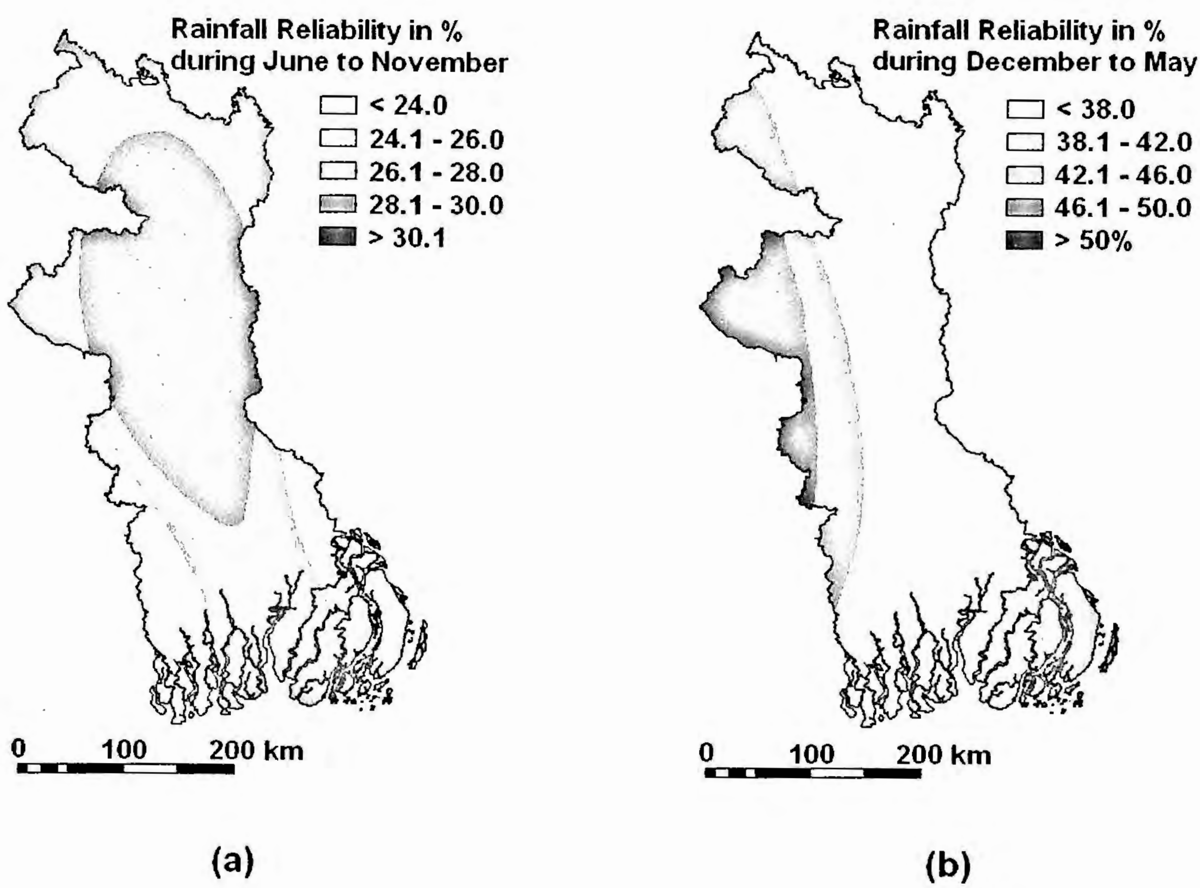
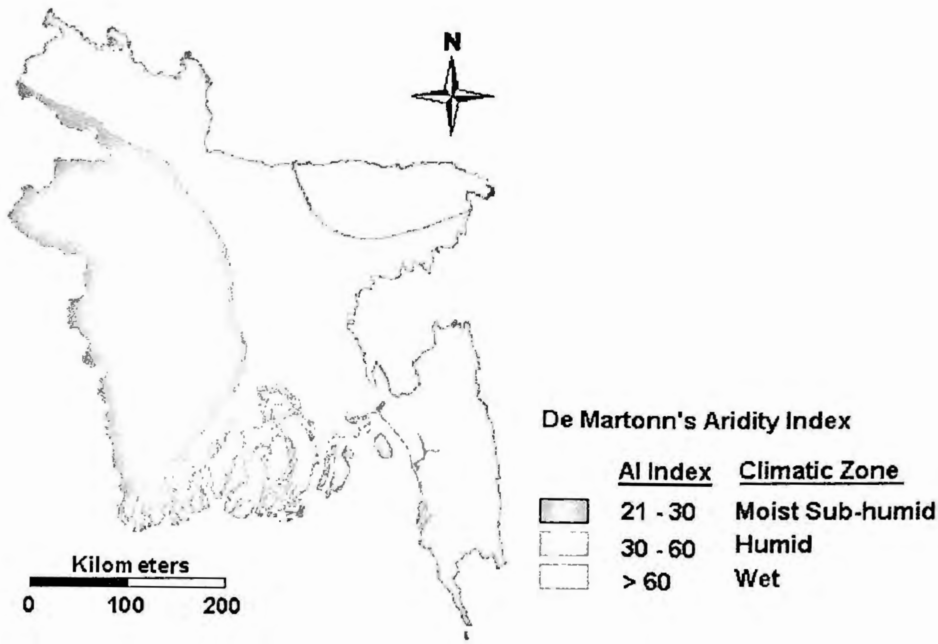


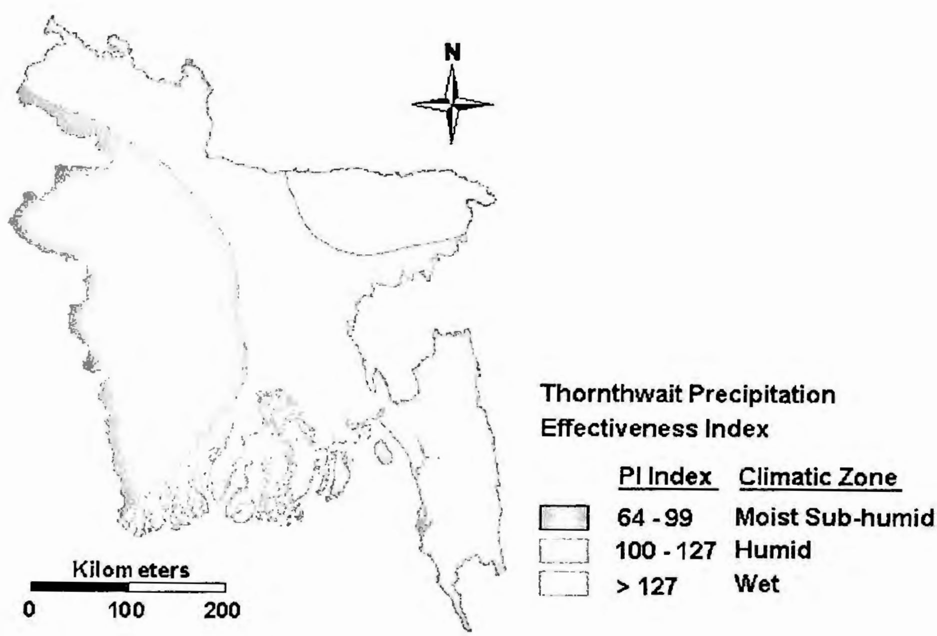
Fig 1.6: Coefficient of variation of rainfall (reliability) during (a) June to November (b) December to May

Dryness study of Bangladesh, carried out using De Martonne aridity index (De Martonne, 1926) and Thornthwaite precipitation effectiveness index (Thornthwaite, 1931) methods, revealed that the study area belongs to sub-humid class. De Martonne and Thornthwaite dryness indices maps of the study area is shown in Figure 1.7(a) and (b) respectively. De Martonne and Thornthwaite indices are 20.89 and 64.04 respectively in the study area which is lowest in the country. The total annual potential evapotranspiration is also lower than or equal to annual rainfall in some places. Therefore, the climate of this region of Bangladesh is sometimes defined as very close to dry (Shahid et al., 2005).

Meteorological drought is a common phenomenon in the region (Paul, 1998; Shahid and Behrawan, 2008). In the last forty years the area suffered eight droughts of major magnitude. Though all the droughts had severe impact on quality of life and economy of the whole country, the northwest districts were affected more compared to other parts of the country (Shahid, 2008). In recent decades, the hydro-climatic environment of northwest districts of Bangladesh has been aggravated by the cross country anthropogenic interventions. Construction of barrage in the upstream of Ganges River and diversion of water by India has reduced the water discharge of the Ganges River in Bangladesh from 3700 m^3/s in 1962 to 364 m^3/s in 2006. The shortage of freshwater discharge to the deltaic area is trailing active ecosystems function, especially in the dry season. Falling groundwater tables, increase water salinity and losses of bio-diversity has been observed in the Gangetic basin of Bangladesh in the recent years (Islam and Gnauck, 2008).



(a)



(b)

Fig 1.7: The aridity maps obtained by (a) De Martonne aridity index; and (b) Thornthwaite precipitation effectiveness index methods from thirty years (1970-1999) rainfall data.

1.4 Review of Previous Studies

A number of hydrological and hydrogeological studies have been carried out in the area. UNDP (1982) divided the country into fifteen hydrogeological zones on the basis of the geologic factors, aquifer characteristics and development constrains. According to UNDP (1982) and MPO (1986) the aquifer systems of Bangladesh are conventionally divided into three groups depending on their vertical distribution. The reports mentioned that in general aquifer in the northwest part of Bangladesh is composed of fine to very fine sand with thin bands of discontinuous clay. Thickness of this zone is variable, but it is thin compared to other parts of the country. There is a silty clay/ clay layer of variable thickness on the top of the upper aquifer. In some area this clay layer is absent. Khan et al. (1986) studied the groundwater potential of the area surrounding Rajshahi city and found the area potential for groundwater.

Mitra and Alam (1986) conducted a detail study of hydrogeology of Rajshahi district and produced hydrogeological map of the area. Chowdhury (1989) studied the groundwater quality of Barind Tract and found that groundwater of the area does not meet all the criteria for drinking. Khan and Sattar (1994) reported that exploitation of groundwater in the region is more than the natural recharge and hence, over drafting of groundwater is going on in the Barind Tract. Jahan et al. (1994) computed the specific yield of the aquifer in the area varying from 8 to 32% with a general decreasing trend from north towards central portion. Shwets et al (1995) suggested that fast discharge of groundwater towards the rivers of Gangetic influenced area results scarcity of both surface and groundwater by declining of water table and ceasing the groundwater withdrawal operations for the domestic and agricultural utilization in bigger scale. Jahan and Ahmed (1997) reported that groundwater level, direction of flow and fluctuation pattern show the general trend of groundwater outflow towards the major rivers, streams and low-lying areas at the end of rainy as well as during dry season. Haque et al. (2000) and Hasan et al. (1999) reported that the thickness of the exploitable aquifer ranges from 10 to 40 m. Azad and Bashar (2000) mentioned that the maximum depth to groundwater table from land surface varies from 7 to 30 m in most part of the study area. Rahman et al. (2001) found that the groundwater fluctuation varies 1m to 11m in place to place. Haque et al. (2002) found that the maximum depth to groundwater table from land surface varies from 7m to 30m. In generally the trend of groundwater flow is southern towards the Ganges, western and eastern side towards the comparatively low land. Sattar et al. (2001) reported that the transmissivity of the aquifers materials ranges from around 100-2200 m^2/day in the western part of the study area. BGS and DPHE (2001) reported hydraulic gradients vary in Bangladesh from about 1.0 m/km in the study area. On the other hand BAMWSP (2002) estimated the hydraulic gradients as 2.0–0.5 m/km in the north of Bangladesh. Rahman and Sahid (2004) modeled groundwater flow regime around a well in the study area to demarcate groundwater well protection zone. They found that due to directional flow of groundwater to southeast direction, the well protection zone highly elliptical. Shahid et al. (2005) analyzed the long-term climate records to map the aridity of Bangladesh and find the northwest part of Bangladesh is much drier compared to other parts of the country. Faisal et al. (2005) conducted a detail study on groundwater development activity in the region and reported that groundwater development activity in the region by BMPP is sustainable. Government of Bangladesh (2002) suggests that recharge to groundwater in the northwest part varies from 210 mm to 445 mm. Bangladesh Agricultural Development Corporation (2005) reported that most of the shallow tube-wells which are widely used for irrigation in the area go below the suction lift capacity in the peak irrigation period. Asaduzzaman and Rushton (2006) estimated the amount of groundwater recharge in the area as at least one-third of the annual rainfall and that is 500 mm per year. They also mentioned that the aquifers in the area are recharged mainly by the annual rainfall infiltrating into underground. Additional recharge occurs from the river channel and as well as some other surface bodies in wet months. Islam and Kanungoe (2005) used water balance study and aquifer simulation modeling and estimated the long-term annual average recharge of 152.7 mm to the groundwater reservoir. They also reported that presence of thick clay layer at near surface has significantly reduced the vertical recharge potentiality in this Barind Tract area. Therefore, during the dry period normal river discharge significantly reduced due to the withdrawal of water at upstream by neighboring country. Shahid (2008) reported that northwest part of Bangladesh is much more drought prone compared to others parts of the country due to high variability of inter-annual rainfall in the region. The study also found that a moderate deficit of rainfall in a year causes groundwater level to decline in the area. Shahid and Behran (2008) mentioned that northwest part of the country is also highly vulnerable to drought hazards due to high occurrence of poverty and dependency on irrigation.

Hill (2009) used ordinary kriging to spatially map arsenic contamination in shallow aquifers of northwest Bangladesh for the management of contaminated groundwater. Shahid and Hazarika (2010) conducted a detail study on groundwater droughts and scarcities in the northwest Bangladesh. Their study revealed that groundwater droughts in a every year phenomena in the region due to high withdrawal of groundwater for irrigation. Adham et al. (2010) studied the groundwater recharge potentiality in Barind Tract of northwest Bangladesh using Geographical Information System (GIS) and Remote Sensing technique. They reported that 85% of the area has low, and rest has moderate groundwater recharge potentiality. They also reported that only 8.6% of the total average annual precipitated water (1685mm) percolates into subsurface and ultimately contributes to recharge the groundwater.

1.5 Framework of the Thesis

The thesis has been organized into seven chapters. In the first chapter of the thesis background studies have been carried out in details. The objectives of the study have been chalked out and the study area has been selected. Geography, geology, climate and environment of the study area have been discussed in details. Reviews of previous studies on groundwater in the study area have been done in the first chapter.

Collections of data from different sources and the methods used for analysis of data have been discussed in chapter 2. Descriptions include the methods used for the estimation of irrigation water demand, estimation of domestic water demand, trend analysis of rainfall and temperature data, drought study using standardized precipitation index, spatial interpolation and mapping, modeling climate change scenarios, and mapping groundwater drought/scarcity.

The third chapter of the thesis gives soil information and long-term average meteorological data are used to estimate groundwater demand in the study area. For the estimation of total groundwater demand, irrigation and domestic demands are calculated separately and then summed together. Spatial distribution of irrigation water requirements is calculated by using FAO-56 model within a Geographical Information System (GIS). Domestic water use is computed from population census data and per capita daily water requirements proposed by United Nations Development Program.

In the fourth chapter of the thesis regional climate scenario generation model MAGICC/SCENGEN is used to predict the future climate change in the study area. The models of MAGICC/SCENGEN are first used to simulate the present climate (rainfall and temperature) over the study area (Northwestern Bangladesh). Average of three-year (2000-2002) monthly temperature and rainfall predicted by different models are compared with actual data to measure the performance of each model and select the best models for the future change of climate in the study area.

The fifth chapter of the thesis comprises groundwater scarcity in the study area has been studied. Spatial distribution of groundwater droughts is conducted using cumulative departure method. GIS is used to show the spatial distribution of groundwater scarcity situation in the study area. Groundwater hydrographs are analyzed, relation of groundwater level with meteorological droughts is investigated and regional flow of groundwater examined to identify the probable causes of groundwater scarcity in the region.

The sixth chapter of the thesis presents a study that has been carried out to assess the impact of climate change on groundwater in the study area. This has been done through the modeling of change on groundwater demand. Change in dry-season *Boro* rice irrigation water demand in the context of climate change has been studied. Long-term average meteorological data and soil information have been used to estimate the irrigation water demand in an area. Impacts of climate change on water requirements for land preparation, evapotranspiration for paddy field, effective precipitation and rice phenology has been computed to project the change irrigation water demand. Finally, the impacts of changing irrigation water demand on groundwater scarcity in the study area have been assessed.

Finally, in the seventh chapter of the thesis, conclusions are made based on the outcome of the study carried out in the thesis. The future works that can be envisaged are also discussed in this concluding chapter.

Chapter-2

DATA & METHODOLOGY

2.1. Introduction

The major objective of the present research is to model groundwater scarcity, to identify the causes of groundwater scarcity and to assess the possible impacts of climate change on groundwater scarcity. To achieve the objectives agricultural statistical data, soil information, and long-term average meteorological data are used. Spatial distribution of irrigation water requirements is calculated by using FAO-56 model (Allen et al., 1998) within a Geographical Information System (GIS).

Penman-Monteith method is used to calculate the reference evapotranspiration from climate data. Domestic water use is computed from population census data and per capita daily water requirements proposed by United Nations Development Program. Thornthwaite soil water balance algorithm is used to model the soil moisture deficiency to compute the water required for land preparation. Climate change modeling software SCENGEN is used to project the future change in rainfall and temperature in the study area. A temperature based crop phenology method known as degree-day method has been used to model the change in rice growth period under increased temperature.

2.2. Data Collection

The data used in the present study are mostly secondary in nature. Data are collected from different sources including Bangladesh Bureau of Statistics (BBS), Bangladesh Meteorological Department (BMD), Barind Multipurpose Development Authority (BMDA), Bangladesh Water Development Board (BWDB),

2.2.1. Description of data

Average *HYV Boro* rice cultivated area during the period of 1998-2002 in northwest districts of Bangladesh obtained from agriculture census data of Bangladesh Agricultural Development Corporation (BADC). The agricultural census data are mainly Upazilla scale data. High-Yield Variety (*HYV*) *Boro* rice cultivated areas of all Upazillas are used to map the spatial distribution of *Boro* rice cultivated land in the area. Long-term monthly rainfall and temperature data (1958-2007) are collected from Bangladesh Meteorological Department (BMD). BMD records rainfall, temperature and other climate data at seven stations situated in and around the study area. The climate data are recorded daily. However, BMD supplied the monthly data by summing the daily data of different months. Soil map of Soil Resources Development Institute (SRDI) of Bangladesh is used for the computation of seepage and percolation losses through paddy field and modeling soil water balance. The soil map is in the scale of 1:5000 provides all physical and hydrological properties of soil necessary for the study. Five years (1998-2002) monthly groundwater level data available at eighty-five sites in the study area are collected from Bangladesh Water Development Board (BWDB) to study the spatial distribution of groundwater droughts in the area. Long term monthly groundwater fluctuation data (1985-2002), available in nine sites in the study area are collected from Barind Multipurpose Development Authority (BMDA) to correlate groundwater level with meteorological droughts. Water level of *Little Jamuna* River recorded at a river gauge in the eastern side of the area is collected from Flood Forecasting Center (FFC) of BWBD to study the groundwater recharge/discharge periods.

2.2.2. Quality control of data

Among the data collected from different sources for the present study, major problem was found only with climate data. The main problem of climate data is number of missing data in the time series. About 2% of data are found missing in the seven stations used in the present study. Most of the missing data are found during the time period 1971-1976. In the present study, climate record of the full year is discarded if consecutive three months data of that year is found missing.

Data quality control is a necessary step before analyzing their trends (You et al., 2008). A number of checks are carried out for quality controls of data such as precipitation values below 0 mm, winter rainfall higher than 100 mm and dry month in monsoon. In some cases data are validated by the climate records of nearby stations. Histograms of the data are also created which reveal problems that show up when looking at the data set as a whole (Aguilar et al., 2005).

Several strategies have been described in the literature to detect non-homogeneities in the data series (Peterson et al., 1998). In this study, both the subjective double mass curve method and the objective student T test were applied to the annual precipitation time series of each station.

The double mass curve (Kohler, 1949) is a plot of the deviation from a station's accumulated values versus the average accumulation of the base group. Non-linearity or bends plots can be an indicator of changed conditions (Su et al., 2006). Results of the double mass curves of all stations are almost a straight line. No breakpoints are detected in the time series of precipitation.

Student's T test can also be used to assess homogeneity by determining whether or not various samples are derived from the same population (Panofsky and Brier, 1968). In a homogeneous series, variations are caused only by the variation in weather and climate (Conrad and Pollak, 1950). Thus, modified series obtained through the subtraction of the reference series from the original series of each station should be more capable of detecting any inhomogeneity resulting from non-climatic factors (Su et al., 2006). After filtering out the possible climatic abruption, T test is applied on each station. The results reveal a wide range of the 95% confidence interval of the difference including zero. So, it is clear that there is no statistically significant variation or break point existing in the rainfall and temperature time series.

2.3. Methodology

The methods used in the present study are discussed below in details.

2.3.1. Spatial distribution of irrigation water requirements

Spatial distribution of irrigation water requirements is calculated by using FAO model (Brouwer et al., 1986) within a Geographical Information System (GIS).

High-Yield Variety (HYV) Boro rice cultivated areas are mapped from ASTER image. Penman-Monteith method is used to calculate the reference evapotranspiration from climate data. Soil textural composition data is used to estimate the spatial distribution of percolation and seepage loses through the paddy field. A simple soil water balance algorithm is employed to model the soil moisture deficiency to compute the water requirements for land preparation. Domestic water demand is computed from population census data and per capita daily water requirements proposed by United Nations Development Program (2006).

According Brouwer et al. (1986), irrigation water requirements can be calculated as,

$$W_{irr} = ET_{crop} + W_{lp} + W_{ps} + W_l - P_e \qquad (2.1)$$

Where,

W_{irr} – Irrigation water requirements

ET_{crop} - Crop evapotranspiration

W_{lp} – Water for land preparation

W_{ps} – Percolation and seepage losses

W_l – Water to establish water layer for initial stages.

P_e – Effective precipitation

Crop evapotranspiration is calculated as,

$$ET_{crop} = EC \times ET_{ref} \qquad (2.2)$$

Where, EC is the crop coefficient, and

ET_{ref} is the reference potential evapotranspiration

Reference potential evapotranspiration is calculated from monthly mean climatic data at six stations situated in and around the study area using Penman-Monteith method. *Ref-ET* Software (Allen, 2001) is used for this purpose.

Water required for land preparation is calculated from soil moisture deficiency data. The soil moisture deficiency is calculated using simple soil water balance method developed by Thornthwaite (Komuscu et al., 1998). The method uses three independent variables viz. precipitation (P), potential evapotranspiration (PE) and soil moisture storage (ST). Whenever precipitation exceeds the climatic demand for water, the soil moisture begins to increase. When P exceeds PE, actual evapotranspiration is equal to potential evaporation, and the excess water of PE replenishes ST. When the soil moisture reaches field capacity, a water surplus develops resulting in increased runoff from the area. However, no surplus can develop as long as soil moisture storage is below the field capacity. On the other hand, a water deficit occurs when P is less than PE (Komuscu et al., 1998). In that case, soil moisture starts to deplete by an amount of (PE - P). In most of the climatic stations in the study area, PE starts to exceed P in the month of November and continues up to April. This means that soil moisture deficit starts to buildup in November. In the present work, the amount of water required to replenish the soil moisture deficit in the month of rice transplantation is considered as the water required for land preparation including tillage and puddling.

Total water losses through percolation and seepage from the rice field are calculated from soil data. Following Brouwer et al. (1986), it is considered that percolation and seepage losses for a sandy soil is 8 mm/day, for a clayey soil is 4 mm/day, and for loom 6 mm/day. Percolation and seepage losses through a particular soil class are calculated according the percentage of sand, clay and loom exists in that soil class.

For the better yield of crop, 50 to 70 mm standing water in the rice field is expected during the growing stages of rice. Therefore, 50 mm of water is considered for establishing water layer in the paddy field throughout the irrigation period.

Effective precipitation is computed by using USDA method (Soil Conservation Service, 1993) as given below,

$$P_e = SF(0.70917 P_t^{0.82416} - 0.11556)(10^{0.02426 ET}) \qquad (2.3)$$

Where:

P_e = average monthly effective precipitation (in inch)

P_t = monthly mean precipitation (in inch)

ET = average monthly crop evapotranspiration (in inch)

SF = soil water storage factor

The soil water storage factor is defined by:

$$SF = (0.531747 + 0.295164 D + 0.057697 D^2 + 0.003804 D^3) \qquad (2.4)$$

Where:

D = the usable soil water storage (in inch)

The term D is generally calculated as 40 to 60 percent of the soil water capacity in the crop root zone, depending on the irrigation management practices used. In the present case, D is calculated as 50% of the soil water capacity.

2.3.2. Spatial distribution of domestic water demand

Domestic water use in the study area is computed by using following equation:

$$W_{dom} = 365.4 \times Pop \times W_{pcw} \qquad (2.5)$$

Where,

W_{dom} - domestic water requirements

Pop - total population in an area

W_{pcw} - per capita daily water requirement

In the present paper, 46 liter or 0.046 m^3 was considered as per capita daily water requirement as proposed by United Nations Development Program (2006) for Bangladesh. GIS is used to develop the sub-district level domestic water requirement map from population census data.

Spatial distribution of total groundwater demand in the study area is calculated by integrating the maps of irrigation water requirements in HYV Boro rice field and domestic water demand by using following equation:

$$GW_{total} = W_{irr} + W_{dom} \qquad (2.6)$$

Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) image of study area is used for the mapping of HYV Boro rice cultivated area. The ASTER is a high resolution multispectral imaging device on board of NASA's TERRA platform. The ASTER records data in 14 spectral bands: 3 bands in Visible Near-InfraRed (VNIR) with 15 meter spatial resolution, 6 bands in Short Wave InfraRed (SWIR) with 30 meter spatial resolution and 5 bands in Thermal InfraRed (TIR) with 90 meter spatial resolution. The image is acquired on January 24, 2007. All ASTER sensors are active during acquisition of image and the image is free from clouds. ASTER Level 1B image of the study area is used for the mapping for HYV Boro rice cultivated area at 30 meter resolution. In ASTER Level 1B image, the raw digital counts of ASTER Level 1A data are already converted to radiance values and transformed to a geo-referenced coordinate system. Therefore, further radiometric and geometric corrections are not necessary.

Image processing software ENVI is used for the processing of ASTER image. Supervised classification technique is applied for the extraction of cultivated area from the satellite image. Fifteen training areas are chosen to represent the cultivated land. For each training class the multi-spectral pixel values are extracted to define a statistical signature. Maximum Likelihood method is used as the decision rule for supervised classification of ASTER image.

2.3.3 Trend Analysis of Rainfall and Temperature data

Trend of rainfall and temperature is calculated to envisage the temporal pattern of climate in Bangladesh. There exist numerous parametric methods, such as moving average or running mean (Sneyers, 1990, Salinger *et al.*, 1995), linear regression (Gregory, 1978; Lanzante, 1996), etc. and non-parametric method, such as Mann–Kendall's test, Spearman's test, etc. (Sneyers, 1990) for the trend analysis. As mentioned by several authors (Yu and Neil, 1993; Suppiah and Hennessy, 1998), complementary information can be obtained by using both the techniques. In the present study, The Mann–Kendall trend test (Mann 1945; Kendall 1975) has been used in the present study to analyze the trends of rainfall and temperature. Sen's slope method is used to measure the magnitude of change in rainfall and temperature. Confidence levels of 90%, 95%, and 99% are taken as thresholds to classify the significance of positive and negative trends. Standardized Precipitation Index (*SPI*) method (Mckee *et al.*, 1993) is used to identify the wet and dry months from rainfall time series data. Geographical Information System (GIS) is used to show the spatial variation of trends over the country. The methods used for the spatio-temporal analysis of climate in and around the study area are discussed below.

2.3.3.1. Mann-Kendall trend test

In Mann-Kendall test (Mann 1945; Kendall 1975) the data are evaluated as an ordered time series. Each data is compared to all subsequent data. The initial value of the Mann-Kendall statistic, S, is assumed to be 0 (*e.g.*, no trend). If a data from a later time period is higher than a data from an earlier time period, S is incremented by 1. On the other hand, if the data from a later time period is lower than a data sampled earlier, S is decremented by 1. The net result of all such increments and decrements yields the final value of S. If x_1, x_2, x_3 ..... x_i represent n data points where x_j represents the data point at time j, then S is given by,

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sign(x_j - x_k) \qquad (2.7)$$

Where: $sign(x_j - x_k) = 1$ if $x_j - x_k > 0$

$= 0$ if $x_j - x_k = 0$

$= -1$ if $x_j - x_k < 0$

The probability associated with S and the sample size, n, are then computed to statistically quantify the significance of the trend. Normalized test statistic Z is computed as follows:

$$Z = \frac{S-1}{\sqrt{VAR(S)}} \text{ if } S > 0 \qquad (2.8)$$

$$= 0 \text{ if } S = 0$$

$$= \frac{S+1}{\sqrt{VAR(S)}} \text{ if } S < 0$$

At the 99% significance level, the null hypothesis of no trend is rejected if $|Z| > 2.575$; at 95% significance level, the null hypothesis of no trend is rejected if $|Z| > 1.96$; and at 90% significance level, the null hypothesis of no trend is rejected if $|Z| > 1.645$. More details of Mann-Kendall test can be found in Sneyers (1990).

2.3.3.2. Sen's slope estimator

Some trends may not be evaluated to be statistically significant while they might be of practical interest (Yue and Hashino, 2003; Basistha *et al.*, 2007). Even if climate change component is present, it may not be detected by statistical tests at a satisfactory significance level (Radziejewski and Kundzewicz, 2004). Therefore, in the present study, linear trend analysis is also carried out and the magnitude of trend is estimated by Sen's Slope method (Sen, 1968). Sen's Slope method gives a robust estimation of trend (Yue *et al.*, 2002). The method requires a time series of equally spaced data. The method proceeds by calculating the slope as a change in measurement per change in time,

$$Q' = \frac{x_{t'} - x_t}{t' - t} \tag{2.9}$$

Where, Q' = slope between data points $x_{t'}$ and x_t

$x_{t'}$ = data measurement at time t'

x_t = data measurement at time t

Sen's estimator of slope is simply given by the median slope,

$$\begin{aligned} Q &= Q'_{[(N+1)/2]} \qquad \text{if } N \text{ is odd} \\ &= (Q'_{[N/2]} + Q'_{[(N+2)/2]})/2 \qquad \text{if } N \text{ is even} \end{aligned} \tag{2.10}$$

Where, N is the number of calculated slopes.

2.3.4. Drought Studies using Standardize precipitation index

Standardized precipitation index (Mckee *et al.*, 1993) is a widely used drought index based on the probability of precipitation for multiple time scales, e.g. one-, three-, six-, nine-, twelve-, eighteen- and twenty-month. It provides a comparison of the precipitation over a specific period with the precipitation totals from the same period for all the years included in the historical record. Consequently, it facilitates the temporal analysis of wet and dry phenomena.

To compute SPI, historic rainfall data of each station are fitted to a gamma probability distribution function:

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} \qquad for \quad x > 0 \tag{2.11}$$

Where $\alpha > 0$ is a shape parameter, $\beta > 0$ is a scale parameter, $x > 0$ is the amount of precipitation, and $\Gamma(\alpha)$ defines the gamma function.

The maximum likelihood solutions are used to optimally estimate the gamma distribution parameters, α and β for each station and for each time scale:

$$\alpha = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right) \tag{2.12}$$

$$\beta = \frac{\bar{x}}{\alpha}$$

Where:

$$A = \ln(\bar{x}) - \frac{\sum \ln(x)}{n}$$

n = number of precipitation observations.

This allows the rainfall distribution at the station to be effectively represented by a mathematical cumulative probability function as given by:

$$G(x) = \int_0^x g(x)dx = \frac{1}{\beta^\alpha \Gamma(\alpha)} \int_0^x x^{\alpha-1} e^{-x/\beta} dx \qquad (2.13)$$

Since the gamma function is undefined for $x = 0$ and a precipitation distribution may contain zeros, the cumulative probability becomes:

$$H(x) = q + (1-q)G(x) \qquad (2.14)$$

Where, q is the probability of a zero. The cumulative probability $H(x)$ is then transformed to the standard normal distribution to yield the SPI (McKee *et al.*, 1993).

As the precipitation rate is fitted to a gamma distribution for different multiple time scales for each month of the year, the resulting function represents the cumulative probability of a rainfall event for a station for a given month of the dataset and at different multiple time scale of interest. This allows establishing a classification values for SPI. McKee *et al.* (1993) classified wet and dry events according to SPI values as given in Table 2.1. Detail of the SPI algorithm can be found in McKee *et al.* (1993; 1995).

Table 2.1: Drought categories defined for SPI values

SPI Value	*Drought Category*	*Probability of Occurrence*
0 to -0.99	Near normal or mild drought	34.1%
-1.00 to -1.49	Moderate drought	9.2%
-1.50 to -1.99	Severe drought	4.4%
-2.00 and less	Extreme drought	2.3%

2.3.5. Spatial Interpolation

For the mapping of spatial pattern of trends from point data Kriging interpolation method is used. Geostatistical analysis tool of ArcMap 9.1 (ESRI, 2004) is used for this purpose. Kriging is a stochastic interpolation method (Journel and Huijbregts, 1981; Isaaks and Srivastava, 1989), which is widely recognized as standard approach for surface interpolation based on scalar measurements at different points. Study showed that Kriging gives better global predictions than other methods (van Beers and Kleijnen, 2004). Kriging is an optimal surface interpolation method based on spatially dependent variance, which is generally expressed as semi-variogram. Surface interpolation using Kriging depends on the selected semi-variogram model and the semi-variogram must be fitted with a mathematical function or model. Depending on the shape of semi-variograms, different models are used in the present study for their fitting.

Climate is a dynamic phenomenon, which changes over time and space. Complete analysis of rainfall events requires study both of its spatial and temporal extents. Hydrological investigation over a large area requires assimilation of information from many sites each with a unique geographic location (Shahid *et al.*, 2000; Shahid *et al.*, 2002). GIS maintains the spatial location of sampling points, and provides tools to relate the sampling data contained through a relational database. Therefore, it can be used effectively for the analysis of spatially distributed hydro-meteorological data and modeling. In the present research, GIS is used to show the spatial variation of rainfall trends.

2.3.6. Modeling climate change scenarios and water demand

To predict the future climate change in the study area, regional climate scenario generation model MAGICC/SCENGEN is used. SCENGEN constructs a range of geographically-explicit climate change scenarios for the world by exploiting the results from the Models for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC) and a set of GCM experiments, and combining these with observed global and regional climate data sets. SCENGEN contains a set of greenhouse gas-induced patterns of regional climate change obtained from 16 different General Circulation Models (GCM) experiments and also sulfate aerosol-induced patterns of regional climate change. A geographically-explicit climate change scenario can be constructed by selecting a future time interval, selecting one or more of the greenhouse gas-induced GCM climate change patterns and by selecting the regional aerosol patterns (Houghton et al., 2001).

In the present study, the models of MAGICC/SCENGEN are first used to simulate the present climate (rainfall and temperature) over the study area (Northwest Bangladesh). Average of three-year (2000-2002) monthly temperature and rainfall predicted by different models are compared with actual data. Root Mean Squared Error (RMSE) method is used to measure the performance of each model. The models are ranked according to their performance to simulate rainfall and temperature and the best models are picked up to project the future change of climate in the study area. The models are run with the IPCC B2 SRES scenario (Intergovernmental Panel for Climate Change, 2000). B2 storyline and scenario family describes a world in which emphasis is given on local solutions to economic, social and environmental sustainability and lower green house gas emission. Similar to B2 scenario, population for Bangladesh and surrounding region is projected to increase continuously but at a lower rate. GDP projection also represents the intermediate level of economic development like B2 scenario (Nair et al., 2003). Lower emission of green house gas close to B2 scenario is the mid-to-long term policy of the region (Hong et al., 2007). Therefore, the present study focuses on irrigation water demand under the B2 climate scenario.

Resolution of climate models of MAGICC/SCENGEN is 2.5 degree. The whole Bangladesh can be covered by six pixels only. The study area belongs to two pixels, one covers the northwest and the other covers the southwest parts of the study area. Temperature and rainfall values predicted by the climate models for the two pixels are averaged to get the projected change in mean temperature and rainfall in the study area. It is assumed that change in temperature and rainfall will be uniform over the study area.

2.3.7. Mapping Groundwater Droughts/Scarcity

Groundwater droughts can be identified using three variables viz. recharge, groundwater levels and discharge from groundwater to the surface water system (Tate and Gustard, 2000; van Lanen and Peters, 2000). Recharge and groundwater discharge cannot be measured directly. They are calculated from other measurements or through simulation. This makes them sensitive to errors. One the other hand, groundwater levels characterize the present storage and they can be measured directly with reasonable accuracy and frequency. Indirectly the spatial and temporal aspects of groundwater levels provide knowledge about groundwater recharge and discharge. Therefore, in most of the cases, groundwater levels are monitored to detect groundwater droughts.

The most well known methods used in groundwater drought analysis from groundwater level data are the threshold level approach and the Sequent Peak Algorithm (Tallaken and van Lanen, 2004). However, as groundwater level is a state variable and not a flux like recharge, rainfall and stream flow, the deficit volume calculated with the threshold level approach can identify groundwater droughts or scarcities better compared to other approaches. Although the fixed threshold provides quite acceptable results, the cumulative deficit is preferred as the major droughts can be identified more clearly. The best results can be obtained for a fixed threshold level and the cumulative deficit (van Lanen and Peters, 2000; Peters and van Lanen, 2000). Therefore, in the present study, the Cumulative Deficit (*CD*) approach from threshold groundwater levels is used to identify groundwater droughts.

The cumulative deficit is the summation of groundwater level departed below a threshold level over a time period. Following van Lanen and Peters (2000), in the present study groundwater drought events in a year is identified by calculating the cumulative deficit in meter below a threshold groundwater level,

$$CD_t = CD_{t-1} + \begin{cases} (\varphi_D - \varphi_t) & if\ positive \\ 0 & otherwise \end{cases} \tag{2.15}$$

Where, φ_t represents groundwater level in meter in a particular month of the year, and

φ_D the threshold level in meter.

Because of slow reactions of groundwater level on rainfall, only major meteorological droughts are finally shown up as a groundwater drought. Therefore, the time step to be used in the analysis of a groundwater drought should necessarily be large, usually more than a week or a month (Peters and van Lanen, 2000). Therefore, in the present study monthly time step is used for the study of groundwater droughts. Three threshold levels viz. 30%, 20% and 5% of the mean groundwater level is computed to show the severity of groundwater scarcity or drought at each location.

Cumulative Deficit (CD_t) values at different locations are interpolated to show the spatial extent of groundwater droughts of different severity. Kriging method (Isaaks and Srivastava, 1989) is used for the interpolation of CD_t values. Geostatistical analysis tool of ArcMap 9.1 is used for this purpose.

Chapter-3

ESTIMATION OF WATER DEMAND IN THE STUDY AREA

3.1 Introduction

Irrigation during dry season and domestic supply are the major sectors of groundwater use in northwest Bangladesh (Bari and Anwar, 2000). Though a few number of agriculture-based industries are situated in the study area, groundwater use by those industries are negligible and, therefore, is not considered in this study. (HYV) Boro rice, wheat and vegetables are commonly grown in the area during dry season (Banglapedia, 2003). However, wheat and vegetable cultivated areas are negligible compared with rice-cultivated area. HYV Boro rice is the dominating crop, which covers almost 95% of total cultivated crop area in the dry season. Boro in a winter season, photo-insensitive, transplanted rice cultivated on supplemental irrigation. Irrigation methods commonly used in Boro rice field is *Basin method.* In this system, water is supplied from one side of the plot and the whole plot is flooded with 5–7 cm standing water (Banglapedia, 2003). The irrigation water requirements in wheat and vegetable are less compared with rice. Therefore, irrigation water requirement in the HYV Boro rice field is considered as the groundwater use for irrigation in this study. About 100% of domestic water use in the study area comes from groundwater. Therefore, the total demand of groundwater is computed from the irrigation water demand in HYV Boro rice field and domestic water demand in the area. Estimation of groundwater demand in the study area is carried out in this chapter through the estimation of groundwater demand for irrigation and domestic use.

3.2 Estimation of Groundwater Demand for Irrigation

The thematic map of Boro rice cultivated area is shown in Figure 3.1(a). Sub-district wise distribution of Boro rice cultivated land is shown in Figure 3.1(b). Density of Boro rice cultivation is higher in the low-land eastern part of the study area. About 45% to 56% of the land in the eastern sub-districts of the study area is used for cultivation of Boro rice. On the other hand, less than 25% of the land in some western sub-districts is used for Boro cultivation.

The soil Moisture Holding Capacity (MHC) of different soil groups in the study area is shown in Figure 3.2(a). Soil MHC in most part of the study area ranges between 100 mm and 200 mm. The deficiency of soil moisture in the end of December is computed by Thornthwaite water balance method considering that land is prepared in the end of December for cultivation of Boro rice in the beginning of January. The amount of water required to replenish the soil moisture deficit in the end of December is considered as the water required for land preparation. The map of water requirement for land preparation is shown in Figure 3.2(b). The water required for land preparation varies between 116.8 mm and 125.2 mm in the study area. A strip in the middle part of the study area extends from east to west requires more water for land preparation compared to other parts of the area. As the rainfall during land preparation is very less, potential evapotranspiration acts as the main controlling factor alone with the soil moisture holding capacity to define the water requirement for land preparation. The east-west trending of high water requirement for land preparation is due to the influence of potential evapotranspiration and soil characteristics.

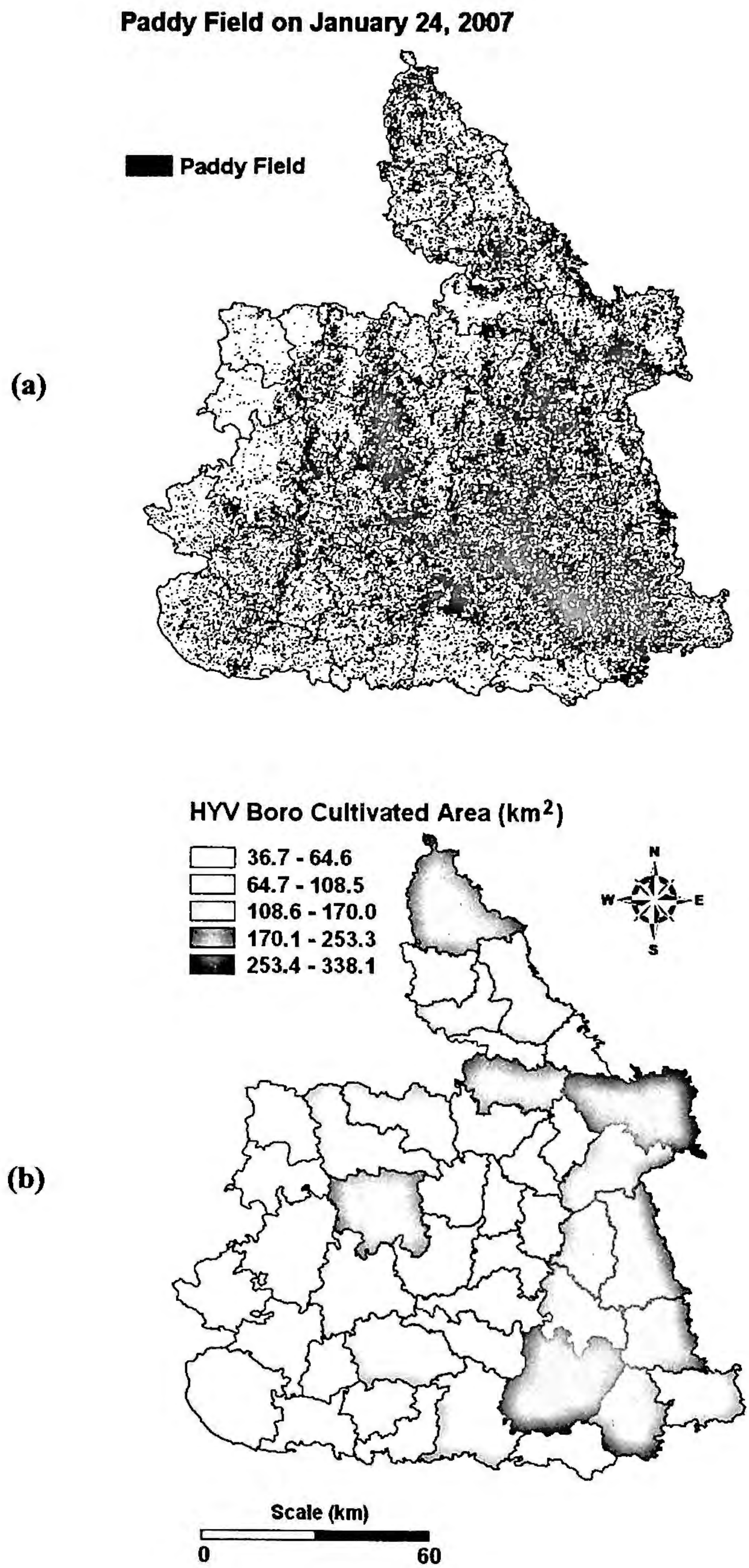


Fig 3.1: (a) HYV Boro rice cultivated area map derived from satellite data; (b) sub-district wise distribution of Boro rice cultivated land.

The textural composition of different soil classes in the study area is shown in Figure 3.3(a). Soil in the area is mostly clayey/silt loom in nature with slow to moderate permeability. The spatial distribution of percolation and seepage losses through the rice field, prepared from soil composition map is shown in Figure 3.3(b). Seepage and percolation losses through the paddy field in the study area vary between 250 mm and 958 mm. These losses are higher in the western part of the study area where soil is mostly silt in nature and less in the eastern part where the soil is mostly clayey. Both the soil moisture holding capacity and percolation loss depend on soils texture. Therefore, the corresponding maps more or less match with each other.

Actual evapotranspiration data collected in an experimental field in Dhaka, more than 200 km away from the study area, has been used for the computation of crop-coefficient of Boro rice. The crop-coefficient of Boro rice at 10 days time interval is shown in Figure 3.4. The crop-coefficient of Boro rice varies between 0.62 and 1.78. Lowest value of crop-coefficient is found in initial stage of paddy, after 10 days of cultivation which may be due to transplantation shock and the highest value is found in the end of vegetative stage.

Reference potential evapotranspiration is computed at ten days time interval by using Penman-Monteith method from long-term (1970-1999) average climate data. The monthly mean values of climate parameters of the study area are given in Table 3.1. Reference evapotranspiration data is multiplied by crop-coefficient for the

(a)

(b)

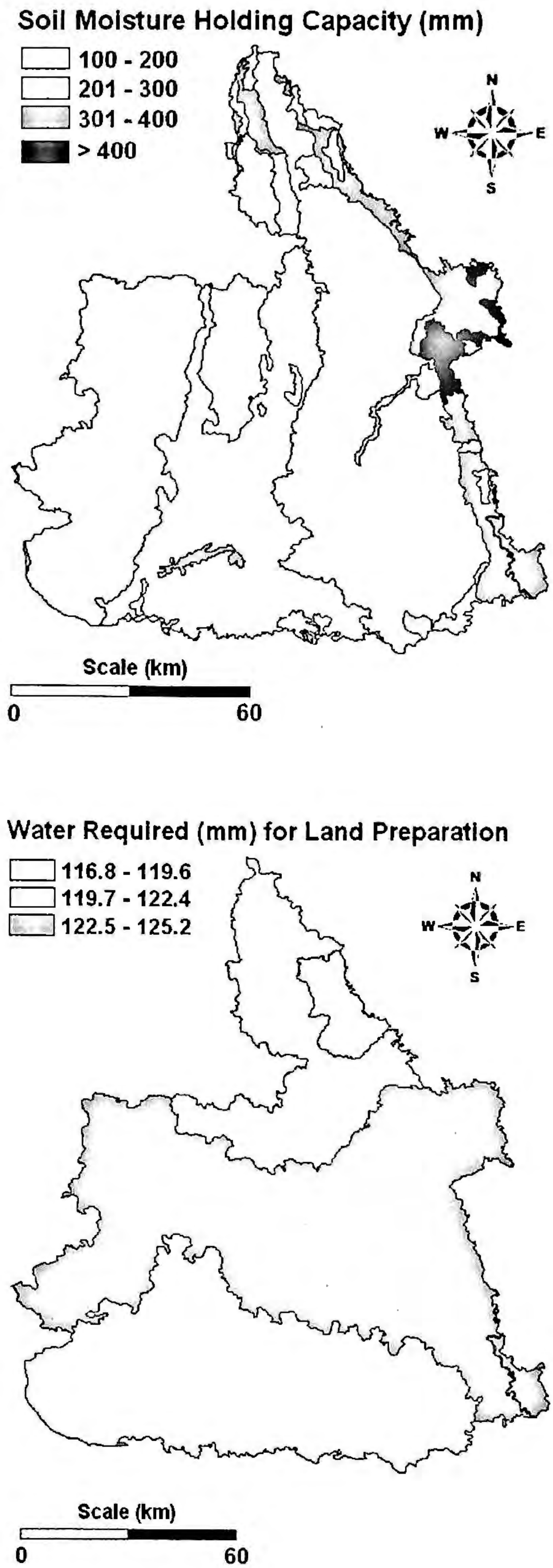
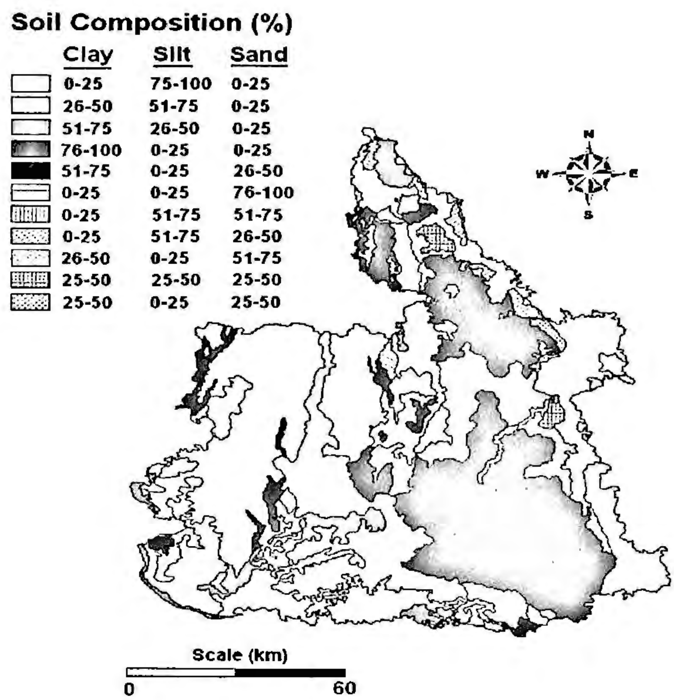


Fig 3.2: (a) Map of soil moisture holding capacity; (b) spatial distribution of water required for land preparation in the study area.

(a)



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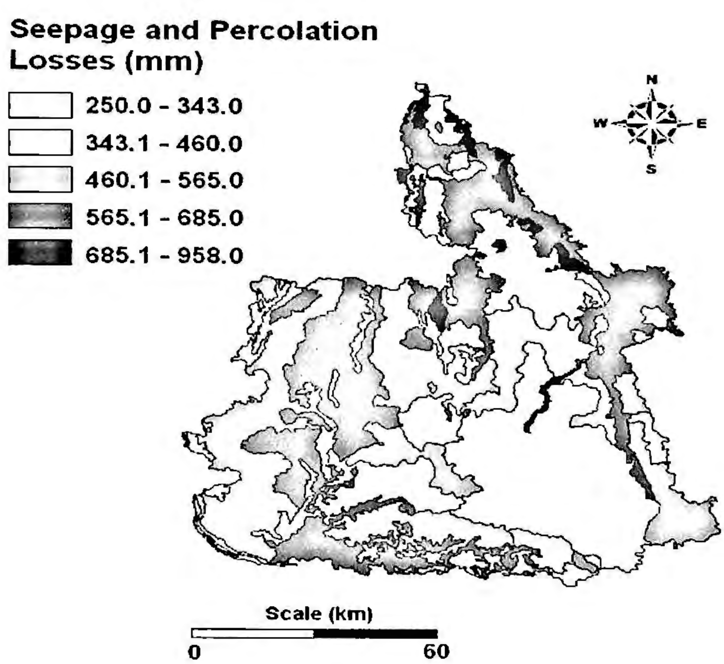


Fig 3.3: (a) Textural composition of soil; (b) spatial distribution of seepage and percolation losses from the irrigated field in the study area.

computation of crop potential evapotranspiration from the Boro rice field during irrigation period. The spatial distribution of crop evapotranspiration in the study area during irrigation period is shown in Figure 3.5. The crop evapotranspiration in the area varies between 396.4 mm and 452.4 mm. However, the value is within the range of 424.5 mm to 438.4 mm in most parts of the area. The map of crop evapotranspiration follows the general pattern of mean temperature of the study area which is different from rainfall distribution.

Table 3.1: Monthly mean values of climate parameters in the study area.

Parameter	**Minimum**	**Maximum**
Minimum Temperature (°C)	11.0	24.0
Maximum Temperature (°C)	24.6	33.6
Humidity (%)	54.9	70.3
Wind Speed (m/s)	0.53	1.52
Solar Radiation (W/m^2)	141.9	324.4

Effective precipitation during the irrigation period is computed by USDA method from long-term (1970-1999) average total rainfall during the irrigation period as shown in Figure 3.6. The spatial distribution of effective precipitation follows a similar pattern as the map of total precipitation. The effective precipitation during irrigation period varies from 7.6 mm in Northwestern part to 50.8 mm in southeast part.

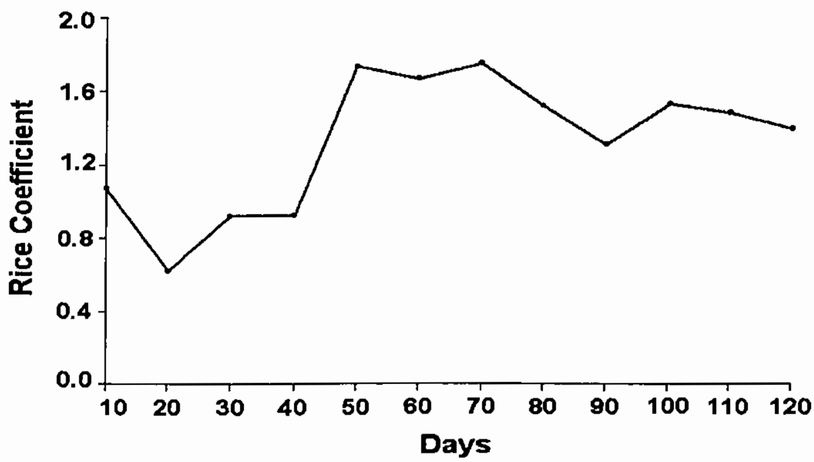


Fig 3.4: Crop-coefficient of Boro rice.

The irrigation water demand map is generated by integrating the thematic maps of crop evapotranspiration, water required for land preparation, effective precipitation, percolation and seepage water losses, and water required to establish water layer step-by-step using the Union tool of ArcMap (ESRI, 2004). First the map of crop evapotranspiration with six polygons is integrated with the map of water required for land preparation having four polygons. This produces an integrated layer with 12 polygons. This layer is then integrated with the map of effective precipitation having four polygons. The process is repeated to integrate the maps of seepage and percolation losses. The final integrated layer consist of 218 polygons contain the information of all parameters required for the calculation of irrigation water demand. The irrigation water requirement at each polygon of the integrated layers is calculated by using the formula given in equation (1). Finally, the polygons of the integrated layer are classified into five classes according to their values of irrigation water requirement to prepare the map of irrigation water demand of the study area which is shown in Figure 3.7. The result shows that the irrigation water demand in the study area varies between 839 mm and 1212 mm. The average value of irrigation water demand in the area is 1035 mm. The resulting irrigation water requirement map is then overlaid on the sub-district map to produce the sub-district scale irrigation water requirement map. GIS is used to overlay irrigation water demand map onto the sub-district map and then calculate the area-weighted average irrigation water requirement for each individual sub-district as shown in Figure 3.8(a). Finally, the Boro rice cultivated area is multiplied by irrigation water requirement to get the sub-district scale map of irrigation water demand volume in the study area which is shown in Figure 3.8(b). Volume of irrigation water demand in the study varies between 39.6 million m^3 and 308.0 million m^3.

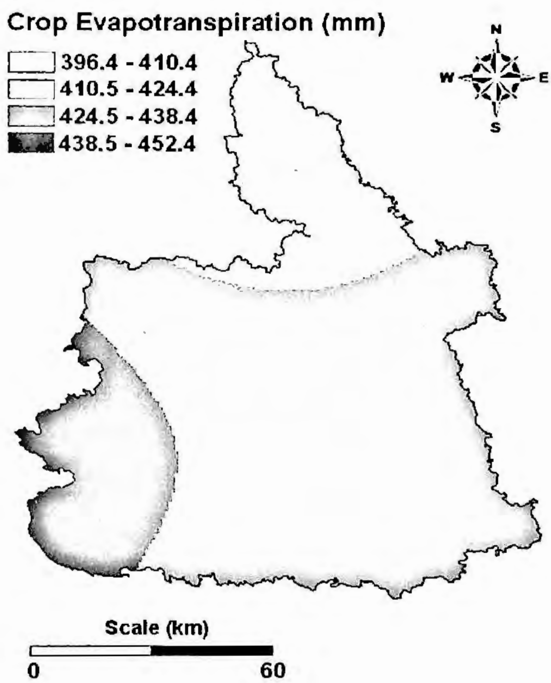


Fig 3.5: Spatial distribution of crop evapotranspiration from Boro rice field in the study area.

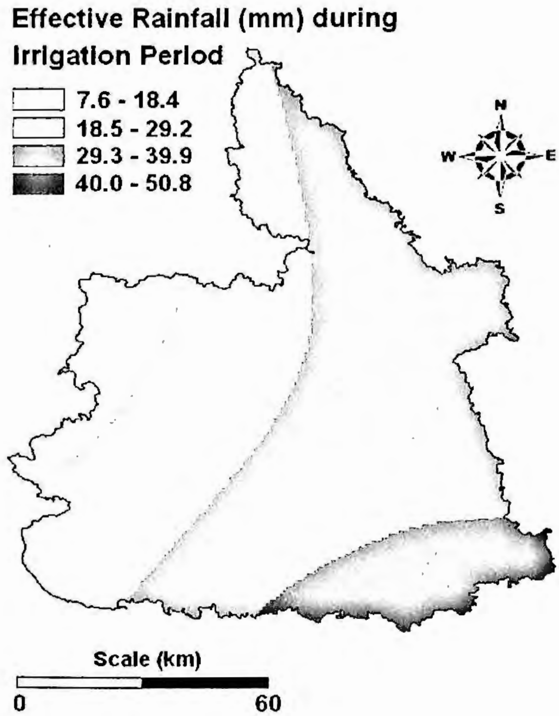


Fig 3.6: Spatial distribution of effective rainfall during Boro rice growing period in the study area.

3.3 Computation of Domestic Water Demand

Population distribution in the study area is shown in Figure 3.9(a). Volumetric domestic water demand in the study area, calculated by using equation (5) is shown in Figure 3.9(b). Domestic water demand volume in the study area varies from 1.4 million m^3 to 11.7 million m^3. Total volume of groundwater demand is computed by using equation (6) and displayed in Figure 3.10(a). Comparison of irrigation and domestic water demand in different sub-district of the study area is shown in Figure 3.10(b). On average 96.5% of total groundwater demand in the study area is for irrigation and the rest is for domestic uses.

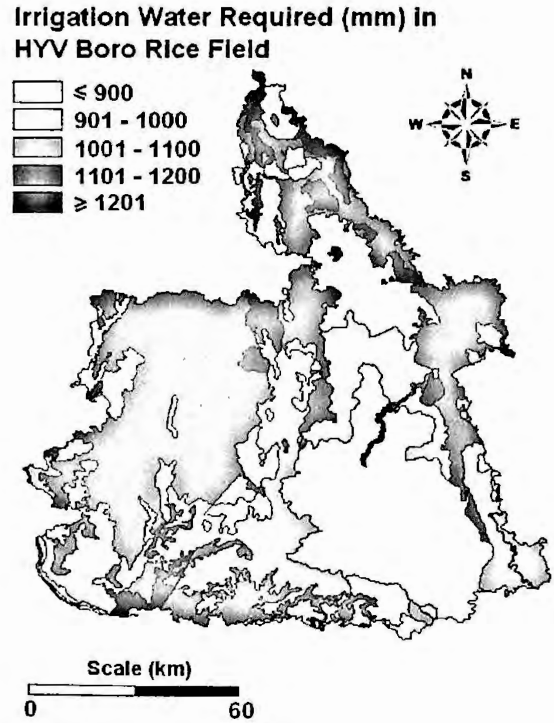
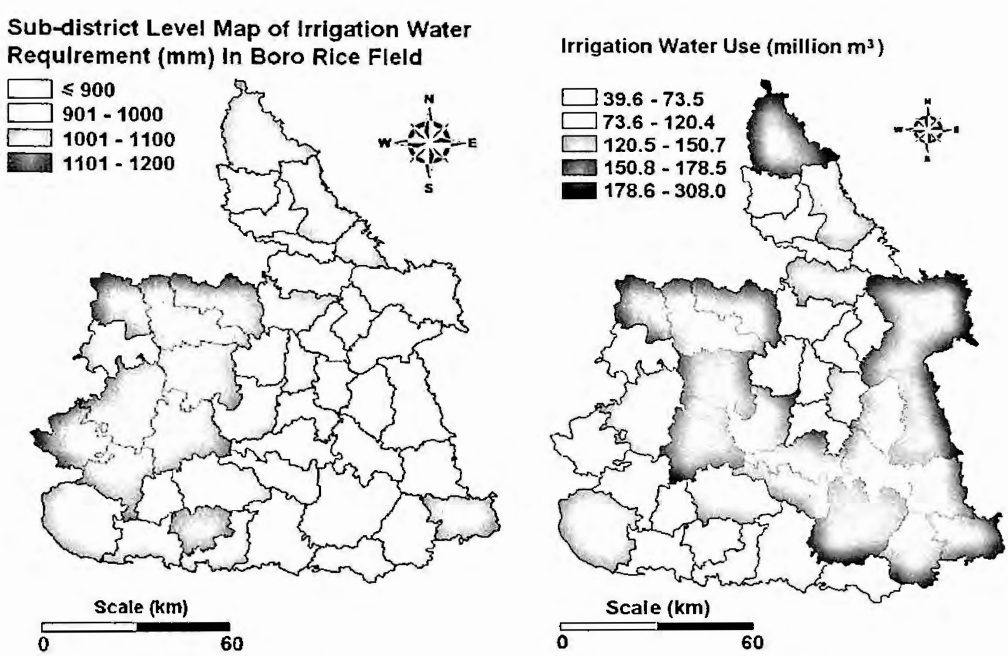
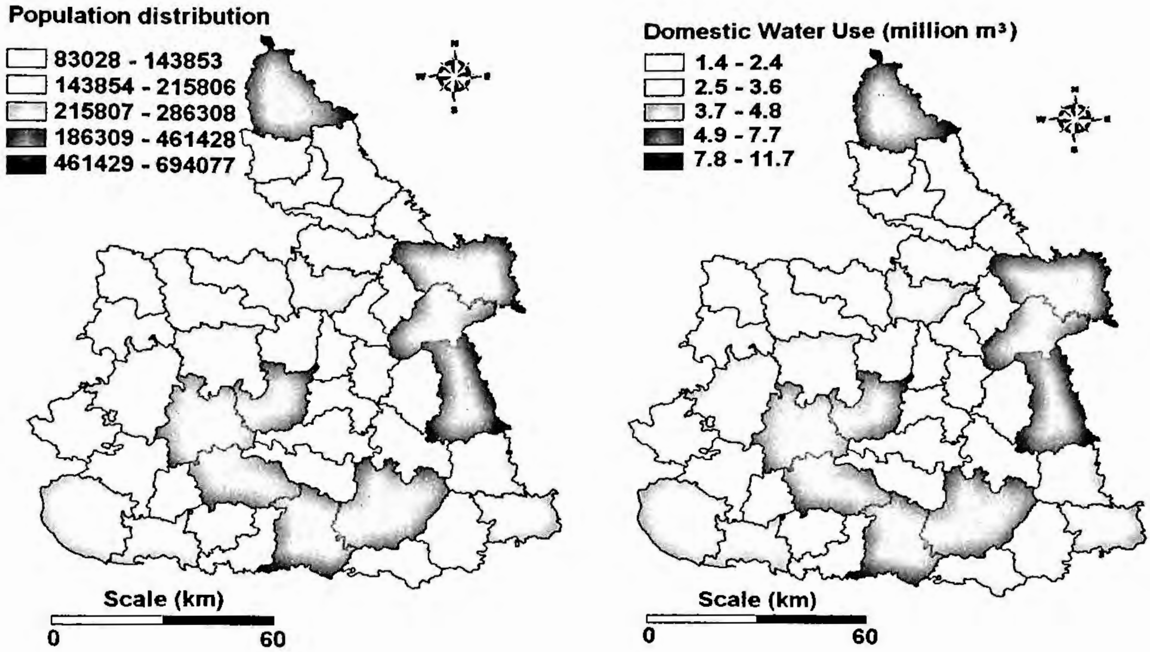


Fig 3.7: Spatial distribution of irrigation water requirement in HYV Boro rice field in Northwestern part of Bangladesh



(a) **(b)**

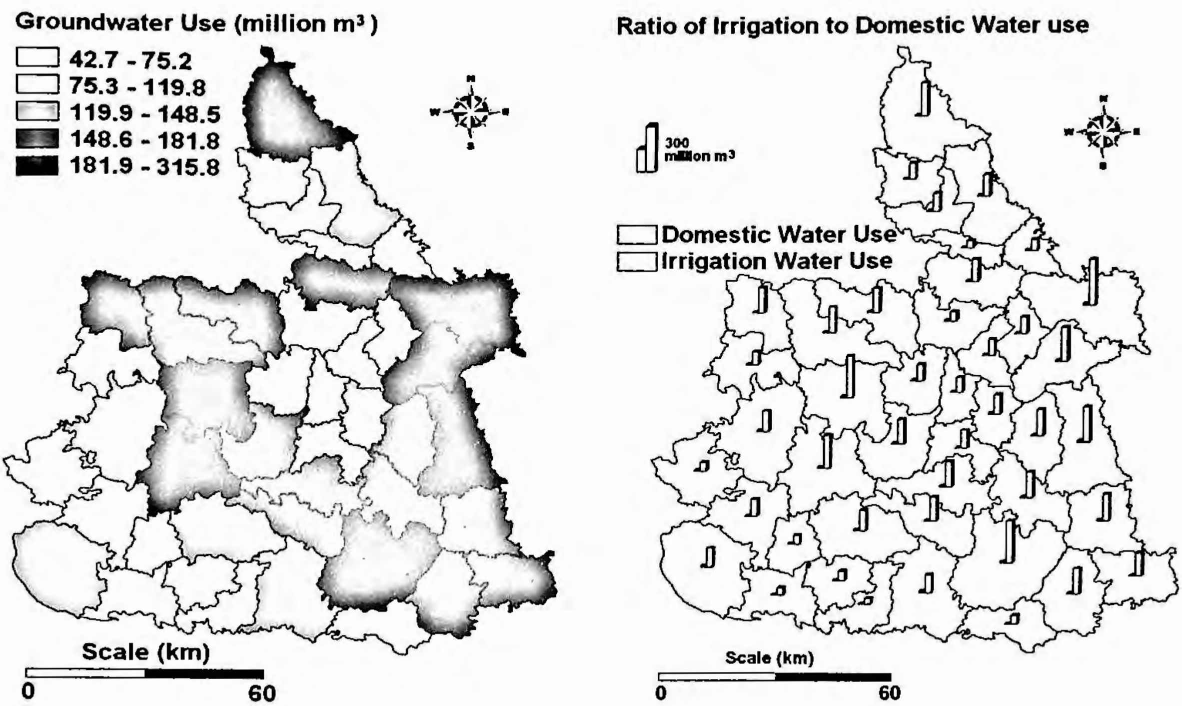
Fig 3.8: (a) Sub-district level map of irrigation water requirement in HYV Boro rice field; (b) Sub-district level volumetric irrigation water use map for Northwestern Bangladesh



(a) (b)

Fig 3.9: (a) Population distribution in the study area; (b) Sub-district level volumetric domestic water demand map of the study area.

The study shows that the irrigation water demand is lowest (below 900 mm) in the eastern part of the study area. This is mainly due to the clayey soil in the area which prevents rapid percolation and seepage losses through the paddy fields. The precipitation in this part of the study area is also higher compared to western part. The irrigation water demand is found highest (more than 1100 mm) in the western part of the area. High percolation and seepage losses due to soil characteristics, high evapotranspiration and low precipitation are the causes of higher irrigation water demand in this part. The pattern of irrigation water demand in the study area shows that it mainly depends on soil characteristics. Evapotranspiration is the second most important factor for irrigation water demand in the area. Rainfall contributes less compared to other factors.



(a) (b)

Fig 3.10: (a) Sub-district level map of total groundwater demand (in million cubic meter) in the study area; (b) comparison of irrigation and domestic water demands in different sub-districts of the study area.

3.4 Conclusion

In the context of growing demand of groundwater in Bangladesh, management of this resource is essential to supply the growing population with sufficient water to increase food production as well as to improve the hygiene and health situation. In the present work, a study has been carried out for spatial assessment of groundwater demand in Northwestern Bangladesh as a part of groundwater resources management. Major outcome of the study is the production of maps of irrigation water demand, domestic water demand and total groundwater demand in the northwest part of Bangladesh.

The study shows that the irrigation water requirements in the western part of the study area are comparatively higher than the eastern part. This is mainly due to the soil characteristics of the area. Higher requirement of irrigation water in the western part may be one of the causes of less cultivation of Boro rice during the dry season. Proper groundwater management policy is essential in the study area to reduce the negative impacts on groundwater resources in the context of its increasing demand due to the growth of population and extension of agricultural land.

It is hoped that the study will be beneficial to a number of stakeholders in the country, particularly farmers and agricultural organization, but also the water development and management organizations, development/planning authorities and educational authorities to improve their understanding on groundwater demand/use in the Northwestern part of Bangladesh. As the assessment of irrigation/domestic water requirement is one of the main aspects of agriculture and water resources development and planning, it is hoped that the maps and the study in general will assist in guiding the operational responses of the various authorities, especially in terms of those interventions aimed at agricultural and water resources development and management in northwest Bangladesh.

Chapter-4

MODELING CLIMATE CHANGE SCENARIOS

4.1 Introduction

To predict the future climate change in the study area, regional climate scenario generation model MAGICC/SCENGEN is used. SCENGEN constructs a range of geographically-explicit climate change scenarios for the world by exploiting the results from the models for the assessment of greenhouse-gas induced climate change (MAGICC) and a set of GCM experiments, and combining these with observed global and regional climate data sets. SCENGEN contains a set of greenhouse gas-induced patterns of regional climate change obtained from 16 different General Circulation Models (GCM) experiments and also sulfate aerosol-induced patterns of regional climate change. A geographically-explicit climate change scenario can be constructed by selecting a future time interval, one or more of the greenhouse gas-induced GCM climate change patterns and the regional aerosol patterns (Houghton et al., 2001).

In the present study, the models of MAGICC/SCENGEN are first used to simulate the present climate (rainfall and temperature) over the study area (Northwestern Bangladesh). Average of three-year (2000-2002) monthly temperature and rainfall predicted by different models are compared with actual data. Root Mean Squared Error (RMSE) method is used to measure the performance of each model. The models are ranked according to their performance to simulate rainfall and temperature and the best models are picked up to project the future change of climate in the study area. The models are run with the IPCC B2 SRES scenario (IPCC, 2000).

B2 storyline and scenario family describes a world in which emphasis is given on local solutions to economic, social and environmental sustainability and lower green house gas emission. Similar to B2 scenario, population for Bangladesh and surrounding region is projected to increase continuously but at a lower rate. GDP projection also represents the intermediate level of economic development like B2 scenario (Nair et al., 2003). Lower emission of green house gas close to B2 scenario is the mid-to-long term policy of the region (Hong et al., 2007). Therefore, the present study focuses on irrigation water demand under the B2 climate scenario.

Resolution of climate models of MAGICC/SCENGEN is 2.5 degree. The whole Bangladesh can be covered by six pixels only. The study area belongs to two pixels, one covers the northwest and the other covers the southwest parts of Bangladesh. Temperature and rainfall values predicted by the climate models for the two pixels are averaged to get the projected change in mean temperature and rainfall in the study area. It is assumed that change in temperature and rainfall will be uniform over the study area.

4.2 Climate Projection over the Study Area

Recorded and modeled average temperature and monthly rainfall by different models for the year 2000 are given in Table 4.1 and Table 4.2 respectively. Modeled average temperature and monthly rainfall by the models for the years 2001 and 2002 are similar and therefore, not tabulated here. RMS errors in prediction of three-year (2000-2002) averaged temperature and monthly rainfall by IPCC climate models are given in Table 4.3.

It can be found from the table that the models CSI296, ECH395, CCSR96, WM_95, CSM_98, IAP_97 and PCM_00 can simulate temperature and the models MRI_TR96, CSM_TR98, HAD295, CERFTR98, ECH4TR98, HAD300, CSI296, and CCC199 can simulate rainfall with reasonable error. Therefore, those models are used for the projection climate in northwestern Bangladesh. The actual and projected average rainfalls and temperatures by the best models for the years 2000-2002 are shown in Figures 4.1 and 4.2 respectively. To show the accuracy of the model outputs, the modeled monthly average rainfall by the best models and the actual recorded monthly rainfall for the year 2000 is shown in Figure 4.3. Similarly, the modeled monthly average temperature by the best models and the actual recorded monthly temperature for the year 2000 is shown in Figure 4.4. The figures show that the modeled output is very near to the actually recorded rainfall and temperature for the year 2000. The projected temperature and rainfall for the years 2025, 2050, 2075 and 2100 using the best models are shown by graphs in Figure 4.5(a) and (b) respectively. Projected average temperature and rainfall during the irrigation months in the year 2025, 2050, 2075 and 2100 are given in Tables 4.4 and 4.5 respectively. These rainfall and temperature values are used in the present study for the calculation of change in irrigation water demand.

The climate models estimate a steady increase in temperature for Bangladesh. More warming is estimated in winter compared to summer. The models predict an average increase of temperature 0.8°C in 2025, 1.4°C in 2050, 1.9°C in 2075, and 2.4°C in 2100.

A maximum increase of temperature in January, about 3°C in 2100 and minimum increase of temperature in July, about 1.4°C in 2100 are projected. In case of rainfall, the models show an annual increase of rainfall. Most of the climate models estimate that precipitation will increase during the summer monsoon as the air over land will warm more than the air over oceans during summer. The models also show a decrease in precipitation in the winter months of December, January and February. Maximum increase of rainfall is predicted for the month of August, about 1.2 mm/day in 2100 and a maximum decrease of rainfall in December, about 0.4 mm/day in 2100.

Table 4.1: Comparison of Recorded average temperature and modeled average temperature for different months of 2000.

Models	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Recorded	11.6	15.3	19.6	25.4	24.9	26.0	25.7	25.8	25.4	24.2	18.5	14.0
BMRC_98	23.1	27.5	33.2	36.8	39.9	38.3	32.1	28.7	26.5	24.4	22.4	22.0
CCC199	19.2	20.6	22.3	24.2	26.4	28.6	27.4	26.4	25.8	24.2	21.4	19.3
CCSR96	14.5	19.1	25.3	29.4	30.7	25.7	23.2	23.2	23.4	21.9	16.7	13.6
CERF98	20.2	23.9	28.5	31.4	34.5	35.6	31.0	28.1	27.5	25.8	23.3	20.1
CSI296	15.8	18.2	21.9	25.8	28.5	28.1	27.6	27.6	27.1	24.6	20.1	16.4
CSM_98	17.3	19.8	24.3	28.2	28.4	26.8	26.5	26.3	26.1	25.2	21.7	18.6
ECH395	15.5	18.7	23.9	27.9	29.5	30.1	28.2	25.9	25.0	22.7	18.3	16.1
ECH498	20.5	24.0	28.1	30.3	31.3	32.1	29.4	28.1	27.5	25.5	23.1	20.6
GISS95	26.8	28.4	31.1	32.1	32.5	31.5	29.4	28.5	28.4	29.0	27.5	26.5
HAD295	21.8	24.6	28.4	32.1	33.5	30.0	28.8	29.6	28.3	27.2	25.2	22.7
HAD300	19.0	22.7	27.3	30.9	33.4	34.8	29.3	28.9	28.4	26.3	22.0	18.5
IAP_97	18.6	20.3	22.3	24.9	27.8	27.5	26.7	26.7	27.1	25.1	21.4	18.9
LMD_98	13.7	16.7	23.1	29.4	31.7	34.1	35.8	35.0	34.4	29.5	22.5	16.6
MRI_96	20.5	23.9	27.2	30.4	29.8	26.5	24.6	24.8	25.5	25.5	24.2	20.4
PCM_00	17.9	20.3	24.1	25.9	26.8	27.0	26.6	26.2	26.6	26.0	23.1	19.2
WM_95	12.5	17.4	25.0	30.6	32.8	30.9	30.0	30.9	30.7	27.3	22.7	16.3

Table 4.2: Comparison of Recorded monthly rainfall and modeled monthly rainfall for different months of 2000.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Recorded	8	14	24	107	257	351	271	317	197	107	21	1
BMRC_98	0	0	0	3	6	129	372	422	273	102	12	0
CCC199	47	64	93	66	133	309	310	226	195	161	141	43
CCSR96	16	8	6	9	118	399	459	415	339	158	42	19
CERF98	12	11	22	54	78	108	239	254	189	93	54	25
CSI296	34	36	62	45	87	264	264	192	147	62	63	31
CSM_98	31	34	22	39	90	264	388	316	180	59	36	16
ECH395	0	0	6	24	62	111	174	198	114	50	3	3
ECH498	3	6	25	48	81	114	239	260	237	68	15	12
GISS95	9	11	16	42	81	123	177	167	117	50	21	16
HAD295	3	3	3	9	65	189	202	140	168	99	30	6
HAD300	12	11	9	18	34	126	409	344	261	115	27	12
IAP_97	56	45	37	27	109	210	195	130	99	50	30	37
LMD_98	6	6	0	0	3	3	9	19	9	19	12	6
MRI_96	12	14	22	15	118	243	366	316	195	112	27	16
PCM_00	25	28	37	99	167	381	406	291	135	102	42	28
WM_95	43	25	12	24	99	282	229	180	201	208	135	65

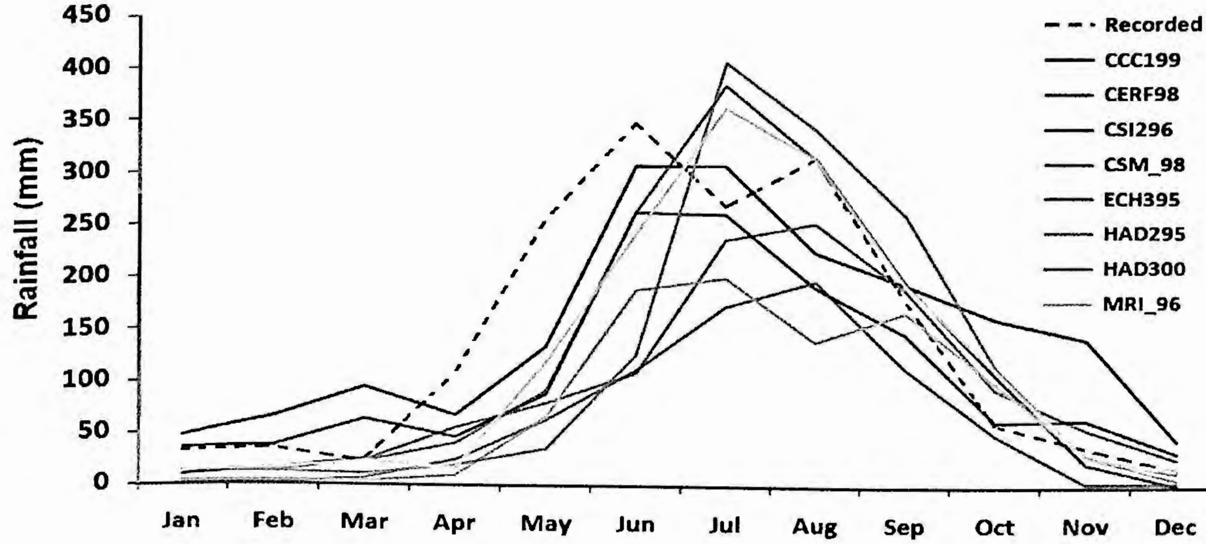


Fig 4.1: The graph showing predicted average rainfall by best eight models for the years 2000-2002.

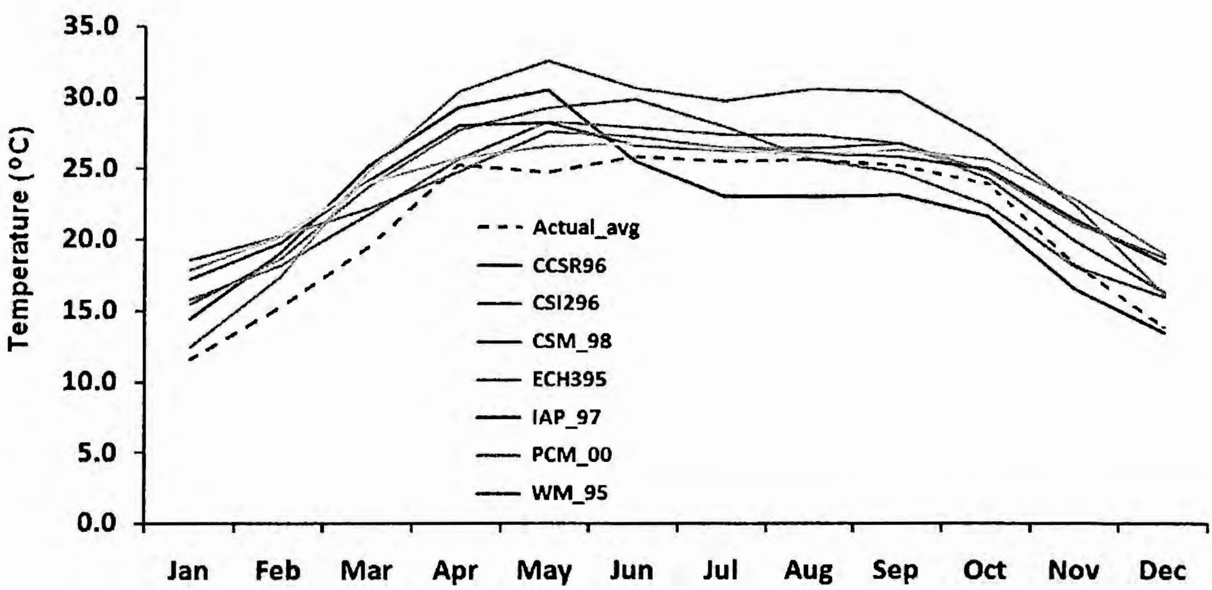


Fig 4.2: The graph showing predicted average temperature by best seven models for the years 2000-2002.

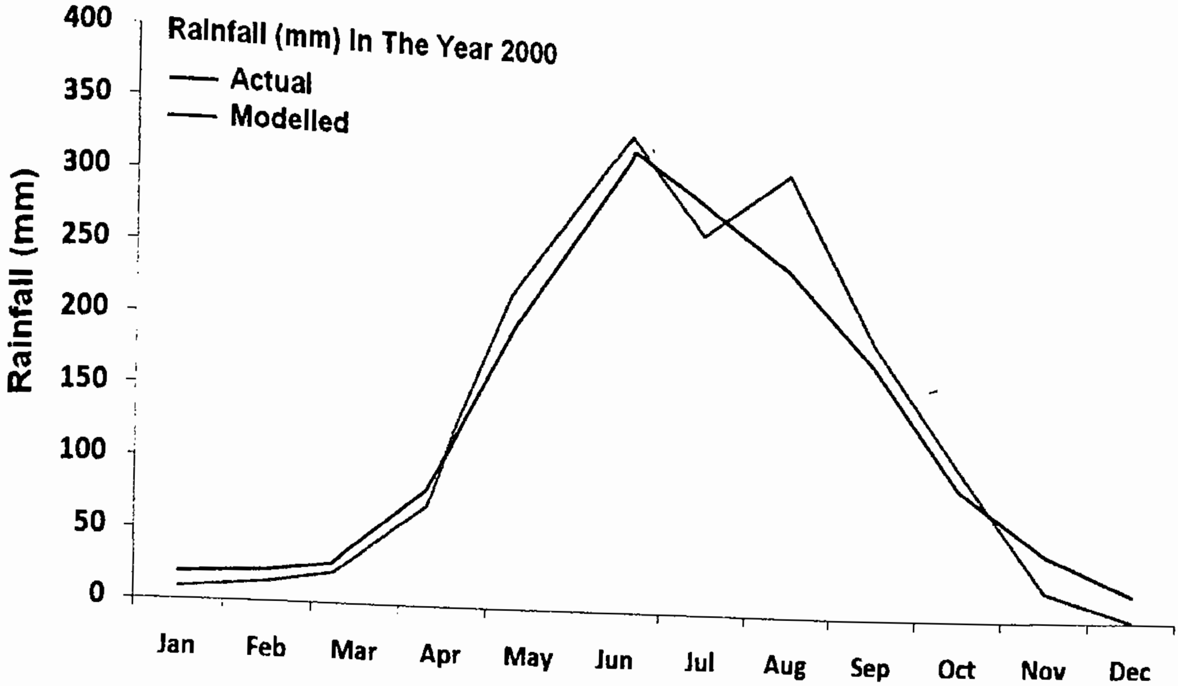


Fig 4.3: The graph showing predicted rainfall by the models and the actual recorded rainfall for the year 2000.

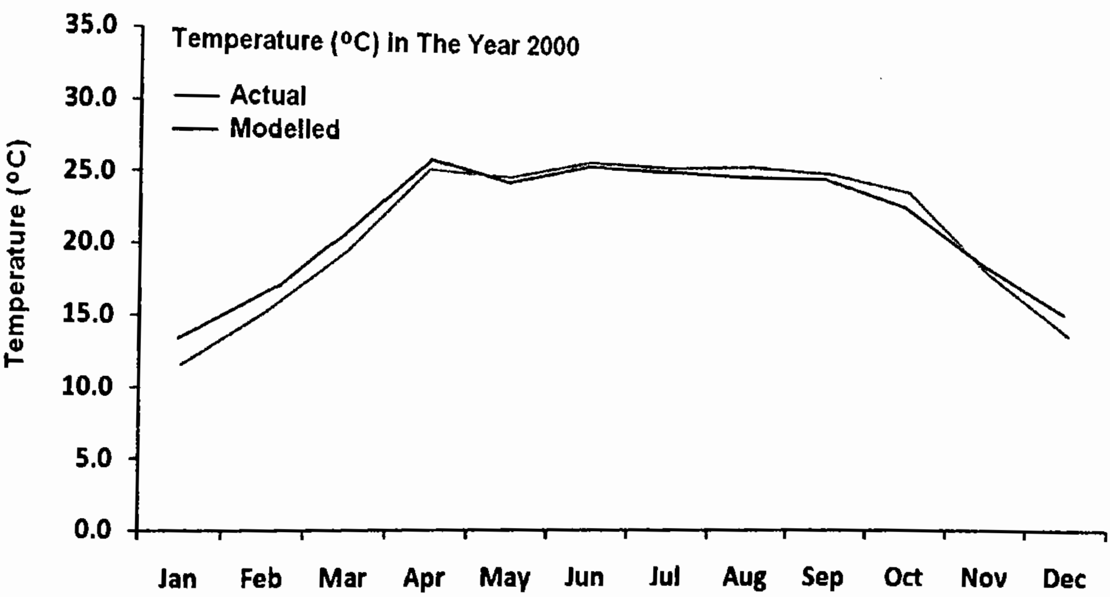


Fig 4.4: The graph showing predicted temperature by the models and the actual recorded temperature for the year 2000.

Table 4.3: Root mean square errors in prediction of temperature and rainfall by different models at 2.5° resolution

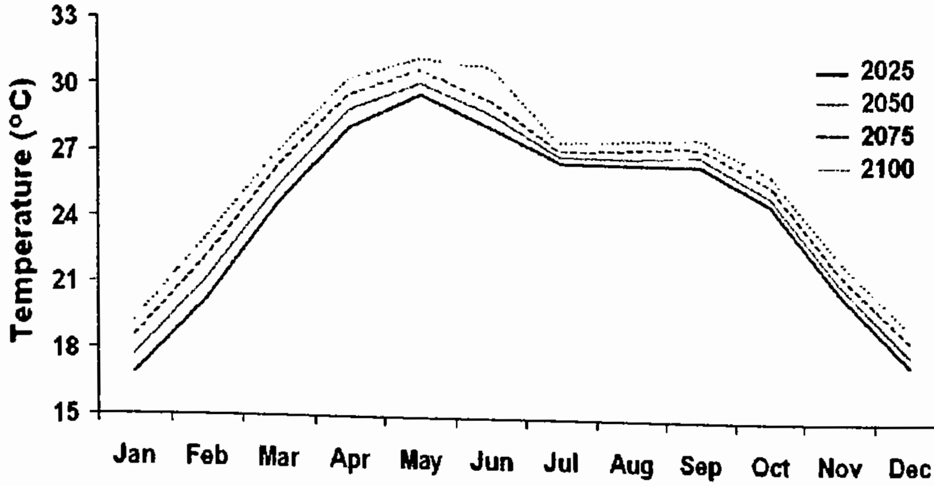
RMS Error in prediction by different models			
Temperature		**Rainfall**	
Model	**Error**	**Model**	**Error**
CSI296	0.147314	MRI_96	7.206
ECH395	0.162126	CSM_98	8.775
CCSR96	0.166604	HAD295	8.868
WM_95	0.200915	CERF98	11.895
CSM_98	0.216026	ECH498	12.823
IAP_97	0.23503	HAD300	19.279
PCM_00	0.236498	CSI296	20.630
CCC199	0.251187	CCC199	20.754
LMD_98	0.259137	BMRC_98	21.894
HAD300	0.325044	PCM_00	22.259
MRI_96	0.346765	ECH395	24.057
ECH498	0.362958	GISS95	24.240
CERF98	0.379847	WM_95	31.119
HAD295	0.422173	IAP_97	33.423
BMRC_98	0.527243	CCSR96	41.845
GISS95	0.585995	LMD_98	54.401

Table 4.4: Projection of average daily rainfall (mm) during irrigation period by climate models

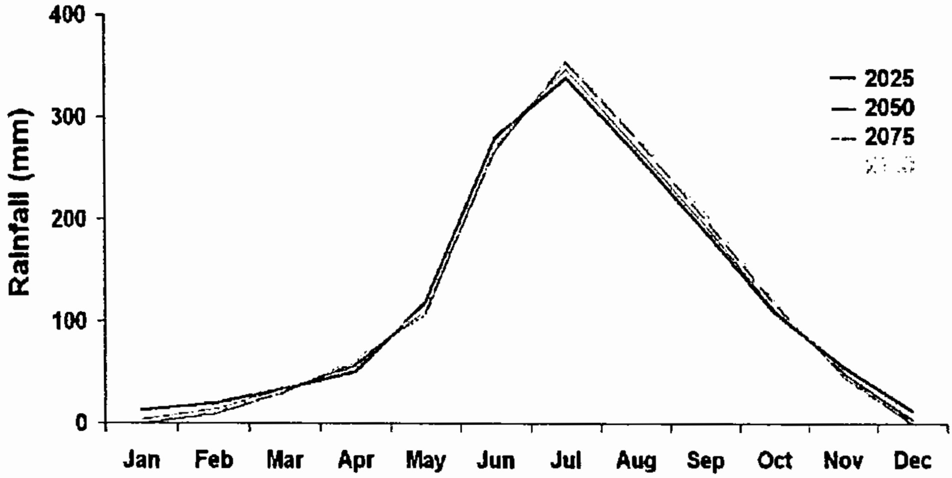
Month	Projected daily average rainfall (mm)			
	2025	2050	2075	2100
Jan	0.4	0.1	0	0
Feb	0.7	0.5	0.4	0.3
Mar	1.1	1.1	1	1
Apr	1.7	1.9	2	2.1
May	3.5	3.6	3.8	3.9

Table 4.5: Projection of average daily temperature (°C) during irrigation period

Month	Projected daily average temperature (°C)			
	2025	2050	2075	2100
Jan	16.9	17.7	18.5	19.2
Feb	20.2	21.2	22.1	23
Mar	24.7	25.5	26.3	27
Apr	28.2	29	29.7	30.4
May	29.8	30.3	30.9	31.4



(a)



(b)

Fig 4.5: Predicted (a) temperature and (b) rainfall in the study area in the years of 2025, 2050, 2075 and 2100.

4.3 Concluding Remarks

The models of MAGICC/SCENGEN are used in this chapter to simulate the rainfall and temperature of twenty-first century of northwestern Bangladesh. The study reveals that the models CSI296, ECH395, CCSR96, WM_95, CSM_98, IAP_97 and PCM_00 can best simulate the temperature and the models MRI_TR96, CSM_TR98, HAD295, CERFTR98, ECH4TR98, HAD300, CSI296, and CCC199 can best simulate the rainfall of the study area. The projected temperature by the best models shows an average increase of temperature 0.8°C in 2025, 1.4°C in 2050, 1.9°C in 2075, and 2.4°C in 2100. Winter temperature is found to increase more compared to summer temperature. In case of rainfall, the models show an annual increase of rainfall. The seasonal projection shows a significant increase of precipitation during the summer monsoon months and a small decrease in the winter months. The resolution of the models used in the study is 2.5 arc degrees only. Therefore, the outputs obtained by these coarse resolution climate models were not matched very closely with the past climate of the area. High resolution models are generally used for more accurate projection of climate at regional scale. However, in annual temporal scale the error between the model outputs and the recorded data was found reasonably less. Usually, MAGICC/SCENGEN models can give a clear idea about overall change of climate for an area extended over several hundred square kilometers.

Therefore, it can be concluded that the model outputs obtained in the present chapter can be used for simulation of climate change impacts on water resources of the study area.

Chapter-5

GROUNDWATER DROUGHTS IN THE STUDY AREA

5.1 Introduction

Hydrological drought is defined as the deficiencies in surface and subsurface water supplies, which lead to a lack of water availability to meet normal and specific water demands (Demuth and Bakenhus, 1994). Groundwater drought is a particular type of hydrological drought that occurs when groundwater recharge, heads or discharge deviate from normal (van Lanen, 2005; Tallaksen and van Lanen, 2004). Calow et al. (1999) defined groundwater drought as a situation where groundwater sources fail as a direct consequence of drought. According to van Lanen and Peters (2000), a groundwater drought occurs if in an aquifer the groundwater heads fall below a critical level over a certain period of time, which results in adverse effects. Groundwater droughts are often out of phase with both meteorological and agricultural droughts (Wilhite & Glantz, 1985; Tallaksen and van Lanen, 2004). Within the hydrological drought sequence groundwater is the last to react to a drought situation (Mendicino and Versace, 2007). Therefore, a groundwater drought is usually lags behind the deficient precipitation. Groundwater levels which provide indirect knowledge about groundwater recharge and discharge are used in the present paper to study groundwater drought. The Cumulative Deficit (*CD*) approach from threshold groundwater levels proposed by van Lanen and Peters (2000) is used to measure the severity of droughts.

5.2 Data

Five years (1998-2002) monthly groundwater level data collected from eighty-five sites in the study area have been used to study the spatial distribution of groundwater droughts. Location of the data points are shown in Figure 5.1. Long term monthly groundwater fluctuation data, starting from mid eighty's to 2002, available in nine sites in the study area, are used to analyze the groundwater hydrographs and correlate groundwater level with meteorological droughts. Thirty-nine years (1964-2002) monthly rainfall data recorded in the meteorological station located at Rajshahi has been used to identify meteorological drought events and severity.

5.3 Spatial Extents of Groundwater Droughts

Spatial extent of groundwater droughts for three threshold levels viz. 30%, 20% and 5% of mean groundwater level for the years from 1998 to 2002 are shown in Figures 5.2, 5.3 and 5.4 respectively. The mean groundwater level is calculated from five years (1998-2002) monthly groundwater level fluctuation data. The figures show that groundwater scarcity is a regular phenomenon in the northwestern districts of

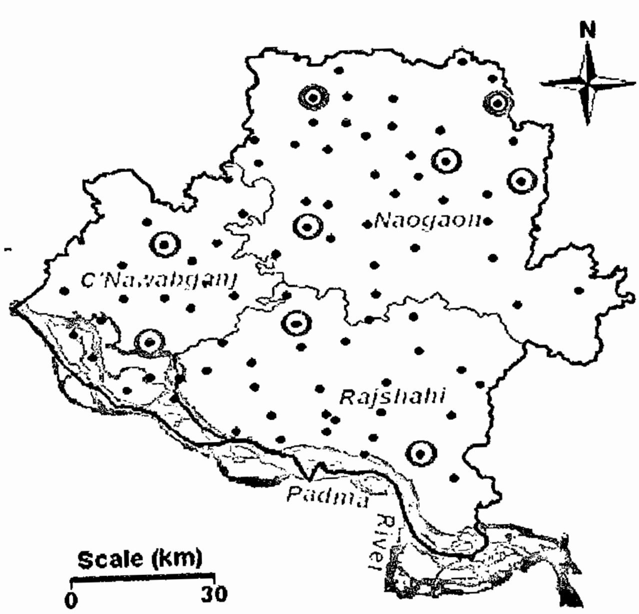


Fig 5.1: Location of groundwater sampling points used to study spatial extents of groundwater droughts.

Bangladesh especially in the eastern side of Rajshahi district and northwest side of Naogaon district. Due to the scarcity of long-term data in all the points, no statistical analysis was possible to correlate the spatial extent or severity of groundwater droughts with the amount and distribution of rainfall. Spatial extents of groundwater droughts with different severity are analyzed in this section only to get an overview of groundwater drought situation in the study area. Figure 5.2 shows that groundwater in at least 42% area goes below 30% of the mean level in every year. Cumulative deficit more than 2 meter is also evident almost every year in some sites. Figure 5.3 reveals that in 39% area groundwater level goes below 20% of the mean level in every year. Though the groundwater drought-affected area varies from year to year, Figure 5.4 shows that groundwater level drop below 5% of the mean level is also common in some parts of Rajshahi district in every year.

The long-term groundwater level data available in few sites of the study area are analyzed and correlated with meteorological droughts in the following sections of the paper to get an idea about possible causes of groundwater droughts in the area.

5.4 Analysis of Groundwater Hydrographs

Long-term groundwater level fluctuation data available in nine sites in the study area show two types of nature viz. (a) *Type-1*: gradual decrease of minimum groundwater levels, but no apparent change in maximum level, and (b) *Type-2*: gradual decrease of both minimum and maximum groundwater levels. Two sample long-term groundwater fluctuation data of *Type-1* and *Type-2* are shown in Figures 5.5(a) and (b) respectively. Both the figures show that average level of groundwater has been declined during the time period 1986-2002. However, the most serious effect is the longer period of groundwater absence above a certain level. The Figures 5.6(a) and (b) show the variation of groundwater levels in different months during the time period 1986-2002 for the sample hydrographs of *Type-1* and *Type-2*. Figure 5.6(a) shows that groundwater never declined below 20 m before 1994, but it is common phenomena in the months of April and May after 1995. Long absence of groundwater level below 10 m and 15 m is also noticeable after 1995. Similar situation can be found in Figure 5.6(b). Declination of groundwater level below 7 m was found to occur only during the months of April and May in the early years, but in the recent years it is common even for the whole year.

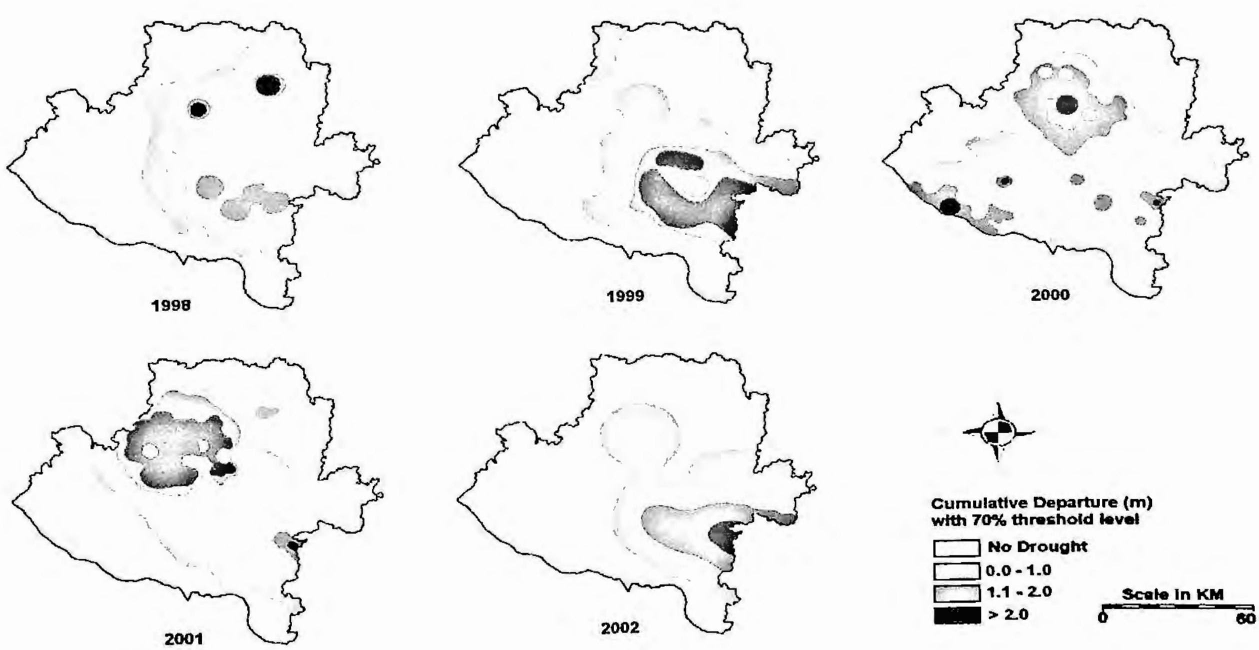


Fig 5.2: Spatial extent of groundwater droughts in the study area computed for a threshold of 30% of the mean groundwater level for the years 1998-2002.

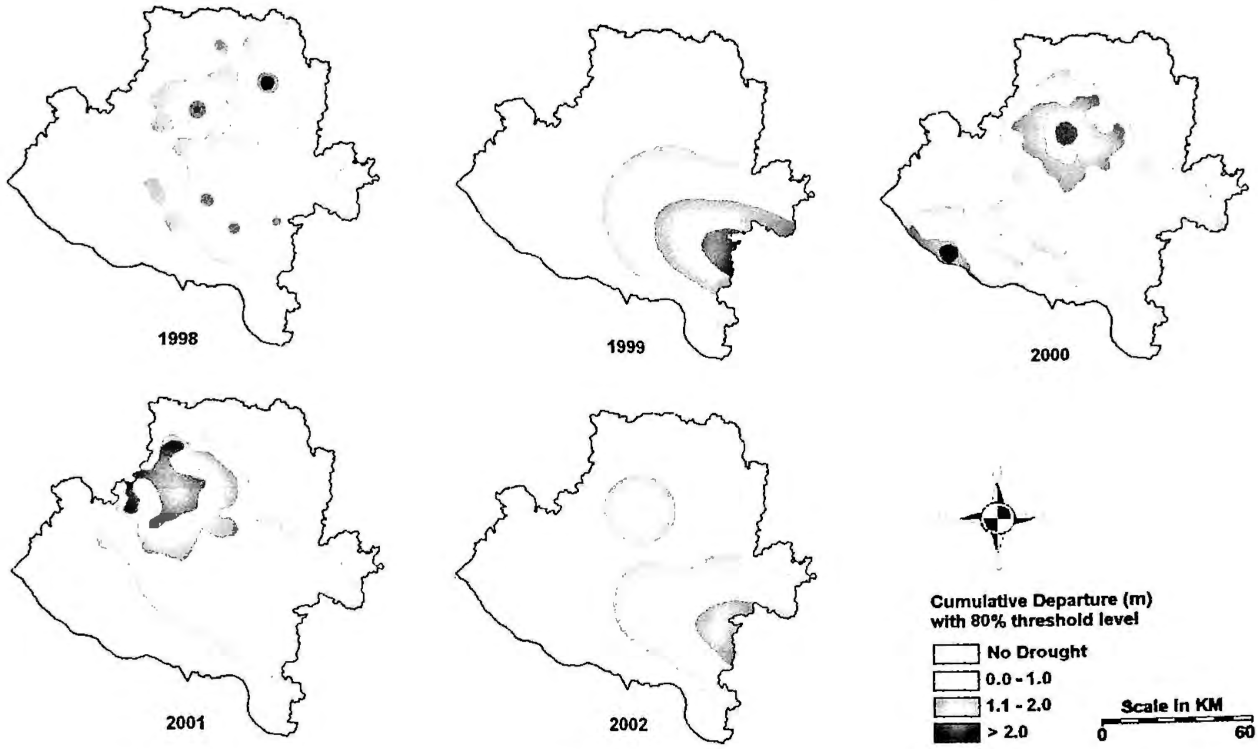


Fig 5.3: Spatial extent of groundwater droughts in the study area computed for a threshold of 20% of the mean groundwater level for the years 1998-2002.

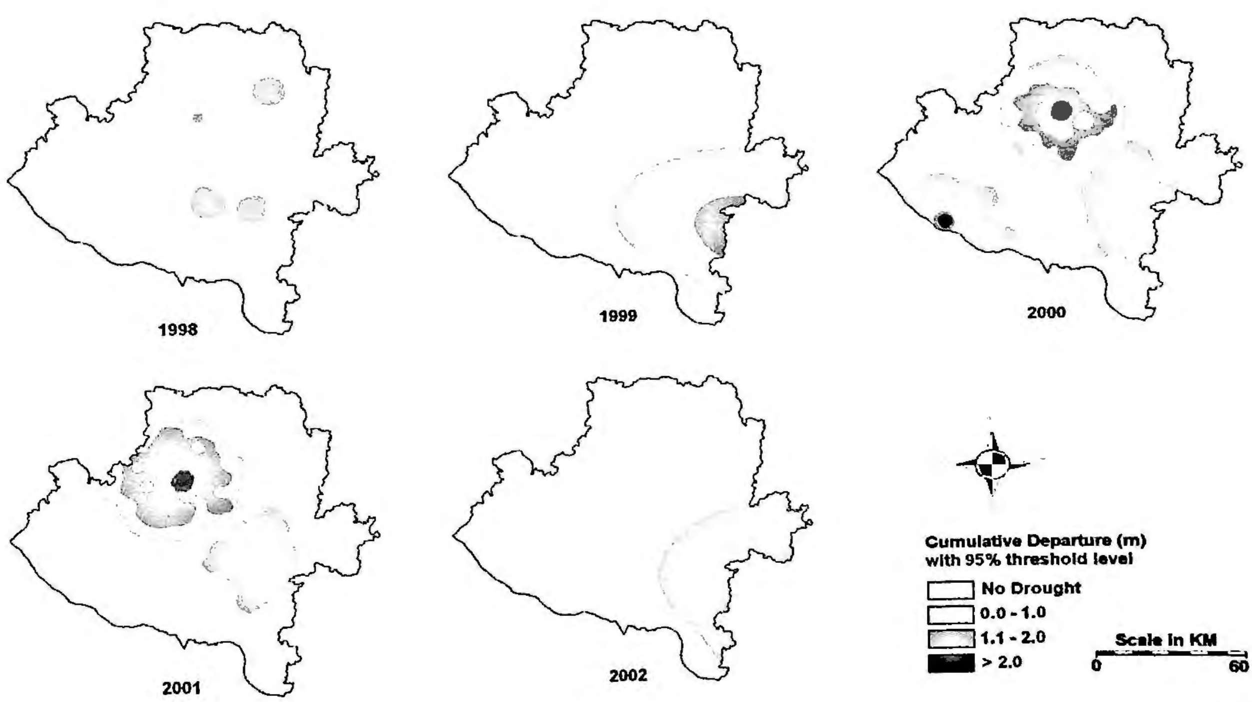


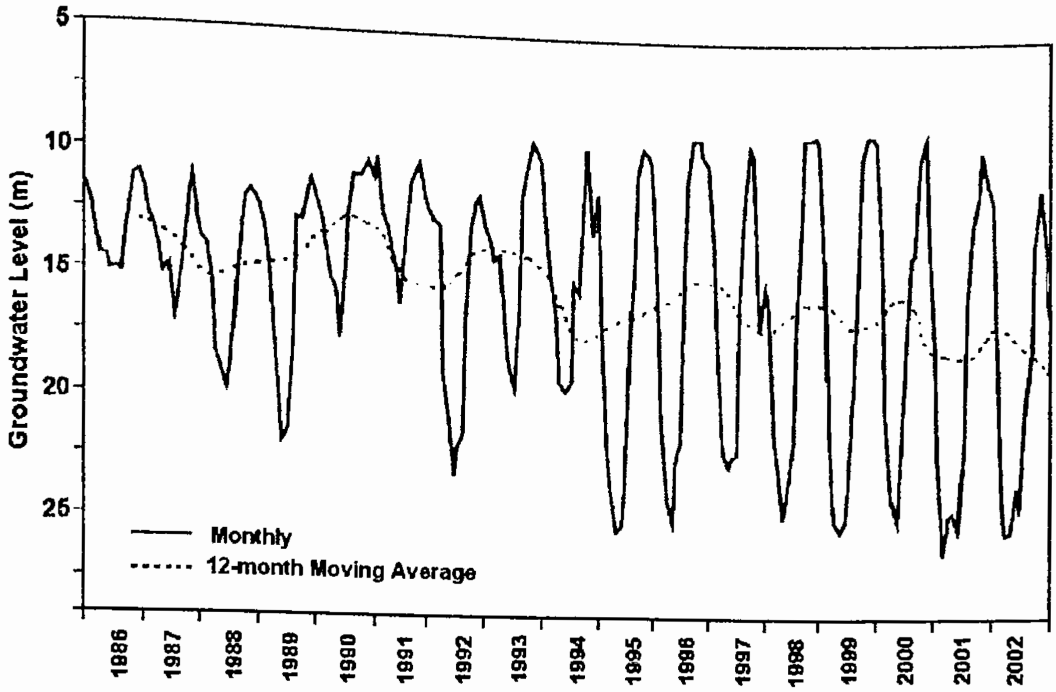
Fig 5.4: Spatial extent of groundwater droughts in the study area computed for a threshold of 5% of the mean groundwater level for the years 1998-2002.

5.5 Relation between Groundwater Level and Rainfall

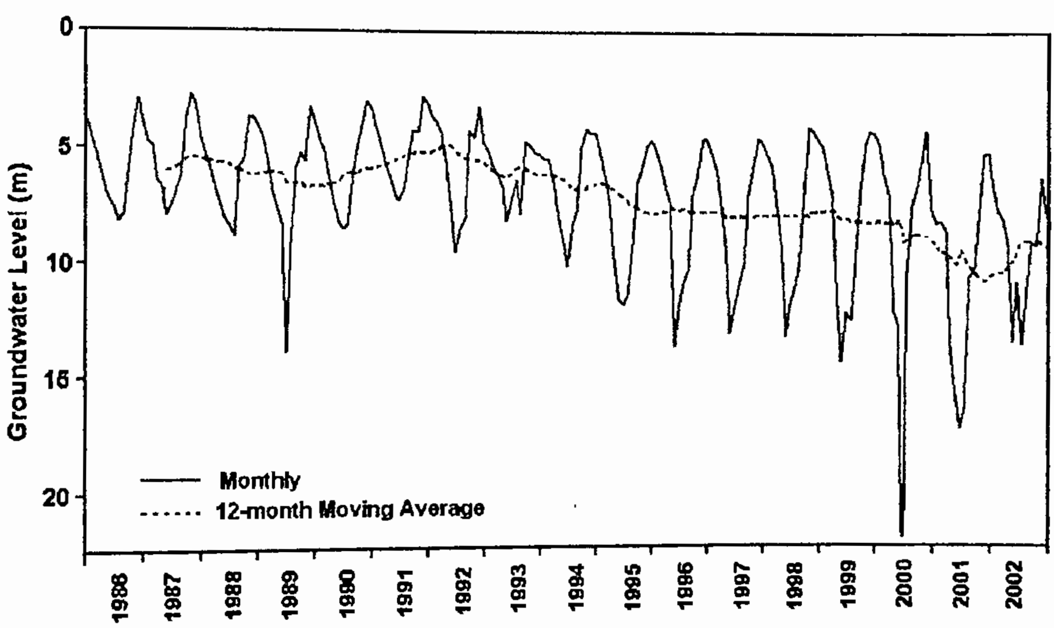
The relation of rainfall and groundwater regimes for the area is shown in Figure 5.7. Five years monthly rainfall and monthly average groundwater fluctuation data available at different points around the rain-gauge station are used to draw the relation. The figure shows a two months lag between maximum groundwater level and the peak in the rainfall amount. The two-month lag of groundwater level with rainfall amount means that a deficit in monsoon rainfall or an early departure of monsoon in one year may cause groundwater drought in following pre-monsoon period. Groundwater drought due to rainfall deficit of one year may also continue almost two months after the beginning of monsoon in the next year.

5.6 Meteorological Droughts and Groundwater Level

The Standardized Precipitation Index (SPI) time series for six-months and one-year time steps for the time period 1964-2002 are shown in Figure 5.8(a) and (b) respectively. The figure shows severe droughts (SPI > -1.5) in the years of 1968, 1969, 1973, 1982, 1989, 1992 and 1994-95 for both six- months and one-year time steps in the study area. The SPI provides a comparison of the precipitation over a specific period with the precipitation totals from the same period for all the years including the historical record. For example, a 6-month SPI of October compares the May to October precipitation total in that particular year with the May to October precipitation totals of all the years. Consequently, it facilitates the temporal analysis of

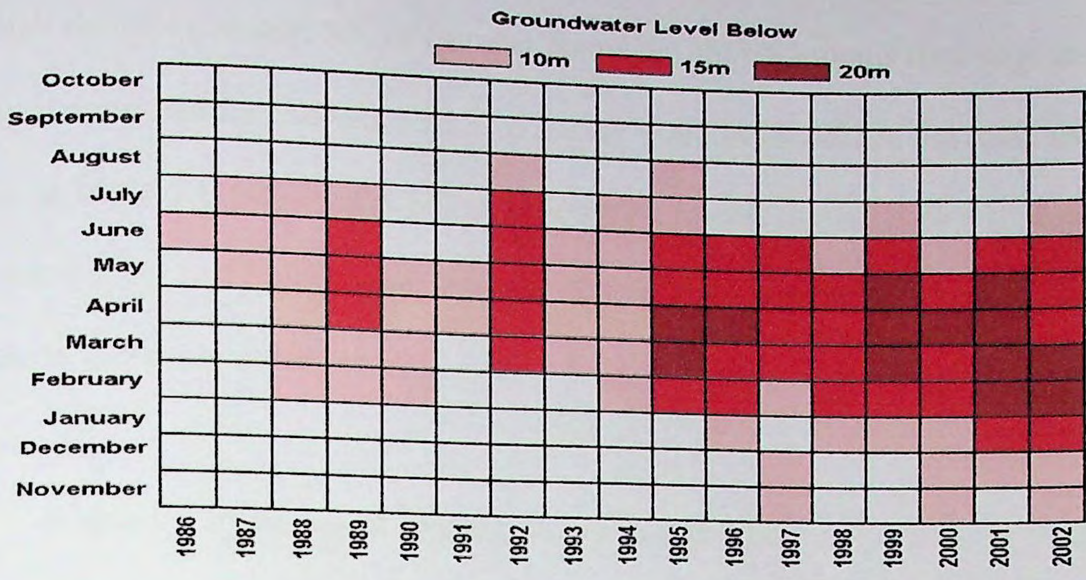


(a) *Type-1*

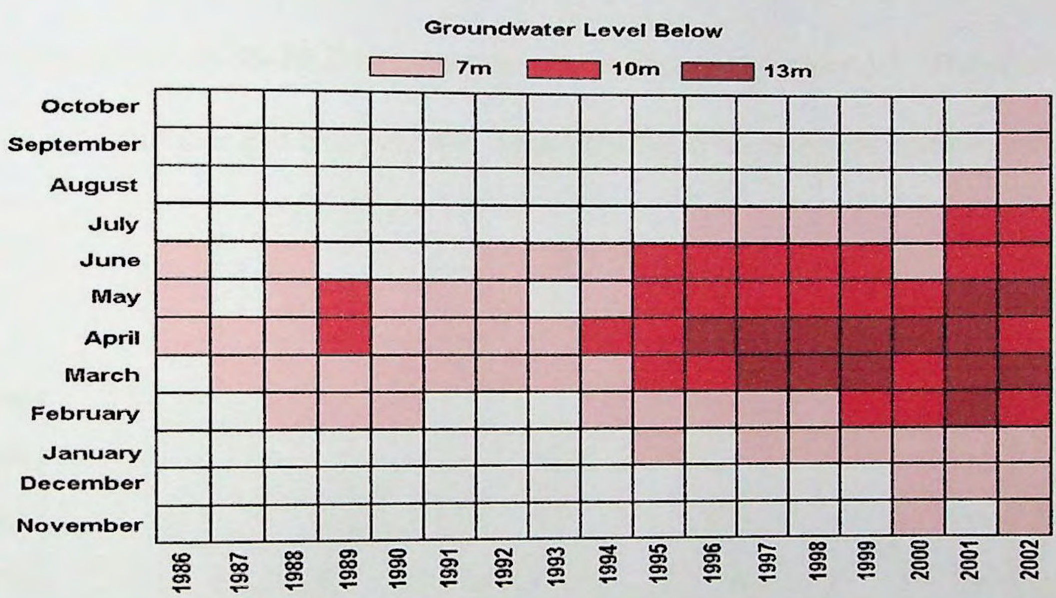


(b) *Type-2*.

Fig 5.5: Two sample groundwater hydrographs in the study area



(a) Type-1



(b) Type-2

Fig 5.6: Availability of groundwater above certain levels for the sample hydrograph of different months during the time period 1986-2002.

rainfall deficit or excess. SPI of October computed for six-months time step and SPI of April computed for one-year time step for the years 1985-2002 in the study area are given in Table 5.1. Six-months SPI in October represents rainfall deficit or excess in monsoon (May to October) and one-year SPI in April represents rainfall deficit or excess in the whole water year.

Within the hydrological drought sequence groundwater is the last to react to a drought situation, consequently groundwater droughts are often out of phase with meteorological droughts. Comparison of SPI values with minimum groundwater level for the time period 1986-2002 in the study area is shown in Figure 5.9. The six-month SPI values of October and one-year SPI values for April are used for comparison.

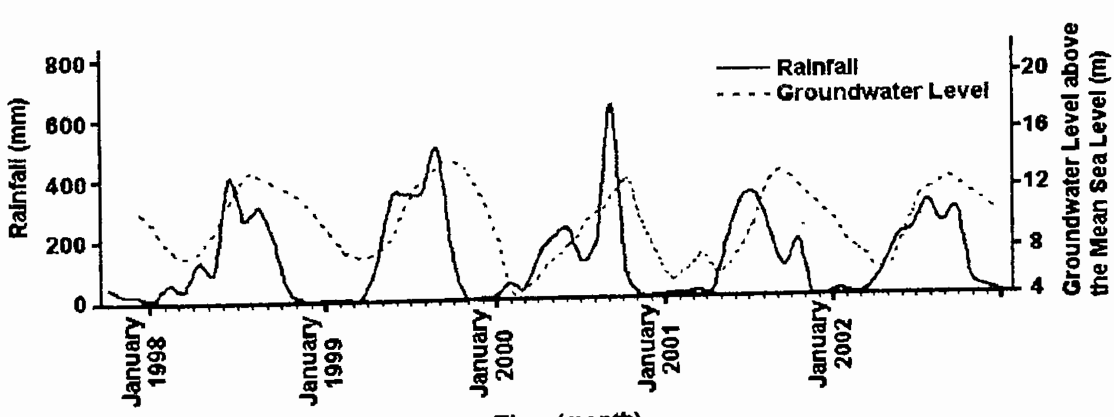
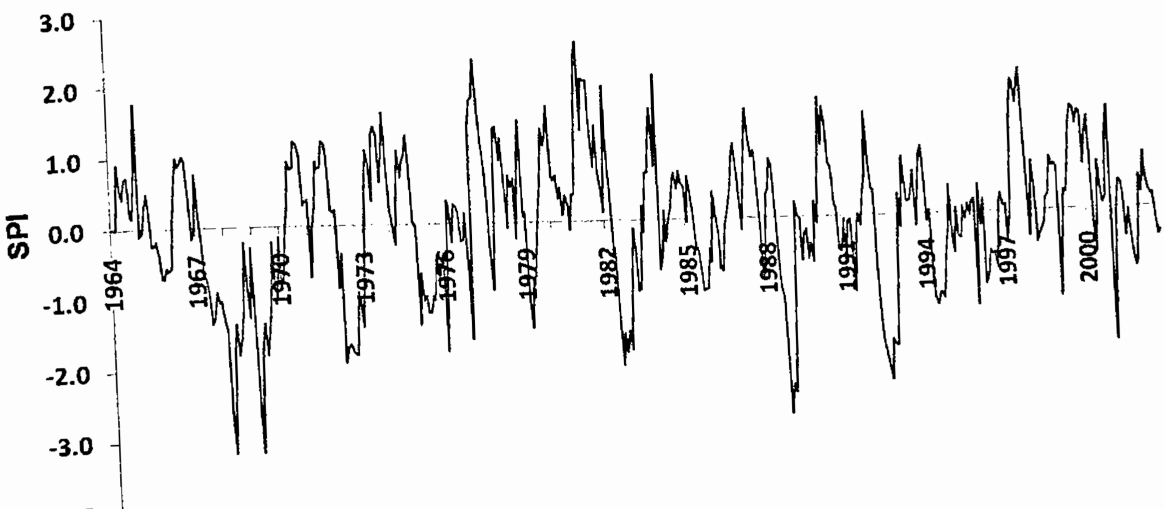


Fig 5.7: Relation of rainfall amount and groundwater table height above the mean sea level in the study area.

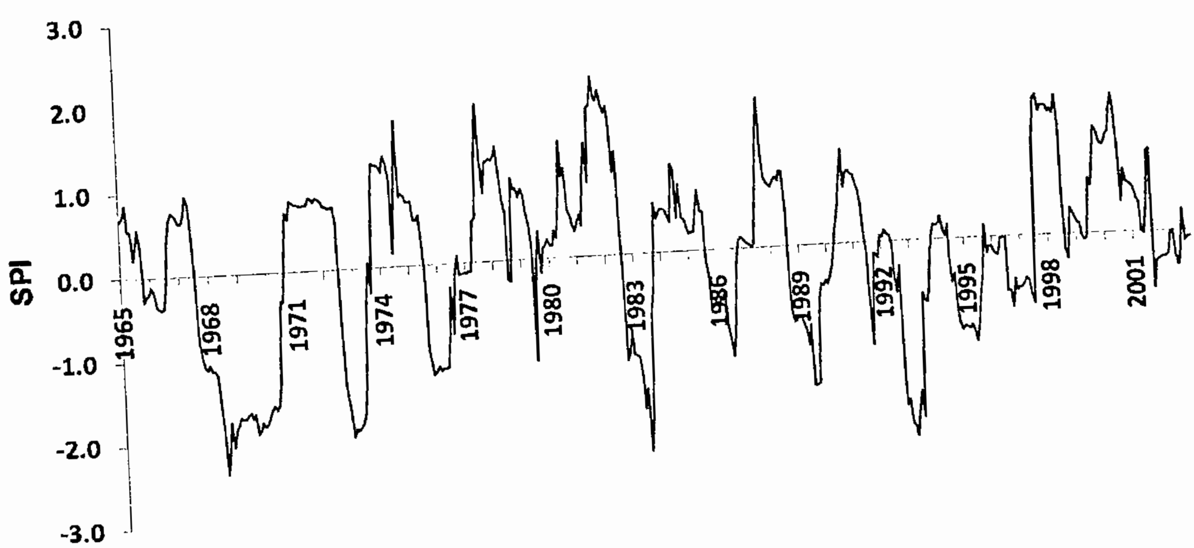
Table 5.1: Six-month SPI of October and one-year SPI of April during the time period 1986 - 2002.

Year	Six-month SPI in October	One-year SPI in April
1985	-0.69	0.47
1986	0.01	-0.54
1987	0.89	0.01
1988	-1.02	0.81
1989	-0.17	-1.22
1990	0.71	0.03
1991	0.03	0.47
1992	-2.21	0.08
1993	0.30	-1.85
1994	-1.16	0.32
1995	-0.09	-1.13
1996	-0.62	-0.02
1997	1.58	-0.55
1998	0.18	1.50
1999	1.51	-0.08
2000	0.35	1.54
2001	-0.03	0.02
2002	-0.16	-0.01

About 88% of rainfall occurs during the months of May to October in the area. Generally, if there is a rainfall deficit during this period (May – October) in one year and no excess rainfall in the pre-monsoon months of the next year, groundwater level goes below the average minimum groundwater level in the beginning of monsoon. On the other hand, if there is an excess of rainfall in the monsoon of one year, the minimum groundwater level is higher than the average minimum groundwater level in the beginning of monsoon in the next year. It can be noticed from Figure 5.9 that up to the year 1995 groundwater level follows the general relation with rainfall deficit as it is the main source of groundwater replenishment in the region. But the trend is different after 1995. Though there were few wet year after 1996 onwards, the minimum groundwater levels have not increased proportionately. This is due to the over-exploitation of groundwater in the region by shallow tube-wells.



(a)



(b)

Fig 5.8: Standardized Precipitation Index for: (a) six-month; and (b) one-year time steps.

However, meteorological drought is also responsible for groundwater level drop in the region. A deficit of monsoon rainfall in 1988 caused the aquifers in the area not to recharge completely. Consequently, the groundwater level drops to minimum level in the month of May-June of 1989. An excess and well distributed rainfall in the year of 1990-91 helps the groundwater level to recover to normal. Deficit of monsoon rainfall in 1994 caused a declination of groundwater to minimum level in the beginning of monsoon of 1995. Successive deficit of monsoon rainfall during the years of 1995-1996 has caused a further declination of groundwater in the consecutive years. After 1996 groundwater level continued to decline with a little response to excess rainfall in monsoon or non-monsoon months. This is due to the over exploitation of groundwater for irrigation in the region. A sharp declination of groundwater is observed in 2001 due to a huge deficit of pre-monsoon rainfall in that year. Rainfall during the months of November to April in 2000-2001 was only 22 mm compared to 225 mm in 1999-2000.

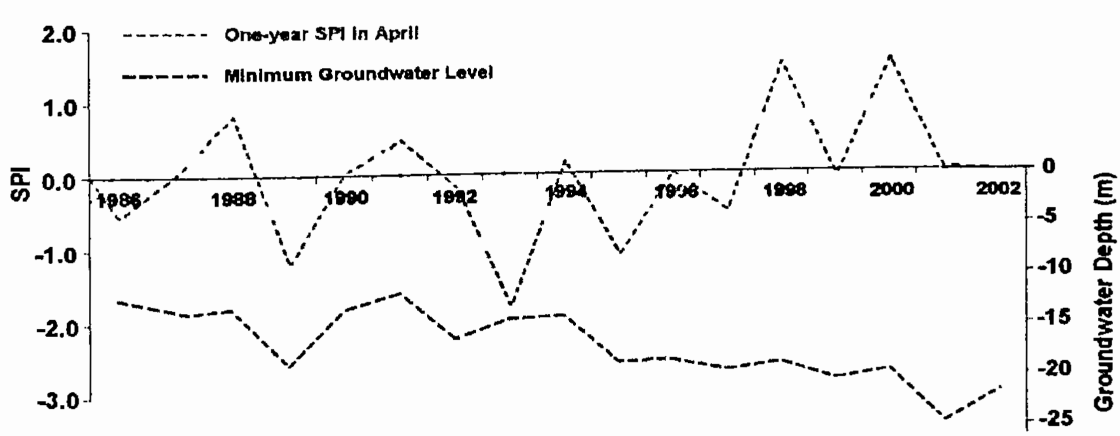


Fig 5.9: Comparison of six-month SPI of October and one-year SPI of April with minimum groundwater level for the time-period 1986-2002.

From the SPI time series and minimum groundwater level curve it can be observed that both the six-month SPI at the end of monsoon and one-year SPI at the beginning of monsoon can indicate natural fluctuation of groundwater level in the study area. To assess the capability of SPI to predict the minimum groundwater level correlation coefficients between SPIs and minimum groundwater level are calculated. As the number of data points is less and the data are not normally distributed non-parametric correlation coefficients are calculated by using Spearman rank correlation. A correlation coefficient of 0.23 is found between six-month SPI of October and minimum groundwater level of next year. On the other hand a correlation coefficient of 0.14 is found between one-year SPI of April and minimum groundwater level of that year. However, none of the correlations are significant at the 95% level of confidence. Therefore, it can be said that only qualitative change in groundwater level can be guessed from SPI values, quantitative prediction of groundwater level is not possible from SPI. Rainfall deficit is not the single cause of groundwater level drop in the study area, but also due to over exploitation of groundwater resources. Therefore, it is not possible to predict the minimum groundwater level using SPI only.

5.7 Conclusions

It is usual that groundwater level responses to precipitation at certain time lag. Therefore, groundwater drought in this region has a direct relation with meteorological drought. If there is no severe anthropogenic intervention in groundwater system, the cause of groundwater droughts is mainly the deficiency in precipitation. The study shows that up to the year of 1995 groundwater level follows the general relation with rainfall deficit or excess as it is the main source of groundwater replenishment in the region. Severe drought in 1994-1995 and overexploitation of groundwater for irrigation after 1995 have caused the ground water level recedes deeper in the consecutive years. Insufficient field information to quantify the recharge and non-consideration of groundwater level based pumping management has caused over-exploitation of groundwater. Though, it has been found that in some cases the aquifers replenish fully during monsoon, large-scale abstraction of groundwater has lowered the groundwater table in dry season which has made the exploitation of groundwater costly for irrigation in the area.

Water scarcity is caused by an imbalance between water supply and demand. Groundwater drought in the study area is caused both by the reduction of supply and increase of demand. Demands of groundwater have been increased due to the extension of agricultural lands and cropping intensities. Huge withdrawal of water in the international rivers in dry season and recurrent occurrence of droughts have reduced the supply of surface water as well as made the people more dependent on groundwater for irrigation. Therefore, it can be concluded that recurrent droughts, rapid expansion of groundwater based irrigation projects and cross-boundary anthropogenic interventions are the main causes of groundwater droughts in the northwest districts of Bangladesh. As groundwater declination is not only due to deficit of rainfall, but also due to overexploitation of groundwater resources, it can be concluded that groundwater droughts in the area is mainly human-induced droughts which is better to term as groundwater scarcity.

Development of surface water resources for irrigation is essential to reduce growing pressure on ground water table. In addition, water conservation program is required which would contribute to the recharging of groundwater to maintain better hydrologic cycle. Steps are required to regulate the extraction of water in the area for sustaining rechargeable groundwater aquifers with full public knowledge. Accurate estimation of groundwater recharge is essential for this purpose. Future research is necessary to estimate the percentage of precipitation that contributes groundwater recharge in the area for various precipitation events for the indirect estimation of groundwater recharge from precipitation easily. Quantitative information about groundwater recharge and groundwater management based on sustaining rechargeable groundwater aquifers may prevent groundwater scarcity in the region.

Chapter-6

IMPACTS OF CLIMATE CHANGE ON GROUNDWATER RESOURCES

6.1 Introduction

Groundwater resource is usually buffered from direct impact of climate change. But the resources can be affected indirectly due to the change in recharge and exploitation. It has already been mentioned that groundwater is the main source of irrigation in northwest Bangladesh. Major portion of water for irrigation *Boro* rice fields in the dry season comes from groundwater. Ever increasing ground water extraction for irrigation caused the ground water level fall to the extent of not getting fully replenished in the recharge season causing overdraft (Government of Bangladesh, 2002). Consequently, the groundwater-based irrigation system in the area has reached a critical phase with croplands in many places going out of the reach of shallow-level aquifer due to fast depleting groundwater table (BADC, 2005). A change in irrigation demand due to climate change will certainly have severe impact on groundwater resources in the region.

It has been mentioned in the most recent report of Intergovernmental Panel on Climate Change (IPCC, 2007) that Bangladesh is one of the most vulnerable countries in the world to climate change. Hydrologic changes are the most significant potential impacts of global climate change in Bangladesh. A study on climate change vulnerability based on certainty of impact, timing, severity of impacts and importance of the sector, ranked water resources as the greatest concern due to climate change in Bangladesh (OECD, 2003). Decreasing rainfall in the dry season with higher evapotranspiration due to temperature rise will demand higher amount of water for irrigation. At the same time the higher temperature will change the crop physiology and shorten the crop growth period. This will reduce the irrigation days. These contradictory phenomena will change the total irrigation water demand. As irrigation is the main sector of groundwater use in northwest Bangladesh, a change in irrigation water demand will cause a high impact of groundwater resources in the region. Estimation of the agricultural water demand in the changing environment is essential to envisage long-term impact of climate change on groundwater resources in the area. A study has been carried out in this chapter to estimate the change of irrigation demand in dry season *Boro* rice field and it's impact of groundwater resources in northwest Bangladesh.

6.2 Change of Irrigation Demand under Climate Change Scenarios

It is very much clear that climate change will affect irrigation water use via changes in rice physiology, rice phenology, soil water balances, evapotranspiration and effective precipitation. Greenhouse experiment of rice showed that Leaf Area Index (LAI) of rice is generally insensitive to elevated CO_2. Due to stomatal closure under elevated CO_2 concentration it is expected that there will be a considerable decrease in actual evapotranspiration (Ainsworth and Long, 2005). However, recent studies show that LAI is insensitive to elevated CO_2 during the first 2 years, but there was an enhancement of LAI under enhanced CO_2 after two years (Harz-Rubin and Delucia, 2001; Anten et al., 2003). The enhancement of LAI will increase evapotranspiration.

Data on tropical plants under changing climate are still few, and it is very difficult to conclude on physiographic change on rice due to increased temperature and elevated CO_2. Greenhouse experiments findings might also be limited in field conditions by abiotic or biotic factors. In the present study, it is assumed that there will be no overall change in crop evapotranspiration due to physiological change of rice under increased temperature and elevated CO_2. Therefore irrigation water use via changes in rice phenology, soil water balances, evapotranspiration and effective precipitation has been studied in the present study.

To study the change of irrigation water demand in the study area due the change of temperature and rainfall, first the increase temperature is used to compute the change in *Boro* rice phenology using degree-day method. The length of growth stages of *Boro* rice modeled by Mahmood (1997) for north and northwest Bangladesh is taken as the base length. Temperature projected by the climatic models during the months of January to May in 2025, 2050, 2075 and 2100 are used to compute the change of growing stages of *Boro* rice in those years. The modeled changed of *Boro* rice phenology due to the rise of temperature is given in Table 6.1. The result shows that the total growing period of *Boro* rice will shorten to 140 days in 2025, 136 days in 2050, 133 days in 2075 and 130 days in 2100. This finding collaborates with the finding of Karim et al. (1999) that the shortening of *Boro* rice growing period of 2 to 12 days. The irrigation days will be shortened to 121 days in 2025, 117 days in 2050, 114 days in 2075, and 112 days in 2100.

The projected temperature and rainfall is also used to compute the change in soil moisture deficiency, evapotranspiration and effective precipitation for the years of 2025, 2050, 2075 and 2100. The soil moisture deficiency of the end of December computed though the Thornthwaite water balance model with projected temperature and rainfall in the year of 2025, 2050, 2075 and 2100 are given in Table 6.2. The table shows that the soil moisture deficiency will increase with the increase of temperature and decrease of rainfall. The increase in soil moisture deficiency in the end of December means that more water will be required for the land preparation due to climate change.

Change in daily evapotranspiration with the projected temperature is given in Table 6.3. It is assumed there will be no change in wind speed, solar radiation and humidity. The result shows an increase in daily evapotranspiration in *Boro* rice growing months. The change in effective precipitation in the study area is given in Table 6.4. The effective precipitation will decrease in January and February, but increase in March, April and May. Overall, there will be an increase of effective rainfall during *Boro* rice irrigation period.

The modeled values of crop irrigation period, evapotranspiration, effective precipitation and soil moisture deficiency for different soil groups are used to compute the change in irrigation water demand. The sub-district level maps of irrigation water

Table 6.1: Changes of growing period of Boro rice with rising temperature.

	Stages(days)					
Year	**Initial**	**Vegetative**	**Flowering**	**Maturing**	**Total**	**Irrigation Days**
1990	25	60	40	20	145	125
2025	24	58	39	19	140	121
2050	23	56	38	19	136	117
2075	22	55	37	19	133	114
2100	21	54	37	18	130	112

Table 6.2: Projection of average soil moisture deficiency at the end of December in the study area.

Year	**Soil Moisture Deficiency (mm)**
Present	119.1
2025	142.6
2050	145.7
2075	147.7
2100	150.4

Table 6.3: Projection of average daily evapotranspiration during *Boro* rice irrigation period

Year	**Daily Evapotranspiration (mm)**				
	Jan	**Feb**	**Mar**	**Apr**	**May**
Present	1.89	2.56	3.53	4.37	4.44
2025	1.96	2.66	3.67	4.51	4.55
2050	2.01	2.73	3.76	4.62	4.64
2075	2.05	2.80	3.85	4.71	4.72
2100	2.09	2.85	3.92	4.81	4.80

Table 6.4: Projection of effective rainfall during *Boro* rice irrigation period

Year	**Effective Precipitation (mm)**				
	Jan	**Feb**	**Mar**	**Apr**	**May**
Present	2.10	3.10	8.79	55.33	62.38
2025	0.00	0.58	7.02	64.87	75.33
2050	0.03	0.93	14.10	78.41	93.46
2075	0.00	0.90	14.12	89.23	104.26
2100	0.00	0.92	15.30	102.52	118.74

demand in the year of 2025, 2050, 2075 and 2100 are given in Figures 6.1 (a), (b), (c) and (d) respectively. The average values of irrigation water demand in the different years are shown by graph in Figure 6.2. The result shows no appreciable change in irrigation water demand in the study area. The average value of irrigation water will increase from 1057 mm to a value of 1059 mm in 2025, then decrease to 1036 mm in 2050, and again increase to 1043 mm in 2075 and 2044 mm in 2100.

The study shows that though the soil moisture will decrease and daily evapotranspiration will increase, there will be no major change in total water requirement due to the shortening of growing length and increase of precipitation. However, the climate change will increase the irrigation rate or daily use of water for irrigation. In base year, an average of 1057 mm water is used for irrigation for the time period of 125 days. In 2025, an average of 1059 mm water will be used for irrigation in 121 days. Consequently the irrigation rate will be increased. The increase of irrigation rate in 21 century in the study area is shown by a graph in Figure 6.3. The irrigation rate in the base year is 8.5 mm/day. It will be about 8.8 mm/day in 2025, 8.9 mm/day in 2050, 9.1 mm/day in 2075 and 9.3 mm/day in 2100.

6.3 Relation between Pumping and Groundwater Level

The drawdown of a well is a function of the discharge/pumping rate, the well radius, the duration of operation of the pump, and aquifer properties. Hydraulic equation relates the drawdown with discharge is given in equation below:

$$s = \frac{Q}{2\pi T} \ln\left(\frac{r}{R}\right)$$

Where, s is the drawdown at the radial distance 'r' from the pumping well.

Q is the discharge rate of the pumping well

T is transmissivity of the aquifer

R is the radius of influence

The equation shows that if other parameters are constant, drawdown is directly related to discharge. A typical head curve giving the relationship between the discharge or pumping rate and the total head in a pumping system is shown in Figure 6.4. The curve shows that more head is required to increase the discharge through the system.

6.4 Change of Groundwater Levels under Climate Change Scenarios

It is now clear that there is a direct relation between groundwater level and pumping rate. If an amount of water is pumped out in less time, it causes more declination of groundwater level. It has been observed that climate change will cause an increase of irrigation rate or daily irrigation demand in *Boro* rice field in northwest Bangladesh.

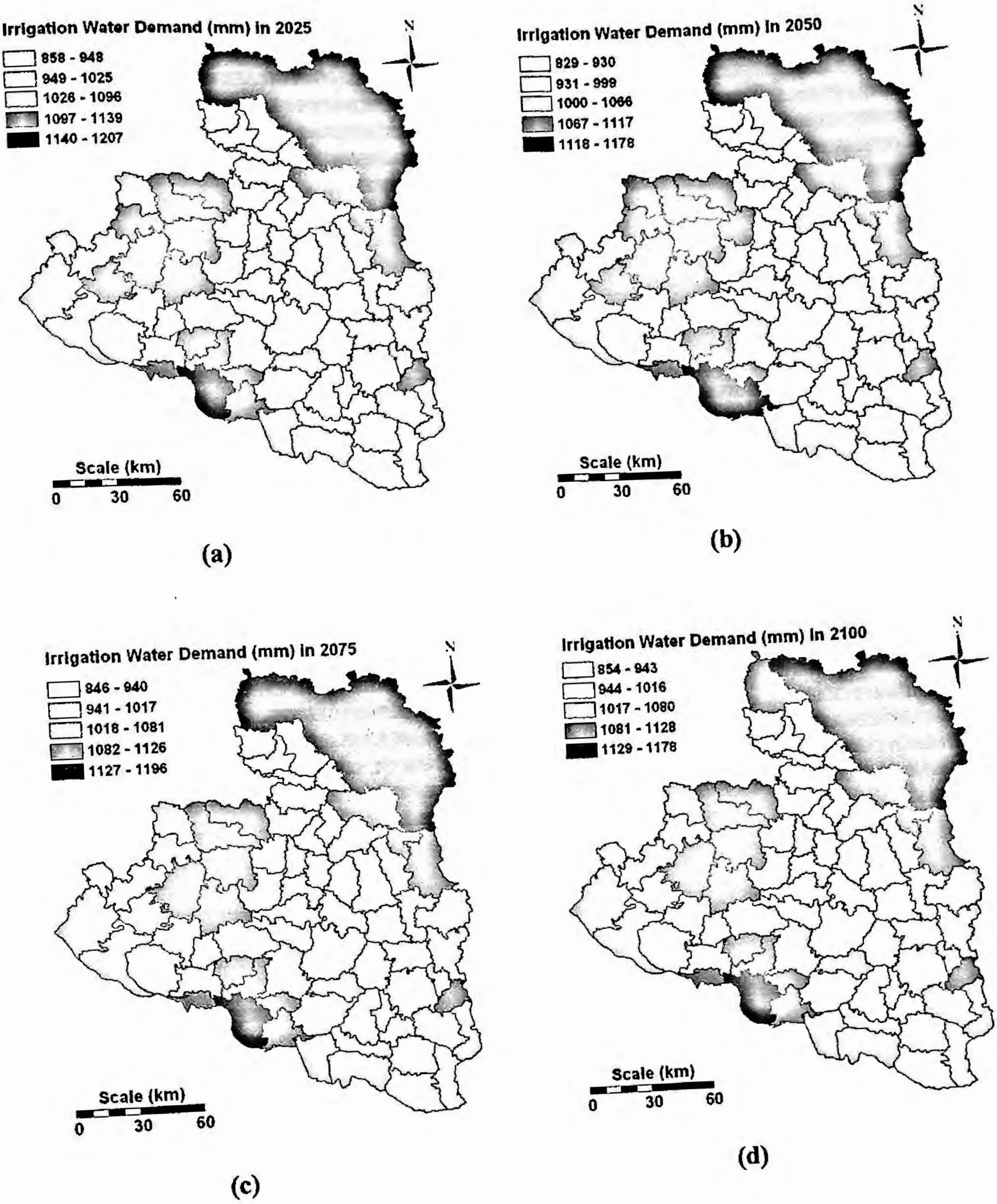


Fig 6.1: Spatial distribution of projected irrigation water demand in *Boro* rice field in the study area in the years of (a) 2025; (b) 2050; (c) 2075; (d) 2100

Higher per day abstraction to meet the irrigation water requirements due to climate change during the peak dry season will cause further declination of groundwater level. As water level declines, the rate of water the well can yield also declines. Consequently, more energy will be required to sustain the yield of groundwater for sufficient irrigation. Therefore, higher abstraction rate of groundwater in the study area will certainly aggravate the declination groundwater level in the area. It will also cause an increase in production cost of rice and severely hamper the Government policy of poverty alleviation through irrigated agriculture.

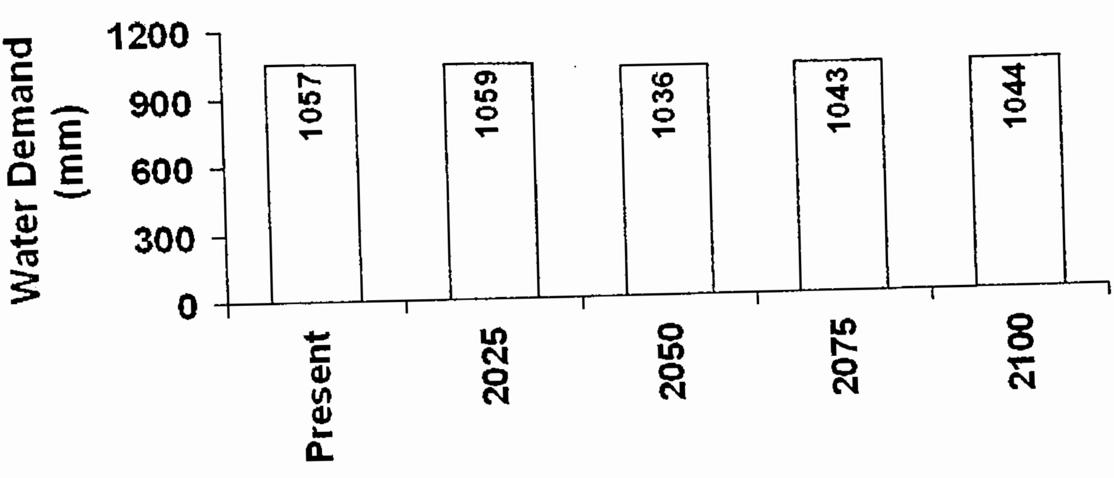


Fig 6.2: Change in average irrigation water demand in *Boro* rice field during the time period 2000 – 2100.

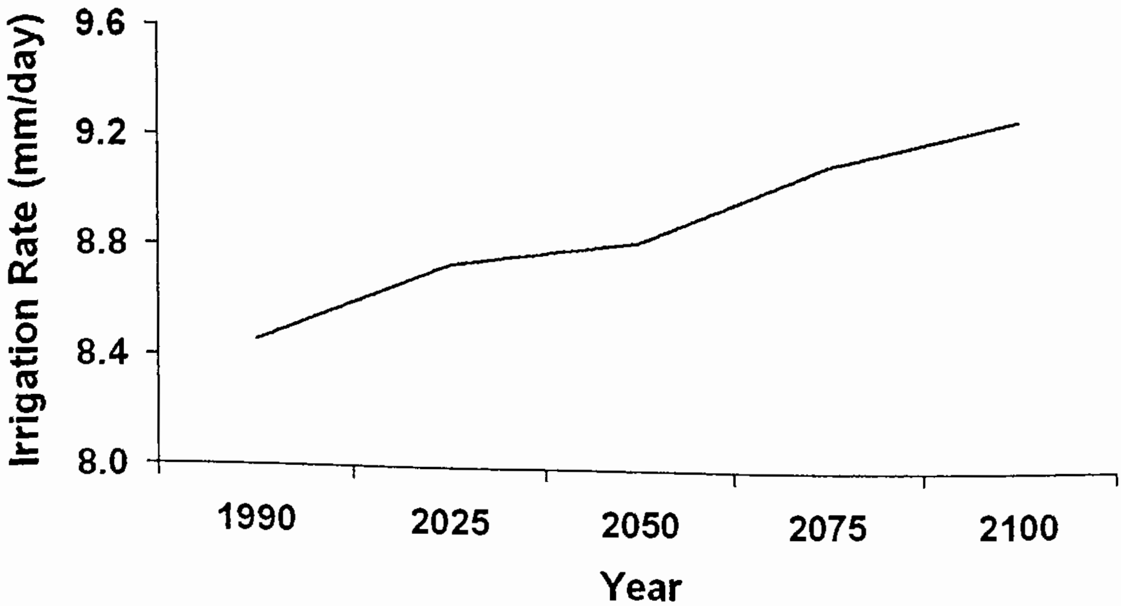


Fig 6.3: Change in average irrigation rate in *Boro* rice field in 21st century.

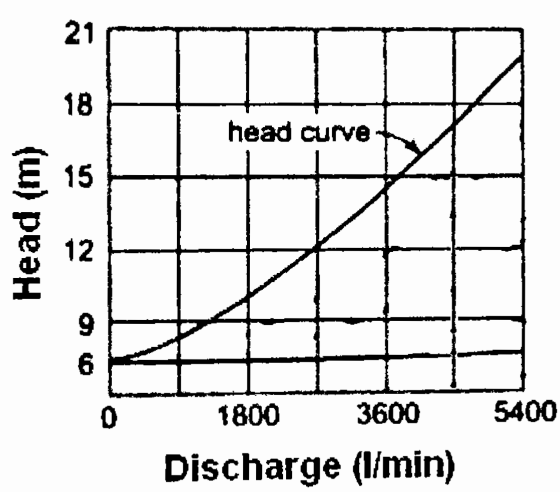


Fig 6.4: A typical groundwater head-discharge curve.

6.5 Impacts Adaptive Measures

Adaptation measures should be taken in advance to reduce the negative consequences of climate change on water demand and its impact on groundwater resources in northwest Bangladesh. Government of Bangladesh has made climate change an integral part of national development strategy and have started to build the country's capacity to tackle the impacts of climate change. Climate Change Strategy and Action Plan (CCSAP) has been developed through a participatory process involving all relevant ministries and agencies, civil society, including NGOs, research organizations and the business community. One of the most fundamental pillars of the strategy is to ensure continuous supply of water for production of food. Now, it is required to take necessary initiatives to grow farmer's awareness about water problems that may be exacerbated by climate change, and implement sustainable water management policy to ensure adequate water supply.

Local water management authority named Barind Multipurpose Development Authority (BMDA) has already taken number of initiatives to ensure continuous water supply for irrigation. Necessary initiatives have been taken to ensure annual withdrawal less than the annual recharge to keep the groundwater level in position. BMDA are trying to estimate groundwater recharge in the area more accurately. Over 15 million seedlings were planted in the area to increase the floral biodiversity. It is expected that huge plantations would have a positive impact on hydro ecosystem in the region. However, still a long way to go to have a climate proof water management system in the region.

Development of surface water resources for irrigation is essential to reduce growing pressure on ground water table. In addition, water conservation program is required which would contribute to the recharging of groundwater to maintain better hydrologic cycle. Steps are required to regulate the extraction of water in the area for sustaining rechargeable groundwater aquifers with full public knowledge. Accurate estimation of groundwater recharge is essential for this purpose. Future research is necessary to estimate the percentage of precipitation that contributes groundwater recharge in the area for various precipitation events for the indirect estimation of groundwater recharge from precipitation easily. Quantitative information about groundwater recharge and groundwater management based on sustaining rechargeable groundwater aquifers may prevent groundwater scarcity in the region. Adjustment of agricultural activities according the shifting of climate to take the maximum advantage of increasing rainfall can also reduce the pressure on groundwater.

Adaptation activities must involve the full range of stakeholders, including community leaders, water management professionals, local government and private organizations, and the NGOs. Because the effects of and responses to climate change will depend on the local context, including demographic, social, economic, infrastructural, and other factors, adaptation options will be more effective if designed, implemented, and monitored with strong community engagement. Vulnerable groups to water scarcity can be identified by their geographical position and socio-economic conditions. NGOs and other private and public organizations working in the water sector could play an active role to identify the vulnerable groups, grow awareness among local community and encourage them to adjust agricultural activities accordingly.

Immediate governmental initiatives are necessary to strengthen the capability of climate forecast system to understand the possible precipitation and the groundwater demand in a year. Climate and Water researchers can play an active role to develop early warning system of the emergence of drought through research on climatic influence on rainfall which is one of the most important secondary measures to prevent the onset of adverse outcomes due to climate change. It is also required to enhance the institutional capacity to government agencies, civil society and private sector to meet the challenges of climate change.

Bangladesh has achieved sufficient efficiency in disaster preparedness and management through community involvement. The people of Bangladesh have adapted over generations to the risks of floods, droughts, water scarcity and cyclones. In areas where inundation is a risk, they raise their houses on mounds, above the normal flood level, and adjust their cropping patterns to take advantage of the monsoon rainfall. Therefore, it can be hoped that strong community involvements would also successfully able to increase the resilience of farmers and other vulnerable groups from the negative impact of climate change on water resources in northwest Bangladesh.

6.6 Concluding Remarks

Only 6% rainfall occurs in the northwestern region of Bangladesh during the *Boro* rice growing season. Therefore, irrigation is a prerequisite for obtaining stable yields. In the present work, a study has been carried out to estimate the change of irrigation water demand in dry-season *Boro* rice field due to climate change. The study shows that water required for land preparation will increase by 31.3 mm, the evapotranspiration from rice field will increase by an average of 0.33 mm/day and effective precipitation will be increased by an amount of 48.5 mm during irrigation period by 2100. However, there will be no appreciable changes in total water requirement due to the shortening of irrigation period by approximately 13 days by 2100. The most interesting finding of the study is that the climate change will increase daily use of water for irrigation by an amount of 0.8 mm/day in the end of this century. As groundwater is the main source of irrigation in *Boro* rice field in northwest Bangladesh, higher abstraction rate of groundwater may have negative impacts on groundwater resources in the area.

Chapter-7

CONCLUSION

Conclusion

Agriculture in northwest districts of Bangladesh relies heavily on groundwater irrigation. Scarcity of groundwater for irrigation during dry season in the recent years has hampered the agricultural production in the area. There is growing concern among the scientist about the severe negative impacts of climate change on groundwater scarcity in the near future. Therefore, it is very urgent to study the causes of groundwater scarcity and the impacts of climate change on groundwater in northwest Bangladesh. A study has been carried out in the present research to identify the causes of groundwater scarcity, estimation of groundwater demand, and projection of the future climate, quantify the impact of climate change on groundwater demand, and finally assess how changing demand of groundwater due to climate change can affect groundwater reserves in the northwest Bangladesh.

Spatial distribution of groundwater scarcity is modeled by using cumulative departure method. Long-term groundwater hydrographs are analyzed and the relation of groundwater level with meteorological droughts has been studied to identify the probable causes of groundwater scarcity in the region. To study the impact of climate change on groundwater scarcity all the possible ways by which climate change can influence the irrigation water demand such as water required for land preparation, evapotranspiration from paddy field, effective precipitation and rice phenology are studied. Climate models are run to project the future climate in the region.

The projected climatic parameters are then used to estimate the change in irrigation water demand. Finally the impacts of irrigation water demand on groundwater level in the study area are identified. Satellite images, soil information, and long-term average meteorological data are used for the study. Net irrigation water requirement has been calculated from reference evapotranspiration, crop coefficients, effective precipitation and amount of water needed for land preparation and seepage lose. Spatial and temporal distribution of irrigation water requirements is also calculated using FAO-56 model within a Geographical Information System. Penman-Monteith method is used to calculate reference evapotranspiration from climatic data. Soil information is used to estimate the spatial distribution of percolation and seepage loses through the paddy field. Thornthwaite soil water balance algorithm is used to model the soil moisture deficiency to compute the water required for land preparation. Climate change modeling software SCENGEN is used to project the future change in rainfall and temperature in the study area. A temperature based crop phenology method known as degree-day method has been used to model the change in rice growth period under increased temperature.

The study reveal that groundwater scarcity in northwest Bangladesh is caused both by the reduction of supply and increase of demand. Demands of groundwater have been increased due to the extension of agricultural lands and cropping intensities. Huge withdrawal of water in the international rivers in dry season and recurrent occurrence of droughts have reduced the supply of surface water as well as made the people more dependent on groundwater for irrigation.

Therefore, it can be concluded that recurrent droughts, rapid expansion of groundwater based irrigation projects and cross-boundary anthropogenic interventions are the main causes of groundwater scarcity in the northwest districts of Bangladesh. As groundwater declination is not only due to deficit of rainfall, but also due to overexploitation of groundwater resources, it can be concluded that groundwater scarcity in the area is mainly human-induced phenomena.

The study of climate change impacts on irrigation water demand shows that water required for land preparation will increase by 31.3 mm, the evapotranspiration from rice field will increase by an average of 0.33 mm/day and effective precipitation will be increased by an amount of 48.5 mm during irrigation period by 2100. However, there will no appreciable changes in total water requirement due to the shortening of irrigation period by approximately 13 days by 2100. The most interesting finding of the study is that the climate change will increase daily use of water for irrigation by an amount of 0.8 mm/day in the end of this century. As groundwater is the main source of irrigation in *Boro* rice field in northwestern Bangladesh, higher abstraction rate of groundwater may have negative impacts on groundwater level which in turn will negatively affect the prevailing situation of groundwater scarcity of the area during dry season.

In the context of growing demand of groundwater in Bangladesh, management of this resource is essential to supply sufficient water to the growing population to increase food production as well as to improve the hygiene and health situation.

It is hoped that the study will be beneficial to a number of stakeholders in the region, particularly farmers and agricultural organizations, and also to the water development and management organizations, planning and educational authorities to improve their understanding on groundwater demand in the northwest part of Bangladesh. As the assessment of water requirement for both irrigation and domestic purposes and its impact on groundwater resources are one of the main aspects of agriculture and water resources development and planning in the region, it is hoped that the maps and the study in general will assist in guiding the operational responses of the various authorities, especially in terms of those interventions aimed at agricultural and water resources development and management in northwest Bangladesh.

In future, the climate models can be downscaled to higher resolution in projecting the spatial variation of climate change. Then the impacts of climate change on crop physiology and groundwater resources can be taken into consideration to tune the irrigation demand.

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