ERASMUS MUNDUS MSC PROGRAMME

COASTAL AND MARINE ENGINEERING AND MANAGEMENT
COMEM

Impact of Sea Level Rise on Agriculture Using Groundwater in Bangladesh

A dissertation submitted in partial fulfillment of the degree of

M.Sc. in

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by

Shamim Mohammad Murshid

University of Southampton

School of Civil Engineering and the Environment

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Prof. Dr. Ir. Marcel J.F. Stive
Delft University of Technology
Faculty of Civil Engineering and geosciences
P.O. Box 5048
2600 GA Delft
The Netherlands

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ABSTRACT

Bangladesh, located on the northern littoral of the Bay of Bengal, is one of the most vulnerable countries to the impacts of climate change and sea level rise. Agriculture is the prime economic activity in the densely populated coastal areas of the country. During the dry season of the year (November to April), when rainfall is low, the irrigation is done by extracting groundwater. Over the years this continuous groundwater pumping causes the depletion of groundwater table. Due to the proximity to the sea, the lowering of groundwater initiates saltwater intrusion into the coastal aquifers and this affects the crop production significantly. The objective of this project was to establish generic models to evaluate the inter-relationships among different cropping patterns, irrigation requirements, groundwater recharge and saltwater intrusion in the south-west coastal region of Bangladesh. The models were initially used to analyze the current situation and then future predictions were also made by considering climate change and sea level rise in the future.

Crop Irrigation models were established in CROPWAT by using CLIMWAT climate data for two meteorological stations in the area (i.e. Khulna and Barisal). Two cropping patterns were considered, i.e. rice cultivation throughout the year and mixed cultivation of rice and vegetables. Crop water requirements (CWR), Irrigation required (IR) and groundwater recharge were calculated. Groundwater modelling was done in MODFLOW and the changes of groundwater head were observed. The distance of landward saltwater intrusion from the shoreline for pumping groundwater was determined by particle tracking method and the safe distance of wells from the sea was calculated for present condition. Future predictions for these were also made by considering climate change and sea level rise.

The analysis showed that mixed cultivation of rice and vegetables increase the groundwater recharge. This cropping pattern also reduces the extent of saltwater intrusion inland. As a result the loss of cultivable land due to groundwater salinity problem is less. For future scenarios, as a consequence of climate change, the analysis reveled that groundwater recharge will be higher in the future due to increase of total annual rainfall. However, if the farmers cultivate rice and vegetables jointly, there is a possibility that in the future the recharge will be so high that it may elevate the groundwater table very close to the ground surface. This will initiate the problem of water logging in the lands. It was also found from the analysis that in Barisal, the safe distance of irrigation wells from the sea to avoid saltwater intrusion will be same in present time as well as in the year 2100. However, for Khulna, this distance will not remain the same.

Contents

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS AND ABBREVIATIONS

Acronyms	Term
CZPo	Coastal Zone Policy of Bangladesh
FAO	Food and Agricultural Organization of the United Nations
IPCC	International Panel on Climate Change
NAPA	National Adaptation Program of Action, Bangladesh

Abbreviation	Term
CWR	Crop Water Requirement
GMSL	Global Mean Sea Level
IR	Irrigation Required
MSL	Mean Sea Level
SLR	Sea Level Rise

Chapter 1

INTRODUCTION AND OVERVIEW

1.1 Background to the Area

Bangladesh is located on the Ganges-Brahmaputra Delta, the largest delta in the world. The country has an area of 1, 47,570 square kilometers and a total coastline length of 710 km (CZPo, 2005). The country is crisscrossed by about 700 rivers including tributaries and as they approach the sea, with a large number in the south-west region of the country. The majority of the delta is formed by the deposition of alluvium carried from the upstream regions by the rivers. The sediments make it one of the most fertile regions in the world. Agriculture is a key economic activity for the 40 million inhabitants in the coastal Bangladesh (Roy, 2011). The standard of living for this vast population is largely dependent on the growth and sustainability of agricultural production. However this area is not only thought to be susceptible to the consequences of climate change and sea level rise but also extremely difficult to protect because of its location and geography (Karim & Mimura, 2008).

The south-west of Bangladesh has adequate freshwater during the wet seasons (June to October) due to excessive rainfall, although which is sometimes responsible for river flooding as well (Rasid & Paul, 1987). However during the dry season (November to April) the rainfall is very low and the lack of flow in the rivers make it almost impossible to use surface water for irrigation purposes. To make the best use of the fertile arable lands, the farmers use groundwater to irrigate their crops during the dry season. So over the whole year, irrigation continues with the conjunctive use of surface water and groundwater. The elevation of the groundwater table as well as the quality of groundwater is the key issue for groundwater use. The recent trend of depletion of groundwater table is the result of overpumping and declining overall recharge in that area (Shamsudduha, et al., 2009). Furthermore the quality of groundwater in the coastal areas is threatened by the salt water intrusion which creates problem to agricultural production and affects the supply of clean water for industrial use (Rahman & Bhattacharya, 2006).

1.2 Agriculture, Groundwater and Climate Change

In the future, groundwater quantity and quality in the south-west region of Bangladesh will be challenged because of the consequences of climate change and global warming. Bangladesh is considered as one of the most vulnerable countries in the world for climate change scenarios and subsequent sea level rise. It is the third most vulnerable country in terms of population and among the top ten considering the percentage of people living in the low-lying coastal zones (Pender, 2008). The change in the climate pattern may result in lack of rainfall during the dry season. The extraction of groundwater for irrigation purpose will increase and overpumping will cause the lowering of groundwater table. At the same time predicted rise of sea level may cause saline water intrusion in the coastal aquifers and this will seriously deteriorate the groundwater quality. Overall, the whole scenario may influence the existing agricultural system. Therefore, preventative as well as adaptive measures are required to sustain the agricultural system.

To cope with the future consequences of climate change and sea level rise especially in the south-west region of Bangladesh, it is vital to understand and investigate the factors and parameters that influence the overall agricultural system. To identify and estimate the future extent of the predicted problems related to groundwater use in agriculture, it will be necessary to interrelate the controlling parameters to generate valid models both in a generic sense as well as considering local features. To make appropriate decision in response to a range of probable conditions, the impact of the various scenarios needs to be studied at a range of different scales – including the effects on a single community to the overall delta as a whole.

In addition to estimate the future extent of the scarcity of usable groundwater, it is also sensible approach to explore alternative solutions that may include changing cropping patterns, limiting the extraction of groundwater and best utilization of the pumping by allocating proper spacing between extraction wells. Overall, a well defined and structured scheme that considers the extent of problems as well as adapt different alternatives in response to certain scenario will be the key to sustain the agricultural development of coastal areas of Bangladesh.

1.3 Aims and Objective of the Project

General Objective: To scope predict the general condition of groundwater in the coastal areas of Bangladesh in response to climate change scenarios and sea level rise and to identify out suitable adaptation measures that have the potential to help farmers to cope with.

Specific Aims:

- Calculate Irrigation Requirements for different seasons considering the crop pattern, soil type, seasonal rainfall and evapotranspiration.
- Develop a generic model for seasonal groundwater table variation and salt water intrusion in typical coastal areas considering existing sea level and climate parameters.
- Calculate well pump rates and safe distance of well from the shoreline to avoid the hazard of groundwater salinity in existing scenario.
- Analyze the impact on above three for future scenario including sea level rise and climate change.

1.4 Organization of the Report

The overall report is comprises of six chapters. The list of references and appendices are included at the end.

Chapter 1 provides a background to the problem in context of Bangladesh. The aims and objectives are also listed here. Chapter 2 deals with literature review. It gives the information about coastal zones of Bangladesh, the existing farming system and the impacts of climate change and sea level rise on this area. Chapter 3 gives an insight of knowledge about the model design and the methodology. It discusses the background theory related to the parameters and describes the designing phase of the model. Chapter 4 explains the construction of models and the findings of the study in the current time. Chapter 5 predicts the future impacts in response to climate change and sea level rise by using existing models. The report ends with chapter 6 that recapitulates the overall findings along with future recommendations to improve the models.

Chapter 2

LITERATURE REVIEW

2.1 Bangladesh: Topographical Features and Coastal Boundary

Bangladesh is located in south Asia with a total area of 1,47,570 sq. km which extends from 20°34' N to 26° 38' N latitudes and from 88°01' E to 92°41' E longitudes. About 6.4% of the country's total area is water body that consists of numerous canals, rivers and tributaries. Formed by a delta plain at the confluence of the Ganges (Padma), Brahmaputra (Jamuna) and Meghna rivers and their tributaries, Bangladesh is a low-lying riverine country that gently sloping from north to the south which allows the entire river system to flow southwards and eventually discharge into the Bay of Bengal. The general topography of the country is characterized by flat terrain of roughly 80% of the total area apart from some hilly regions in the south-east and north-east zones (Wikipedia, 2012).

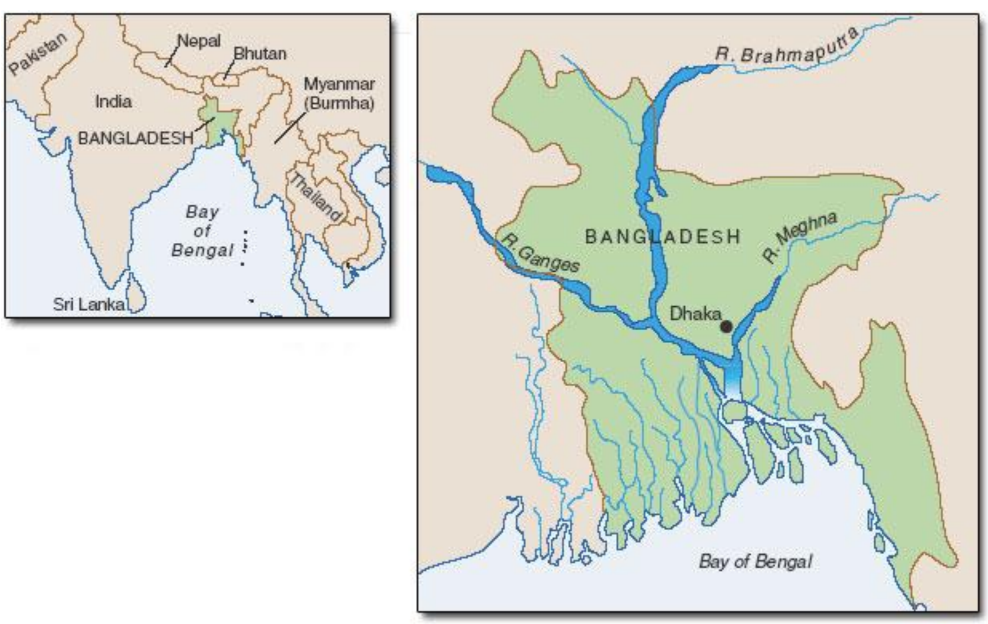

Figure 2.1: Location of Bangladesh in South Asia and the Map of Bangladesh Showing the Extensive Delta Formed by the Rivers Ganges, Brahmaputra and Meghna.

The coastline of Bangladesh is located on the northern littoral of the Bay of Bengal, forming 710 km long coastline. According to the coastal zone policy of the government (CZPo, 2005), out of 64 districts, 19 districts are included in this zone covering a total of 147 upazillas (sub divisions of a district). Among these 19 districts, 12 have direct shoreline with the sea or lower estuary and the rest 7 districts, although they don't have direct exposure to the sea, are greatly influenced by the presence of the Bay of Bengal and the estuary zone. The entire coastal zone is sub-divided into exposed and interior coasts according to its position. Total 48 upazillas of 12 districts are within the exposed zone while 99 upazillas are included in interior coastal zone which lie behind the exposed region (CZPo, 2005). It is quite obvious that the exposed area is the most vulnerable to the SLR as it is threatened by the possibility of inundation of landmass. In case of interior zone, this whole region is largely influenced by the sea and will be affected by SLR in terms of soil and groundwater salinity and other secondary impacts. The total area of the coastal zone is about 47,201 sq km which is approximately 32% of the total landmass of the country (Islam, 2004). The coastal area starts from the shoreline and in different locations it extends from 37 to 195 km, whereas the exposed coast is limited to a distance of 37 to 57 km (Islam, et al., 2006).

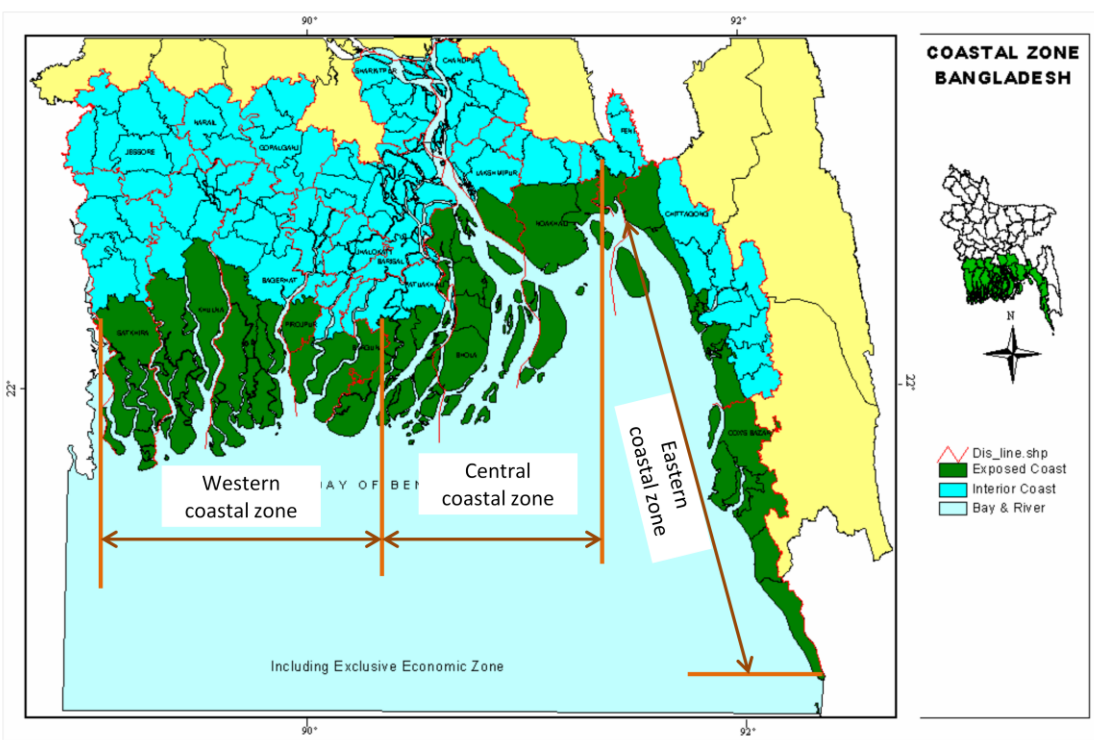

Figure 2.2: Coastal Zone of Bangladesh [image source: (Islam, et al., 2006)]

The coastal zone of Bangladesh is mostly plain lands with extensive river networks and accreted lands. At the eastern part in Chittagong and Cox's bazaar district, the coastal zone is hilly area. The entire coastal zone is divided into three regions namely eastern, central and western region (Pramanic 1983; cited in (Islam, 2001)). The approximate locations of these zones are shown in Figure 2.2.

Eastern Coastal Zone

The eastern coastal zone is very narrow and series of small hills run parallel to this zone. Soil characteristics of this zone are dominated by submerged sands and mudflats (Islam, 2001). Salt production, fishing, shrimp farming and tourism are main economic activities in this zone.

Central Coastal Zone

More than 70% of this zone's sediment load is silt with an addition of 10% sand (Coleman, 1969; cited in (Allison, et al., 2003))**.** Due to large sediment discharge from the Ganges-Bhrahmputra-Meghna river system, this zone is very dynamic in nature and frequent erosion and accretion occur here (Sarwar, 2005). Agriculture and fishing are the main occupation of the inhabitants.

Western Coastal Zone

This zone lies in the south- western part of the country. Soil erosion in this region is not that apparent due to the presence of mangrove forest and the soil characteristics here are silty loam or alluvium (Sarwar, 2005). "This mangrove dominated coastal areas have developed on soil formations of recent origin consisting of alluvium washed down from the Himalayas" (Islam, 2003). Mangrove swamps, tidal flats, natural levees and tidal creeks are dominant features in this zone. Because of the fertile character in this zone, agriculture is the main occupation here for majority of the people. Lower elevation as well as the large population density has made this zone the most vulnerable to SLR.

2.2 Agriculture and Population: Pressure on Land Use

Bangladesh is considered as one of the top most densely populated countries in the world. With an area of 1,47,570 square kilometers, the country accommodates a huge population of approximately 150 million that makes an average population density of about 1000 inhabitants per square kilometer throughout the whole country (UNFPA, 2012). The population in the coastal zone is approximately 35.1 million which is almost 27% of the entire population of the country. Out of 2.85 million hectares of the coastal and offshore areas about 0.83 million hectares are arable lands. This is almost 30% of the country's cultivable area (Haque, 2006). Although the soil characteristics is decent enough in these regions for cultivation, but one of the major threat is soil salinity problem which deteriorates the total crop yielding in last few decades. In the saline soils the main crops include rice, jute, sugarcane, pulses, various kinds of vegetables and fruits. But among these crops rice is always considered as the dominant crop. There are three broad categories of rice namely Aman (July to December), Boro (November to May) and Aus (April to August) [Source: (Banglapedia, 2012)]. During wet season, local Aman rice is grown extensively in the coastal saline areas with typical yields between 2.5 and 3.0 tons per hectare (Haque, 2006) . Season for Boro Rice is during the winter period which is in fact characterized by no rainfall condition. So this rice is grown under irrigated condition and especially in recent years farmers are going for alternatives for this due to increase in salinity in groundwater and lower yield of the crops (CEGIS, 2008).

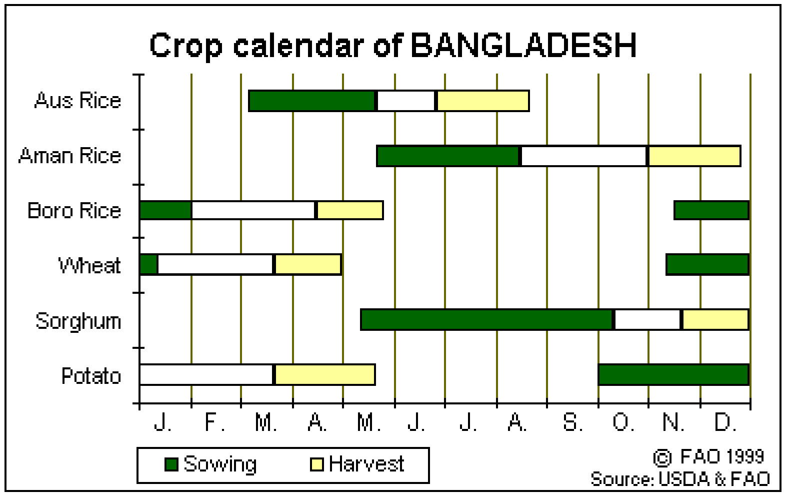

Figure 2.3: Crop Calendar of Bangladesh (source: FAO, 1999)

The increased effects of climate change and SLR are considered as major challenge for the coastal zone to balance between the decreasing trend of crop yield and the increasing growth of population. The displacement of millions of people due to SLR is not only a threat to proper allocation of these people but it will compel the pattern of land use as well. The food security of this region will also be impaired as the total cultivable land would be less than that of present time. The increase of soil salinity will be another issue that may cause the farmers to change their cropping pattern and cropping intensity. In many cases they may switch to different alternatives like shrimp farming or fishing. Overall there will be an immense stress on available land. Proper adaptation measure in this case is key to adapt will this inevitable pressure on land.

2.3 Need for Knowledge on Farming System

To adapt with the future climate change and SLR scenarios, proper knowledge of the ongoing cultivation practice as well as the impacts of altering a part of it is essential. Transferring and sharing of knowledge regarding this may minimize the potential impacts and at the same time it may allow the best use of available resources. As a part of this knowledge, it is required to know the impacts of the current cultivation method, cropping pattern and irrigation practice in next fifty to hundred years by considering the vulnerability of climate change and SLR. At the same time, it is also important to realize the fact that how it is possible to make the overall current practice sustainable by making slight alterations of existing method.

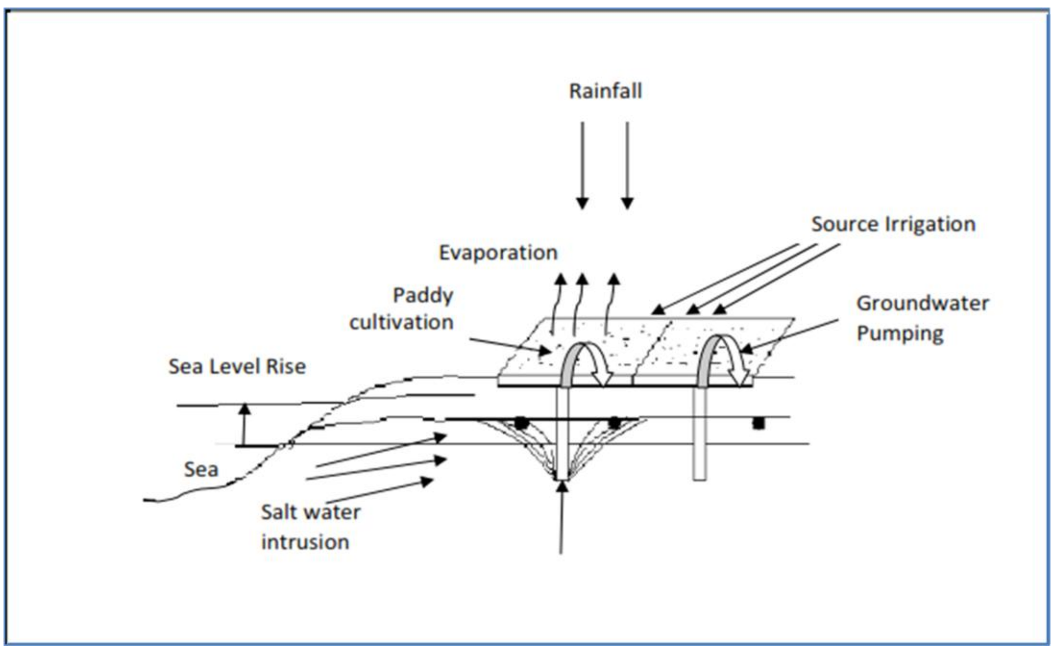

Figure 2.4: Typical Rice Cultivation Scheme in the Coastal Area of Bangladesh

Figure 2.4 shows a typical practice of rice cultivation in the coastal areas of Bangladesh. It has been a conjunctive use of surface water and groundwater for the irrigation purpose. During the wet season, which is characterized by huge amount of rain due to presence of monsoon, the main source of irrigation is surface water. It is provided through irrigation canals from the rivers and their tributaries. The only mode of irrigation during winter (dry season) is the extraction of groundwater. Pumping wells are placed in different locations in the cultivable area and its spacing and discharge rate defines the maximum utilization of groundwater resource. The groundwater recharge depends on the rainfall and evapotranspiration and in future it will vary significantly due to the change of rainfall pattern as a consequence of climate change. At the same time sea level will rise and the combined effect of changed recharge and SLR may cause salt water intrusion at a larger scale. Under these circumstances, it is required to know the safe distance of extraction pumps from the shoreline to minimize the problem of salt water intrusion. Knowledge of this will help farmers to look for other alternatives like storing of sufficient freshwater that can be used during winter season.

2.4 Climate Change Issues

Climate Change is a global phenomenon. “This change is attributed to the net effect of individual and interactive effects of global changes in atmospheric composition, land use, biological diversity, and climate.” (Karim, et al., 1999). The first evidence of climate change due to anthropogenic reasons was first emerged in the international public arena in 1979 at the first World Climate Conference (Depledge & Lamb, 2005). The potential impacts of climate change include global warming which is originated from the depletion of ozone layer corresponding to higher emission of green house gases. It will aggravate the natural calamities, change the rainfall pattern and cause SLR.

Bangladesh is one of the prime vulnerable countries to this issue and it will impose a great influence not only by changing its local climate condition but also deteriorating the standard of living of its vast population. The main factors that will affect the agriculture and irrigation practice of the coastal region of Bangladesh are the change of rainfall pattern, rise of temperature and sea level rise.

The annual rainfall in Bangladesh is influenced by the monsoon period and during the middle of the year from June to September most of the part of the country experience high amount of rainfall. Figure 2.5 shows the annual rainfall and effective rainfall distribution in Khulna region which is located in the south-west part of the country. This distribution of rainfall pattern over the year is more or less similar for almost all other regions of the country.

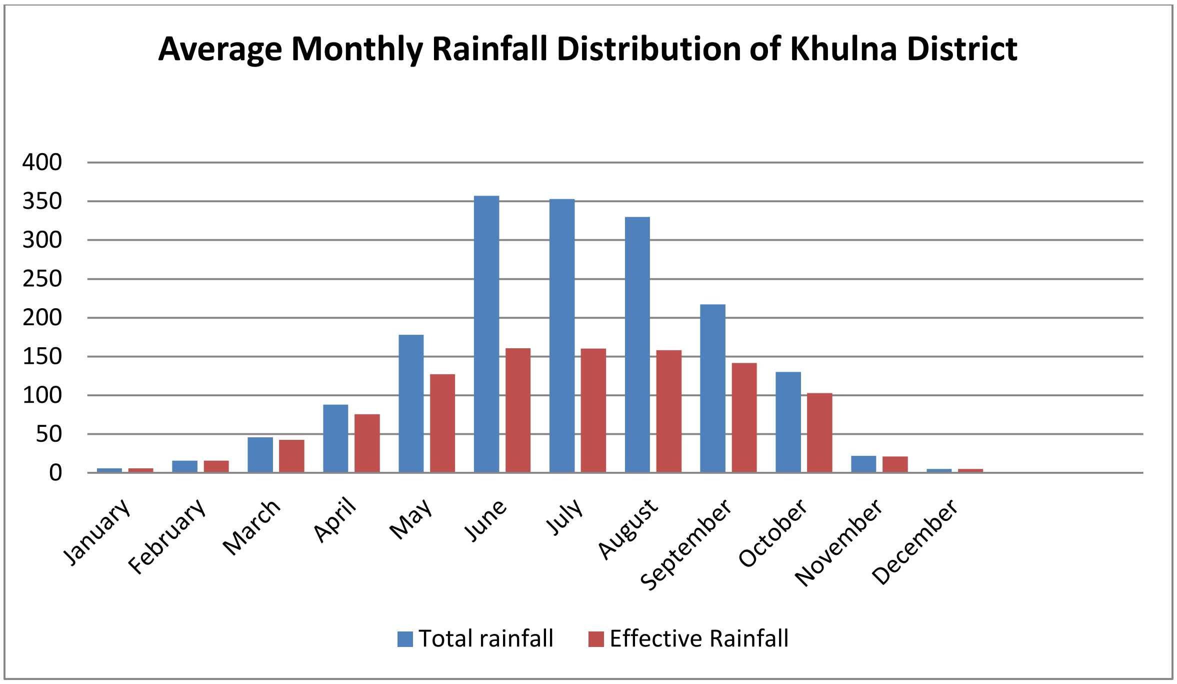

Figure 2.5: Average Monthly Rainfall Distribution of Khulna District [data source: CLIMWAT 2.0]

In recent years, the distribution of annual rainfall has become unpredictable and farmers have been facing the significant variations in the onset and end of monsoon period (Walsham, 2010). From recent rainfall record and future prediction model it is found that the annual average rainfall will sometimes become surplus and sometimes there is a deficit from the average annual. The increase of pre-monsoon rainfall also increased in recent past along with the higher frequency of extreme events. [(Islam, 2009) and (Murshed, et al., 2011)]

2.5 Sea Level Rise

Sea Level Rise in one of the most pronounced effects of climate change and its potential consequences are considered as a great threat to the existence of coastal settlements throughout the whole world at the end of 21st century. It is a global phenomenon and in addition to natural causes, some anthropogenic factors may be responsible for the acceleration of sea level rise.

2.5.1 Causes of Sea level Rise

Sea level rise is caused by the melting of huge volume of polar ice which is initiated due to the global rise of temperature. Due to the emission of carbon dioxide (CO_2) and other green house gases to the atmosphere, the usual mechanism of upward re-radiation of thermal energy is disturbed and consequently the heat is trapped inside the atmosphere that causes global warming. Rising temperature causes the polar ice to melt and at the same time it generates thermal expansion of the ocean water. As a consequence, the volume of water increases and sea level rise occurs. Wigley and Rapper mentioned in their article published in 'Nature' that, "The relative contribution of thermal expansion and ice melting to this sea level rise are uncertain and estimates vary widely, from a small expansion effect through roughly equal roles for expansion and ice melting to a dominant expansion effect" (Wigley & Raper, 1987).

Among the anthropogenic factors, those are accountable for global warming and consequent sea level rise, combustion of fossil fuel and deforestation are the prime ones. Apart from the human induced reasons, some natural local factors such as land subsidence, siltation and large regional ocean currents which move large volume of water from one place to another may cause relative sea level change (both rise and fall) in certain regions.

2.5.2 Global Sea Level Rise Scenario

Although there are some ongoing debates regarding the extent of anthropogenic activities that are accountable for sea level rise, but from the recent data it is irrefutable that sea level is rising and it is rising globally. From the available tidal gauge measurements, it is found that global average sea level increased at an average rate of 1.7 ± 0.3 mm per year from 1950 to 2009 whereas from high precision satellite data this rate was found to be 3.3 ± 0.4 mm per year from 1993 to 2009 (Nicholls & Cazenave, 2010). Almost similar result was reported by White (2011) from the measurements that were made by using satellite altimeters. Over the time period from January 1993 to April 2011, it shows a steady increase in global mean sea level (GMSL) of around 3.2 ± 0.4 mm per year which is 50% higher than the average rate observed over the 20th century (White, 2011). These results suggest that sea level rise is accelerating and it may speed up in the future.

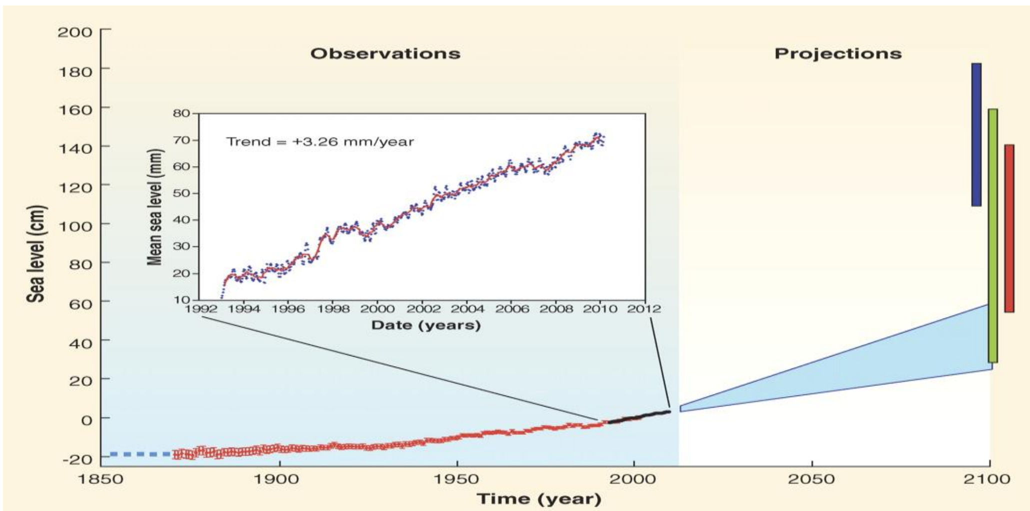

Figure 2.6: Global mean sea level evolution over the 20th and 21st centuries. The red curve is based on tide gauge measurements. The black curve is the altimetry record (zoomed over the 1993–2009 time spans). Projections for the 21st century are also shown. The shaded light blue zone represents IPCC AR4 projections for the A1F1 green house gas emission scenario. Bars are semi-empirical projections: red bar (Rahmstorf, 2007), dark blue bar (Vermeer & Rahmstorf, 2009) and green bar (Grinsted, et al., 2009). [*Image source:* (Nicholls & Cazenave, 2010)]

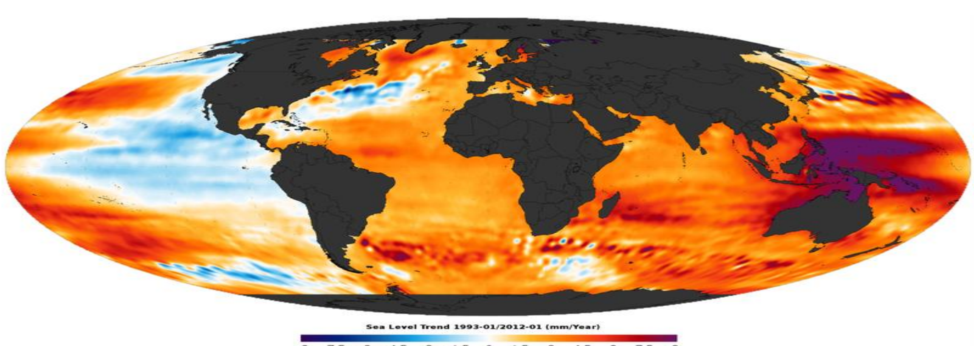

Figure 2.7: 1993–2012 Sea level trends from satellite altimetry [Image source: (Wikipedia, 2012)]

If we look ahead into the future, it apparently seems that this trend of sea level rise will increase and it will be a matter of great concern to the world. In 2007, the IPCC Fourth Assessment Report (4AR) gave similar results, projecting sea level rise of 18 to 59 cm by 2100 (IPCC, 2007). In addition quite a few semi empirical models are also introduced taking into consideration that the rate of sea level rise is proportional to the amount of global warming. That signifies that rate of melting of ice will be accelerated with the increase of temperature and they use past sea level and temperature data to quantify this effect. These models predict quite large rise of sea level in comparison to IPCC estimation and may be over estimated in some cases.

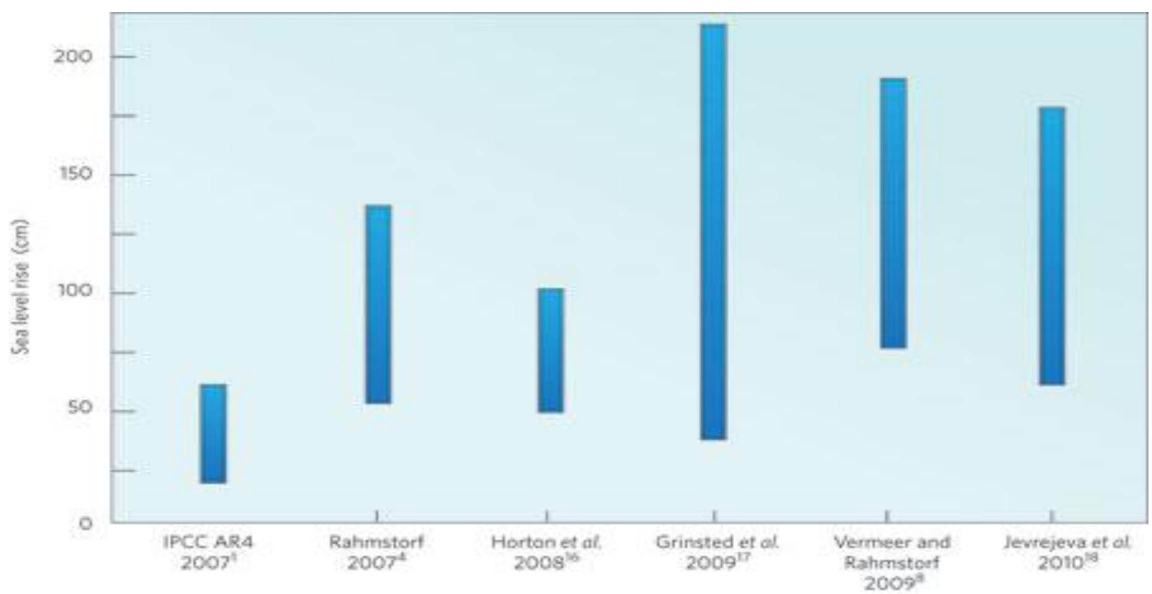

Figure 2.8: Estimates for twenty-first century sea level rise from semi-empirical models (Rahmstorf, 2007), (Horton, et al., 2008), (Grinsted, et al., 2009), (Vermeer & Rahmstor, 2009), (Jevrejeva, et al., 2010) as compared to the IPCC Fourth Assessment Report (AR4). [Image source: (Rahmstorf, 2010)]

2.5.3 Sea Level Rise in Bangladesh

The rate of sea level rise varies from location to location due to numerous reasons and the vulnerability of a coastal zone primarily depends on the topographic features, low elevation, land use, high population density and inadequate adaptive capacity. These features are quite evident in the coastal region of Bangladesh which made it one of the most vulnerable zones to SLR.

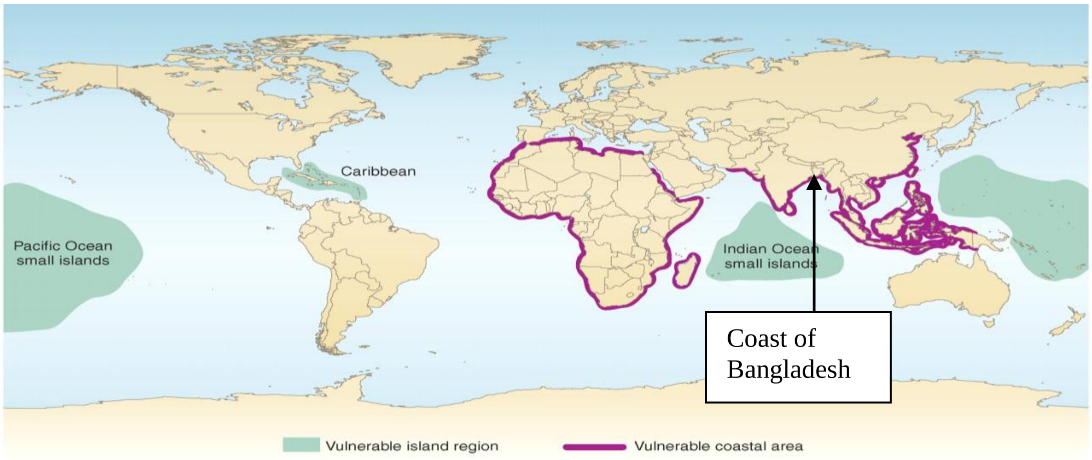

Figure 2.9: Vulnerable Coastal Area in the World for Coastal Flooding due to future SLR [Source: (Nicholls & Cazenave, 2010)]

Bangladesh is highly vulnerable to sea level rise because of its high density of population in the coastal region as well as it is a coastal country of smooth relief comprising broad and narrow ridges and depressions (Brammer, et al., 1993). From the analysis of tidal data from three tidal stations in Bangladesh – Cox'sBazar (21°26' N, 91°59' E), Char Changa (22°08' N, 91°06' E) and Hiron Point (21°48' N, 89°28' E) the obtained SLR trend was found to be 7.8, 6.0 and 4.0 mm/yr respectively from 1977 to 1998 (Source: SMRC 2003, cited in (Alam, 2003)) which is pretty high from the global rate of SLR in the previous century.

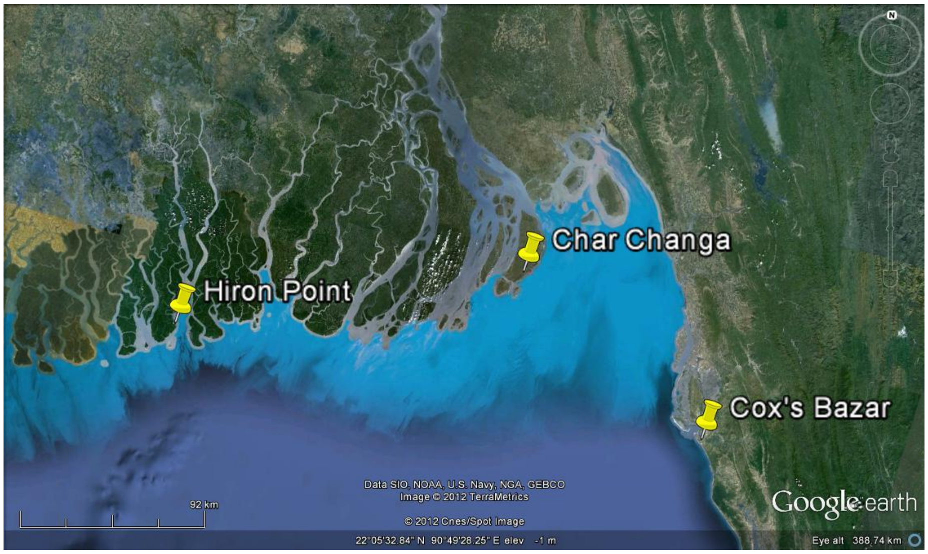

Figure 2.10 : Locations of Three Tidal Stations in Bangladesh

However, local factors such as tectonic setting, high sediment load from the rivers and deltaic subsidence play a crucial role in relative sea level rise in the Bay of Bengal (Warrick & Ahmed, 1996). The impacts of SLR will be more severe in the south-west coastal zone of the country as this region is characterized by low laying terrain and coastal lands are also subsiding here (Mohal, et al., 2007). Appropriate prediction of SLR in next 100 years is crucial in terms of policy making and integrated coastal zone management. The future scenario is predicted by using different models by different organizations and entity in different times and there is quite a large range of variation in these estimations. In an earlier study, potential SLR in coastal zone of Bangladesh was predicted as 30–150 cm by 2050 (DOE, 1993). On the basis of IPCC reports and existing SLR analysis, the NAPA for Bangladesh predicted SLRs of 14, 32 and 88 cm for the years 2030, 2050 and 2100 respectively (MOEF, 2005).

2.5.4 Impacts of SLR in Bangladesh

The most conspicuous impact of SLR is shoreline retreat which inundates the existing land. Bangladesh will be affected by loss landmass due to SLR and the relocation of huge population belongs to this land will be a real challenge. Mathematical models of the Bay of Bengal show that in the year 2100, for 88 cm SLR, about 11% area of the coastal zone will be inundated and water level will rise up to 50 cm for 88cm SLR near Chandpur (see Figure 2.11) which is about 80 km upstream from the estuary (Mohal, et al., 2006). This rise of water level and increase in salinity will compel people to change the land use pattern of these regions. For instance, cultivable lands may be replaced by shrimp farms which are favorable for this condition.

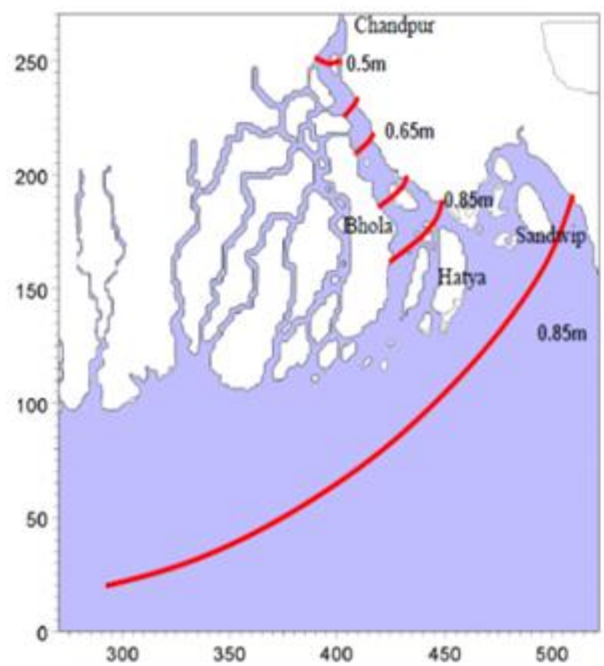

Figure 2.11: Water level rise for 88 cm SLR
[Source: (Mohal, et al., 2006)]

Impacts on Agriculture

Impact of SLR on agriculture will be twofold. There will be a loss of cultivable land and at the same time the existing land will face problem of proper irrigation during the dry seasons due to increase of salinity in both surface and groundwater. Out of 2.86 million hectors of coastal lands, about 1 million hectors of arable lands are affected by different range of salinity problems (SRDI, 2000). Rice cultivation is prevalent in the coastal areas o Bangladesh and quite a large number of researches is going on regarding the impacts on rice and other general crop yields due to SLR. It has been reported that salinity is responsible for the decrease of germination rate of crop plants (Rashid, et al., 2004). Ali (2005) investigated the loss of rice production in a village of Satkhira district (located in the south-west coast of Bangladesh) and found that rice production in 2003 was 1,151 metric tons less than the year 1985 corresponding to a reduction of 69 %. Out of the total decreased production, 77% was due to conversion of rice field into shrimp pond and 23% was because of yield loss (Ali, 2005). A World Bank (2000) study suggests that increased salinity alone from a 0.3 meter sea level rise will cause a net reduction of 0.5 million metric tons of rice production (World Bank, 2000). In a recent study it is found that for SLR of 1, 2, 3, 4, 5m the corresponding loss of rice cropland due to inundation will be 0.54, 1.25, 2.77, 5.33 and 8.34 per cent respectively for Bangladesh (Chen, et al., 2012).

Impacts on Salinity and Groundwater

Salt water intrusion caused by reduced flow from upstream of the rivers during winter season is one of the major concerns that accompanies with climate change and subsequent SLR. This will increase both the soil salinity and groundwater salinity. Due to lack of sufficient flow in the rives, the propagation of sea water during high tide will be more towards the upstream and hence using this water for irrigation will cause the problem of soil salinity more and more. In addition, SLR will allow salt water intrusion through the coastal aquifers and groundwater salinity will also increase. As a result, crops that are cultivated during winter season in coastal areas will suffer the most. Due to lack of sufficient rainfall, the dependency on groundwater will increase more and more in the near future and pumping rate will be higher day by day. This will generate larger drawdown and the zone of influence of wells will spread farther. The combination of this additional discharge from the well and SLR will accelerate the salt water intrusion rate in the coastal aquifers, especially in the dry winter seasons.

A study of Institute of Water Modeling (IWM) Bangladesh shows that 5 ppt (parts per thousand) saline front will penetrate about 40 km inland for SLR of 88 cm. As a consequence, the freshwater pocket of the Tentulia River in Meghna Estuary is going to be greatly affected (shown in Figure 2.12). It also states that "A big chunk of the fresh-water zone will disappear. This will adversely affect the country's ecology and some of the endangered species (marked by IUCN) will extinct forever" (Mohal, et al., 2006) .

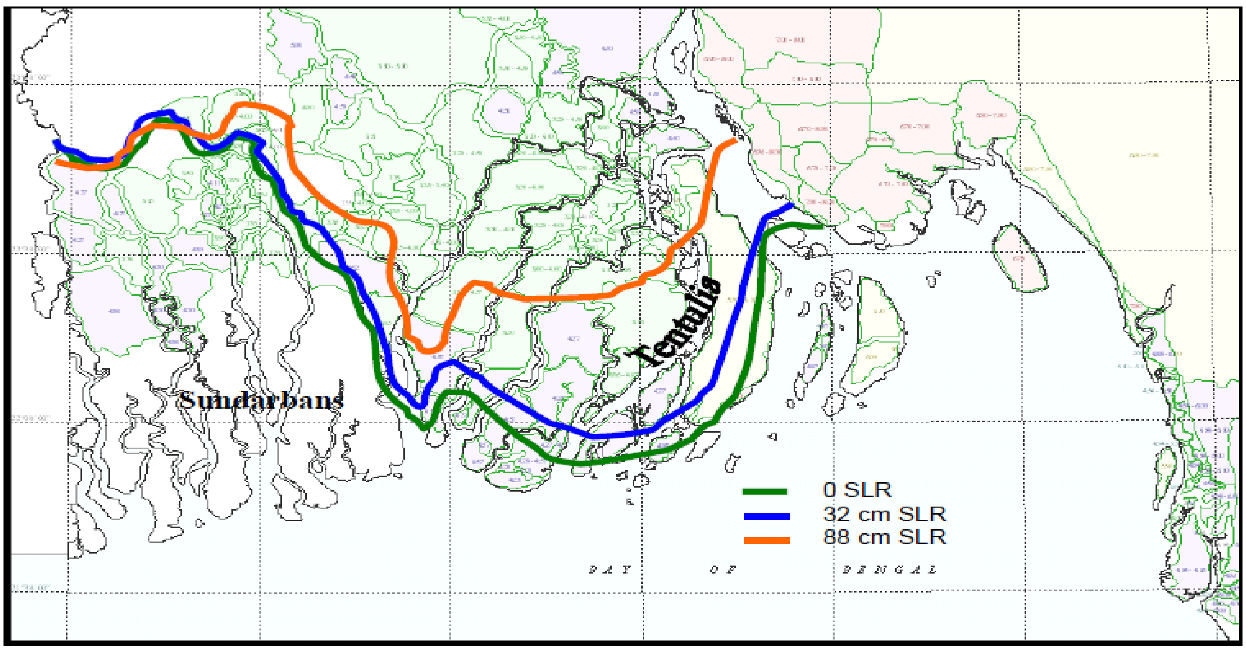

Figure 2.12: The Line of 5 ppt salinity due to Different SLR in Dry Season **(Mohal, et al., 2006)**

From the above discussion of literature review, considering the stress on land use and climate change issues including SLR, it is necessary to analyze the impacts on groundwater use for agricultural purpose in response to future scenarios. By developing generic models for the whole area, it is possible to get an overall idea about the severity of the impacts.

Chapter 3

METHODOLOGY AND MODEL DESIGN

3.1 General Approach

The methodology of the project involves four steps to reach the objectives that were listed in chapter 1 (Figure 3.1 summarizes the sequence). First the crop water requirement (CWR) and irrigation required were calculated for a typical agricultural site in south-west region of Bangladesh. This used the climate data (i.e. rainfall, evapotranspiration, and temperature), irrigation practice (i.e. crop type, cropping pattern) and the soil characteristics (i.e. soil type and its relevant structure and texture). The analysis also provides the overall amount of groundwater recharge of the particular area. The second step was groundwater modelling. This analysis may also provide information of the location of wells that might be affected by saline water. The third step deals with calculating the location and spacing of pumping wells for irrigation during the dry season (November to March). This work resulted in determining inter-relationship among different parameters such as groundwater recharge, cultivated crops and the location of groundwater wells from the sea. The fourth of the project was to analyze the impact of climate change and sea level rise on the irrigation and groundwater.

Data was collected from different sources including databases, previous studies and research findings, literature review and specific assumptions. The irrigation calculations were done using CROPWAT which is a computer program for irrigation planning and management (FAO, 2012). The groundwater related analysis was performed with MODFLOW which is a finite difference flow model for solving groundwater flow equations (USGS, 2012). The data source and model design will be discussed in details in the later parts of this chapter.

The overall general approach is summarized in Figure 3.1

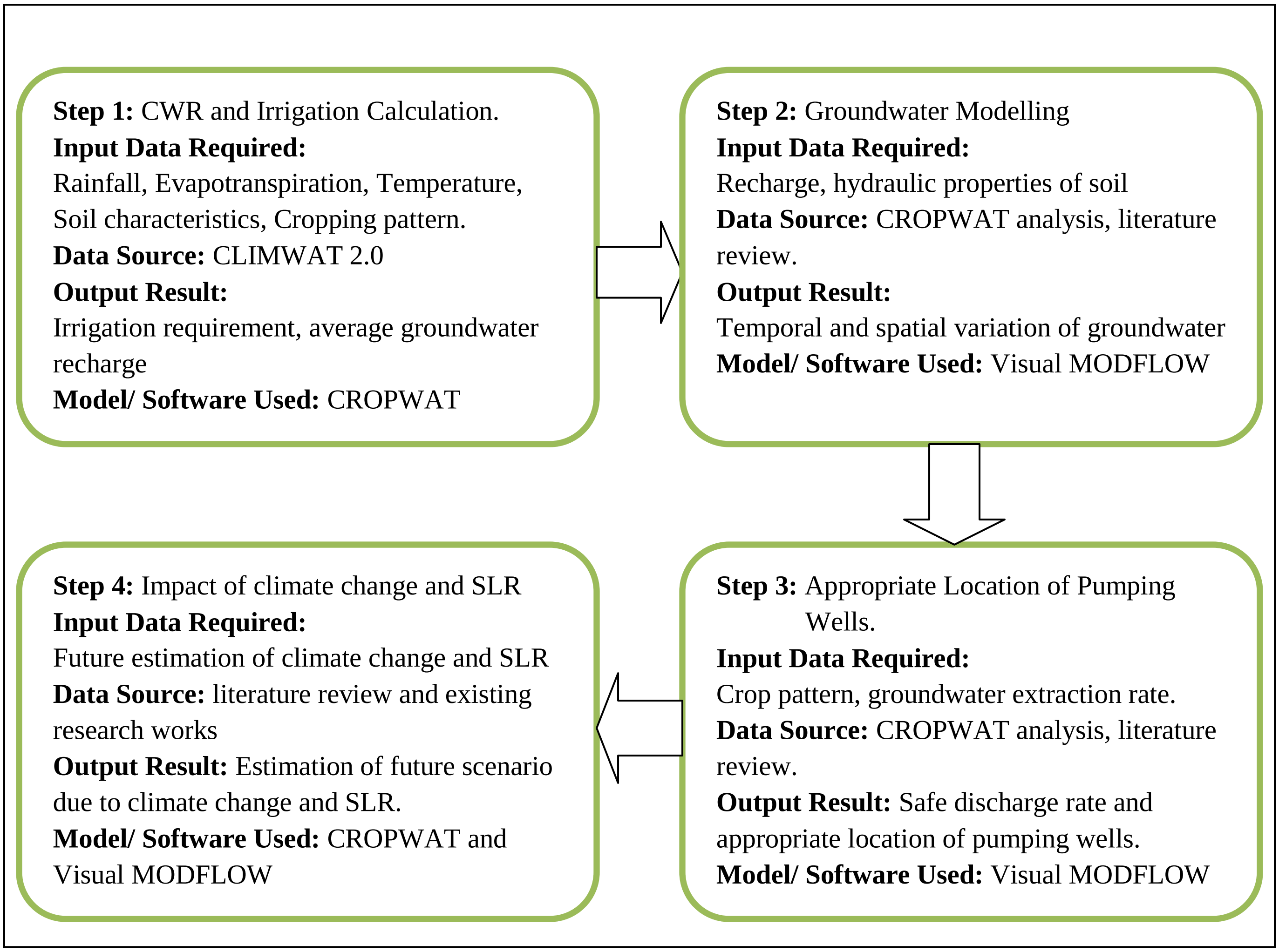

Figure 3.1: Summary of Different Steps of the Project

3.2 Calculating Crop Water Requirement and Irrigation Required

3.2.1 CWR Calculations: Background Theory

Crop water requirement (CWR) is defined as the “amount of water required to compensate the evapotranspiration loss from the cropped field” (Allen, et al., 1998). In other words, it is the amount of water needed by the plants for optimal growth. It always refers to “a crop grown under optimal conditions, i.e. a uniform crop, actively growing, completely shading the ground, free of diseases, and favorable soil conditions (including fertility and water). The crop thus reaches its full production potential under the given environment" (Brouwer & Heibloem, 1986).

The CWR for a particular type of plant can be formulated as,

$$CWR = ET_o \times K_c$$

Where, CWR = ET_{crop} or crop evapotranspiration (mm/day)
ET_o = Reference evapotranspiration (mm/day) [evapotranspiration of reference grass crop]
K_c = Crop factor which is dependent on crop type

The reference evapotranspiration (ET_o) can be calculated using FAO Penman-Monteith method by combining (i) Penman-Monteith equation, (ii) the equations of aerodynamics and (iii) surface resistance (Brouwer & Heibloem, 1986).

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.3u_2)}$$

Where, ET_o = reference evapotranspiration [mm day^{-1}],
R_n = net radiation at the crop surface [MJ m^{-2} day^{-1}],
G = soil heat flux density [MJ m^{-2} day^{-1}],
T = mean daily air temperature at 2 m height [°C],
u_2 = wind speed at 2 m height [m s^{-1}],
e_s = saturation vapour pressure [kPa],
e_a = actual vapor pressure [kPa],
e_s - e_a = saturation vapor pressure deficit [kPa],
D = slope vapor pressure curve [kPa °C^{-1}],
γ = psychrometric constant [kPa °C^{-1}].

CWR mainly depends on:

- The Climate Condition: Crop requires much water per day if sunny and hot climate prevails. Solar radiation, low humidity, high wind speed and hot temperature cause evapotranspiration and it takes away water from the plant. So for the continual growth of the plant, water needs to be supplied either in the form of rainfall or irrigation.

- The Crop Type: The crop factor (K_c) varies from crop to crop. It signifies the relationship between the reference grass crop and the crop actually grown in the field (Brouwer & Heibloem, 1986). For reference grass crop, $K_c = 1$. Depending on the leaf surface area of a plant, the value of K_c can be either greater or less than one.

- The Growth Stage of the Crop: CWR varies in different stages of growth of a plant. A fully grown plants need more water in comparison to its initial stage of planting as the surface area of leafs increase. So the amount of evapotranspiration increases.

3.2.2 Irrigation Required Calculations: Background Theory

The Irrigation requirement for crop production can be defined as "the amount of water, in addition to rainfall, that must be applied to meet a crop's evapotranspiration needs without significant reduction in yield" (Smajstrla & Zazueta, 1996).

Irrigation required (IR) can be formulated as

$$IR = ET_{crop} - P_e$$

Where, IR = Irrigation required, ET_{crop} = Crop evapotranspiration and P_e = Effective rainfall.

Effective rainfall (P_e) is the difference between total rainfall and the actual evapotranspiration. In irrigation, it is the portion of rainfall that remains in the soil for the utilization of plant for its germination.

In reality, there are water losses in field conditions.

$$IR = ET_{crop} + SAT + PERC + WL - P_e$$

Where, SAT is the amount of water needed to saturate the soil for land preparation by puddling. It depends on soil type and root zone depth. PERC stands for percolation and seepage losses which is a function of soil type. WL is the amount of water needed to establish a water layer.

3.2.3 Data Source: CLIMWAT 2.0

CLIMWAT 2.0 is a climate database developed and published jointly by the Water Resource, Development and Management Service (AGLW) and the Environment and Natural Resources Service (SDRN) of Food and Agriculture Organization (FAO) of United Nations. The database is provided by agro-meteorological group of FAO. This database can be used in combination with the computer program CROPWAT 8.0 to calculate CWR, IR and irrigation scheduling for various range of crops in different climatological stations worldwide. It contains observed agroclimatic data of over 5000 stations worldwide (FAO CLIMWAT, 2012).

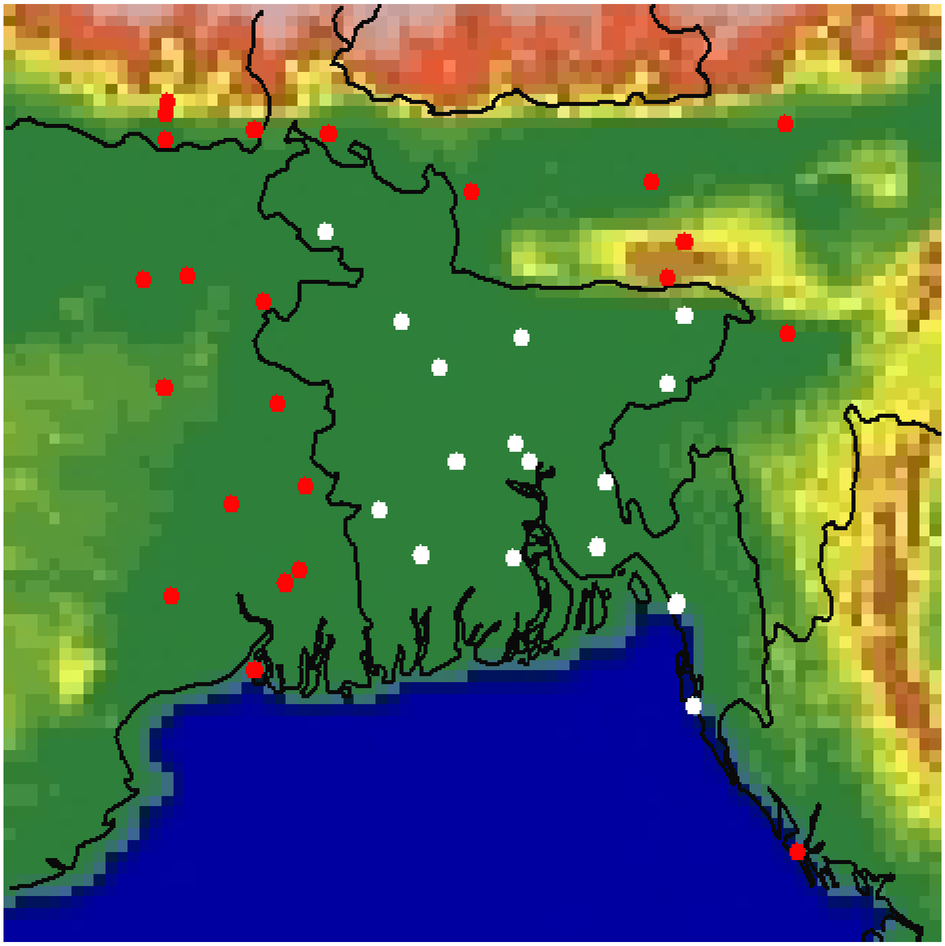

Figure3.2: Climatological stations of Bangladesh available in CLIMWAT 2.0 (white dots in the Figure)

CLIMWAT 2.0 provides long-term monthly mean values of seven climatic parameters, namely:

- Mean daily maximum temperature in °C
- Mean daily minimum temperature in °C
- Mean relative humidity in %
- Mean wind speed in km/day
- Mean sunshine hours per day
- Mean solar radiation in MJ/m2/day
- Monthly rainfall in mm/month
- Monthly effective rainfall in mm/month
- Reference evapotranspiration calculated with the Penman-Monteith method in mm/day.

The climate database was made on the basis of available dataset from the period of 1971-2000. For some stations the dataset may be broken due to unavailability, e.g. 1961-70 and 1992-2000, but they contain at least 15 years of data (FAO CLIMWAT, 2012)

3.2.4 Model Design in CROPWAT 8.0

CROPWAT 8.0 is a computer program that act as a decision support tool by calculating CWR and irrigation requirements based on soil climate and crop data. Irrigation scheduling and developing irrigation scheme is another feature of this program. CLIMWAT 2.0 climate files can be imported into CROPWAT 8.0.

In this project, the CROPWAT model was created by using climate data from CLIMWAT 2.0 for the two stations of south-west Bangladesh. The typical soil type for those regions was selected and the crop pattern (crop type, planting and harvested date, percent of cultivated area) was created from the literature review. Details of model construction and the input parameters will be discussed in chapter 4.

3.3 Groundwater Modelling

Groundwater modelling in this project was done by using MODFLOW. Data sources for the input parameters were obtained from (i) literature considering the typical soil characteristics of the region and (ii) result obtained from the analysis of climate data in CROPWAT.

3.3.1 USGS MODFLOW Model: General Concept

MODFLOW, a finite difference flow model developed by U.S. Geological Survey, is a computer code that is used to solve the groundwater flow equation. The software is extensively used by the hydrogeologists to simulate the three dimensional (3D) groundwater flow and contaminated transport through the aquifers beneath the earth's surface.

In MODLOW, a 3D rectangular model is considered with number of rows, columns and layers. The overall system consists of numerous cells and the computer code is developed to solve partial differential groundwater flow equation in each individual cell.

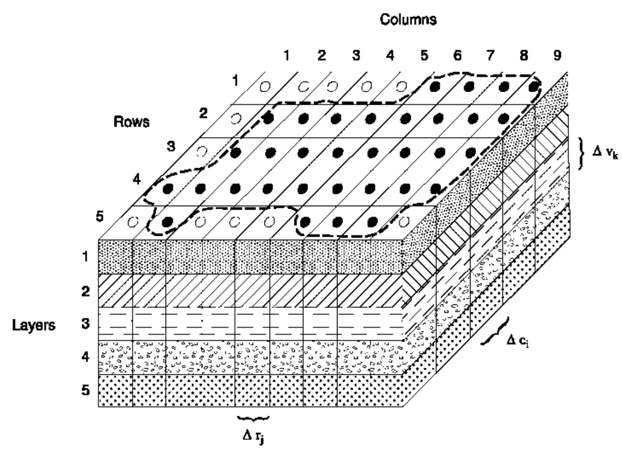

Figure 3.3: Typical 3D Grid Model in MODFLOW
[Image source: (Harbaugh, 2005)]

According to (USGS, 2005) the governing partial differential equation used in MODFLOW is:

$$\frac{\partial}{\partial x}\left[K_{xx}\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_{yy}\frac{\partial h}{\partial y}\right]+\frac{\partial}{\partial z}\left[K_{zz}\frac{\partial h}{\partial z}\right]+W=S_s\frac{\partial h}{\partial t}$$

Where,

K_{xx}, K_{yy}, K_{zz} are the values of hydraulic conductivity along the *x*, *y*, and *z* coordinate axes (L/T)

h is the potentiometric head (L)

W is a volumetric flux per unit volume representing sources and/or sinks of water, where *negative* values are extractions, and *positive* values are injections (T^{-1})

S_s is the specific storage of the porous material (L^{-1}); and t is time (T)

3.3.2 Applying MODFLOW to the Upper Unconfined Aquifer in Bangladesh

An unconfined aquifer (also known as free or phreatic aquifer) is an aquifer underlain by an impermeable stratum (usually solid rock or clay), but the upper part of it is physically in contact with the atmosphere through the groundwater surface. Unconfined aquifers can be replenished or recharged by the percolation process of rainfall.

Groundwater extraction for irrigation purposes in Bangladesh is mainly carried out using shallow wells and it is limited to the upper unconfined aquifers only (Shamsudduha, et al., 2009). According to the British Geological Survey, in the coastal belt and deltaic region of Bangladesh, the shallow aquifer is affected by salinity problem (BGS, 2001).

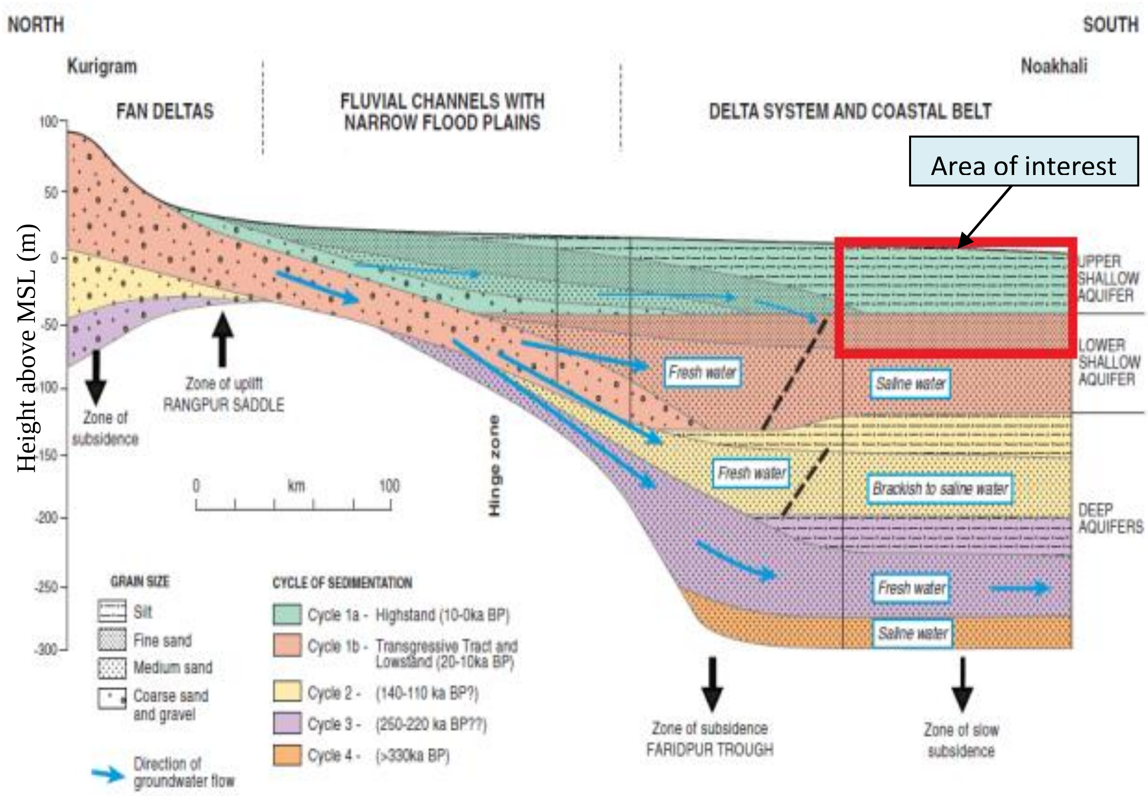

Figure 3.4: Hydrogeological cross section from north to south across Bangladesh (BGS, 2001).

3.3.3 Model Formulation

In MODFLOW, the model was designed by considering the geography of the south-west region of Bangladesh. The area is divided into a number of peninsula like land blocks; i.e. land bordered by water on three sides but connected to mainland (Figure 3.5). These land blocks vary in width and shape in different locations. To make a generic model, a rectangular model was designed for different widths. A trapezoidal shaped model was also considered for ground water modelling to account for the land blocks becoming wider inland.

Figure 3.5: Peninsula Shaped Land Blocks in South-west Region of Bangladesh.
(Scale is shown in the bottom left of the image)

To design the model, the upper unconfined aquifer was considered. So a single layer 3-D MODFLOW model was constructed with typical aquifer properties and boundary conditions. The area is generally flat and for simplicity to design a generic model, the upper surface of the model was taken as a constant elevation (i.e. no slope is considered in both x and y direction). The land is bounded by sea/river in both sides and no flow was considered beyond the extent of the model.

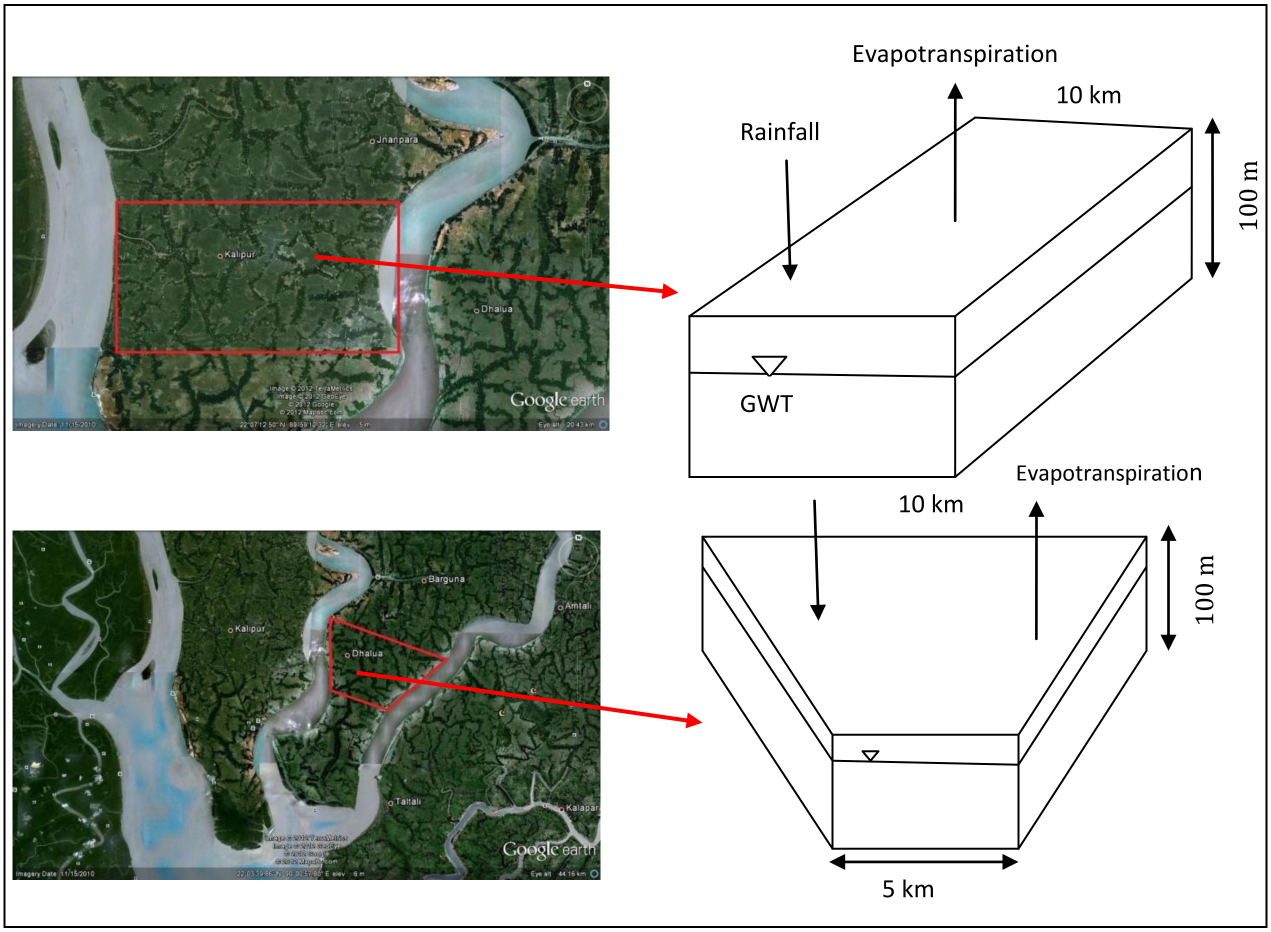

Figure 3.6: Groundwater Model Design

Internal drains and irrigation canals are evident over the agricultural areas. In some places gates and sluices are used to control the amount of irrigation. To replicate this and to analyze salt water intrusion by particle tracking, a model was constructed which had 1km× 1km in dimension and had salt water flow in one side of it. The flow in the opposite side was fresh water flow. This conceptual model represents a block of agricultural land adjacent to the sea and which contains a drain on the inland side. The salt water intrusion here can happen from only one side while in the large scale model it is possible from two sides.

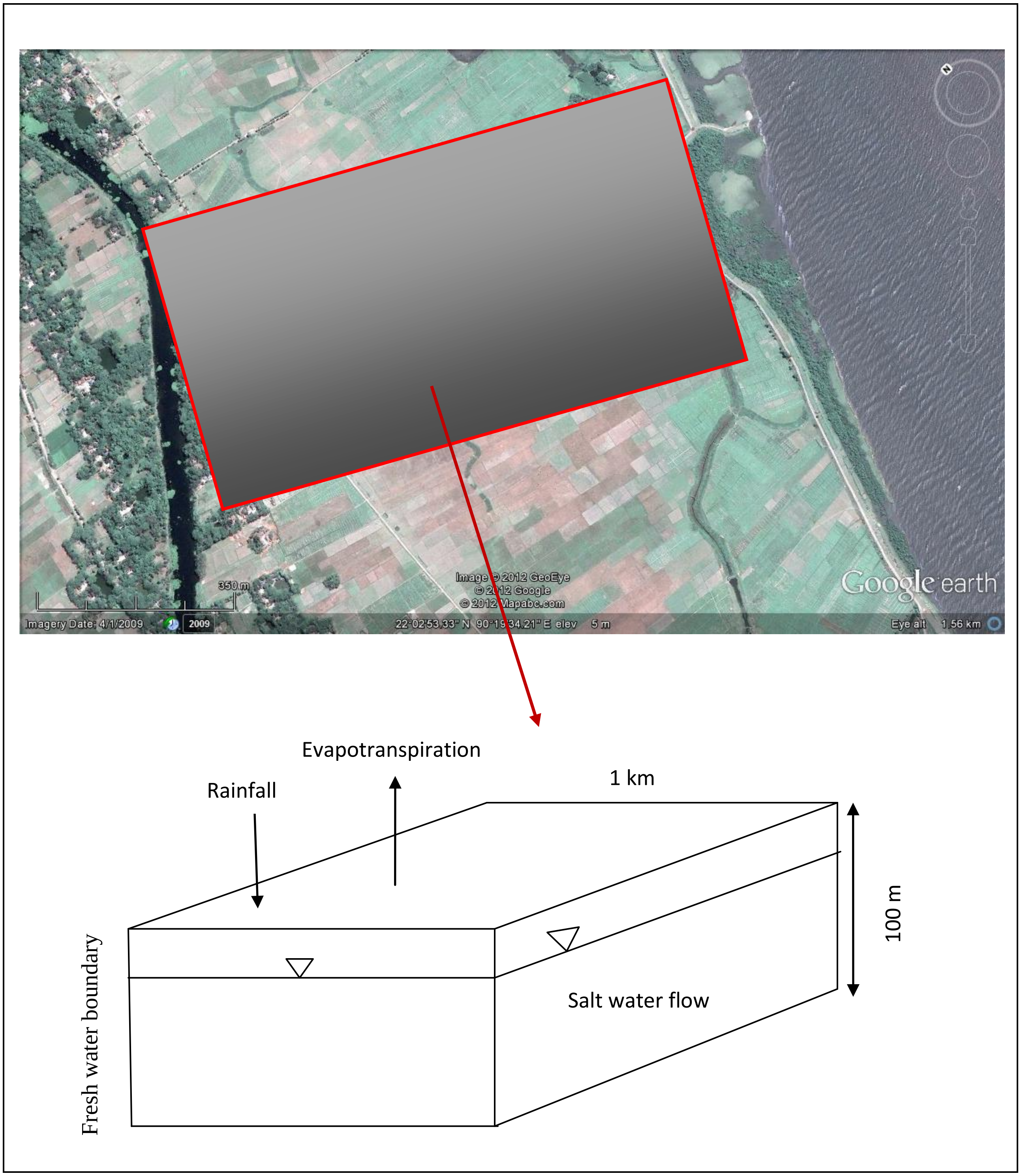

Figure 3.7: Groundwater Model Design for 1km×1km Model

3.3.3.1 Aquifer Properties

The aquifer properties that are required for the MODFLOW model design include:

Hydraulic Conductivity (K): A measure of soil's ability to transmit water when subjected to a specific hydraulic gradient. It is the "proportionality factor in Darcy's law as applied to the viscous flow of water in soil, that is, the flux of water per unit gradient of the hydraulic potential" (AAFC, 2011)

For one dimensional vertical flow, Darcy's law can be written as, $V = K\frac{dh}{dz}$

Here, V is the average velocity of fluid through a geometric cross-sectional area within the soil, h is the hydraulic head, z is the vertical distance. K is the hydraulic conductivity (unit m/s). It depends on soil grain size, structure of soil matrix and the type of fluid. For three dimensional flows K_x, K_y and K_z are hydraulic conductivities in x, y and z directions respectively.

Specific Storage (S_s): It is the amount of water released from storage from per unit volume of a saturated porous medium per unit decrease in hydraulic head. It represents the capacity of an aquifer. It can be written as $S_s = \rho_w g(\alpha + n\beta)$, where α and β are the compressibility of aquifer skeleton and water respectively (m^2/N), n is the porosity and S_s is the specific storage (m^{-1}).

Specific Yield (S_y): It the amount of groundwater released from the storage due to drainage from lowering the water table in an unconfined aquifer. Specific yield is caused by gravity and the value ranges between 0 and 1. Porosity is the upper limit of specific yield; i.e. $S_y \leq \text{porosity}$.

Porosity: Total porosity of an aquifer is the fraction of pore spaces (including both permeable and impermeable voids) within the total volume of soil. On the other hand, effective porosity can be defined as the fraction of pore spaces that will drain in a reasonable period of time under the influence of gravity (Buddemeier & Schloss, 2000). Effective porosity is always less than total porosity.

Values of the aquifer properties vary with the soil type on the basis of grain size. The reported range of values of these parameters differs slightly in the literature.

3.3.3.2 Boundary Conditions

Boundary conditions describe the exchange of flow between the model and the external systems. Two boundary conditions are considered in the model. They are:

i. Constant Head: The water level on the river estuary or the east and west side of the modelled area is assumed to be constant. The approximate average elevation in the project area is around 10 m above mean sea level. So, the constant head in the boundaries of the model was set as 10m below the soil surface.
ii. Recharge: The recharge boundary describes the effects of rainfall and evapotranspiration and it is constant over the whole model domain. The value of typical annual recharge was set to 500 mm/year. This is the average of the annual recharge of the two stations (Khulna and Barisal). The calculation for the recharge is shown in section 4.2.3.

3.3.3.3 Flow Types: Steady State Flow and Transient Flow

When the magnitude and direction of flow is constant with time over the entire model domain, the flow is steady state. On the other hand, transient flow occurs when the flow properties fluctuate with time. The hydraulic head remains constant with time in steady state flow, whereas it changes in the case of transient flow. Steady state flow does not mean that there is no movement of groundwater, rather it indicates that in a groundwater aquifer system the amount of inflow and outflow is equal over time (Freezy & Cherry, 1979).

For Transient Flow: $$\frac{\partial(\rho_w q_w)}{\partial x} + \frac{\partial(\rho_w q_w)}{\partial y} + \frac{\partial(\rho_w q_w)}{\partial z} = \frac{\partial(\rho_w \emptyset S_w)}{\partial t}$$

For Steady State Flow: $$\frac{\partial(\rho_w q_w)}{\partial x} + \frac{\partial(\rho_w q_w)}{\partial y} + \frac{\partial(\rho_w q_w)}{\partial z} = 0$$

Where, ρ_w = density of water, q_w = Darcy flux of water, $\emptyset$ = porosity, S_w = saturation.

Steady state flow is considered in the model for determining yearly average groundwater conditions whereas transient flow is used to calculate the seasonal variations of groundwater.

3.4 Location of Pumping Wells

During the dry season (November to March), there is insufficient rainfall and low flows in the rivers and their tributaries. Farmers extract groundwater for irrigation using low lift shallow pumps. The location of pumping well in a coastal agricultural area is influenced by its distance from the coastline. Sea water has a different density from freshwater it may intrude in the aquifers due to lack of recharge and over extraction of groundwater. In MODFLOW, the particle tracking method is used to determine how far saline water intrudes. To design the model for this purpose, different layout of wells were considered and the pumping rate was calculated based crop type and required amount of irrigation.

3.4.1 Salt Water Intrusion

When groundwater is pumped from aquifers, there is a possibility that saline water from the sea may flow towards the well. The phenomenon of seawater intrusion can cause the well to become unusable. Saltwater intrusion can also occur due to lowering of groundwater table which may result from lower recharge. The encroaching sea water will encounter an area known as the zone of dispersion where an interface is formed due to mixing of fresh and saline water with different densities. The interface moves back and forth because of fluctuation in the recharge rate of freshwater (Ranjan, 2007).

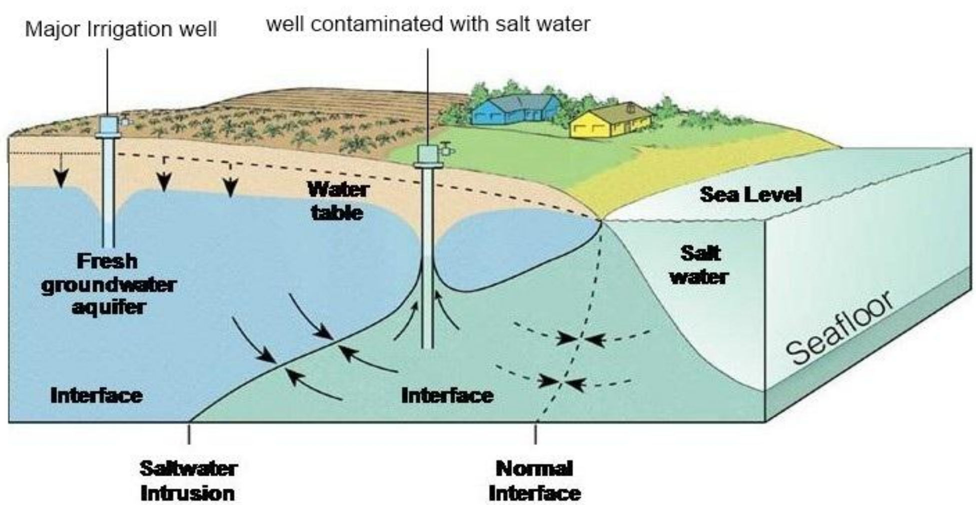

Figure 3.8: Schematic Illustration of Salt Water Intrusion in Coastal Areas
(Source: http://www.rw.ttu.edu/2302_butler/chapter9.htm)

The seawater intrusion phenomenon was described by Ghyben-Herzberg relation. This relates the elevation of water table to the elevation of the boundary of the interface between the freshwater and underlying salt water zones of an aquifer (Figure 3.9). The equation states as follows:

$$z = \frac{\rho_f}{\rho_s - \rho_f}\, h$$

Here, h is the thickness of the freashwater zone above sea level; z is the thickness of the freashwater zone below sea level; ρ_f and ρ_s are the density of freaswater and saltwater respecyively. The typical value of freshwater and saltwater are 1000kg/m^3 and 1025 kg/m^3 respectively and this gives the equation: $z = 40\ h$.

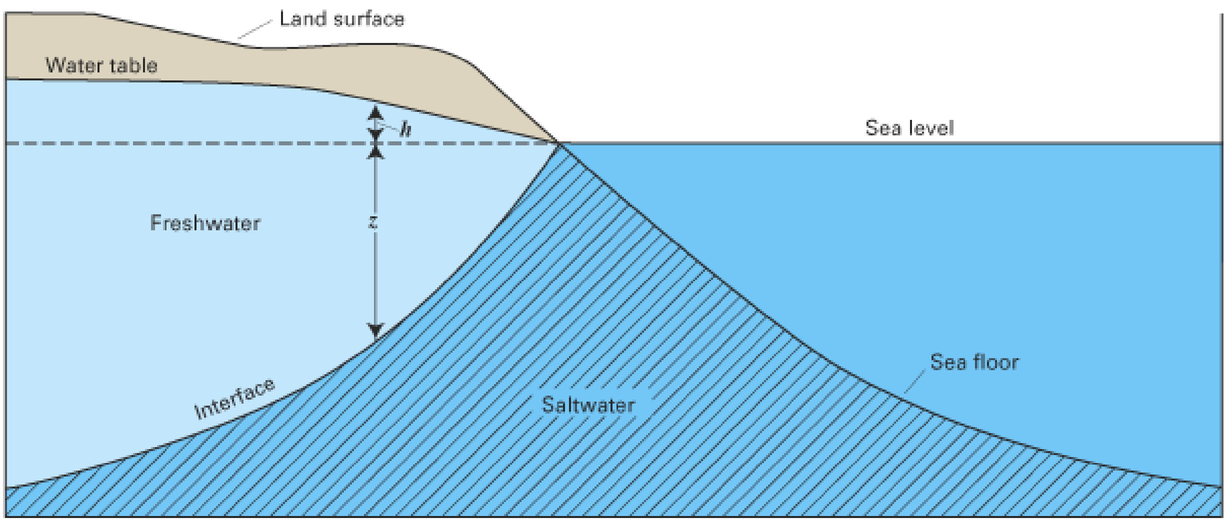

Figure 3.9: Simplified Freshwater- Saltwater Interface in a Coastal Water table Aquifer. [Image source: (Barlow, 2003)]

This is based on simplifying assumptions that include: (i) hydrostatic condition prevails within the aquifer which implies no vertical gradient in groundwater level; i.e. there is a horizontal groundwater table within the aquifer and (ii) there is a sharp boundary between the freshwater and saltwater zones in the interface (Barlow, 2003). In reality, in most of the cases these assumptions are invalid and that limits the implication of this method. Moreover, this method has some limitations such as: (i) No presence of groundwater pumps (ii) sufficiently thick aquifer

(iii) no tide is considered and (iv) constant recharge is required over time. Nevertheless, in spite of its limitations, this method can provide some quick and general insight into the extent of the salt water intrusion in a coastal area.

3.4.2 Particle Tracking

To analyze the potential extent of sea water intrusion, the particle tracking method was used. This was done by running MODPATH, a post-processing package for MODFLOW. According to the description from the user's manual of Visual MODFLOW 4.1, MODPATH computes three-dimensional flowpaths using output from steady-state or transient ground-water flow simulations by MODFLOW. MODPATH uses a semi-analytic particle tracking scheme that allows an analytical expression of the particle's flow to be obtained within each finite-difference grid cell. Particle paths are computed in MODPATH by tracking particles from one cell to the next until the particle reaches a boundary, an internal sink/source, or satisfies some other termination criterion (MODFLOW, 2005). The input particle used was seawater.

3.5 Impacts of Climate Change and Sea Level Rise

The final step of the project is to analyze the impacts of climate change and consequent sea level rise on crop water requirement (CWR), irrigation required (IR), groundwater recharge and sea water intrusion. CWR and IR will be influenced by climate change because there will be change in effective rainfall. There will be change in total yearly rainfall and the distribution of rainfall throughout the year will differ from the existing situation. This may compel the farmers to change their cropping pattern and irrigation scheduling. There will be change in groundwater recharge and a lowering of groundwater table may enhance the saltwater intrusion. Moreover, sea level rise will cause the sea water to propagate towards inland and the salinity will be increased both in surface water as well as in groundwater.

Change of precipitation and groundwater recharge, sea level rise in the concerned area and change in cropping pattern is considered while designing the models that represent future scenarios. The comparison was made in changes in CWR, IR, recharge, groundwater table fluctuations, and the extent of saltwater intrusion and the safe distance of pumping wells from future shoreline.

3.6 Summary

Chapter 3 of this thesis report describes the methodology of the model design. In addition, this chapter introduced the data source and states related background theories along with the explanation of relevant terminologies and parameters. Now the next chapter describes the construction, testing and calibration of the model. It will also discuss the obtained results.

Chapter 4

MODEL CONSRUCTION AND TESTING

4.1 Introduction

This chapter contains a detailed description and explanation of model parameters such as climate, geology, hydrogeology, cropping patterns and irrigation practice. The model is analyzed and tested with the current day scenario. Crop water requirement and required irrigation were calculated by models constructed in CROPWAT /CLIMWAT and the groundwater modelling was done with MODFLOW.

4.2 Crop Water Requirement and Irrigation Required

The model used to calculate the crop water requirement (CWR) and irrigation required (IR) was CROPWAT 8.0. The data source for climate data is CLIMWAT 2.0. The model was created for two climatological stations (Khulna and Barisal) that are located in the south-west region of Bangladesh. In spite of having the same overall climate pattern, there are variations in rainfall and evapotranspiration between these two places. To investigate the effects of this dissimilarity, separate models were constructed for Khulna and Barisal and comparison was made.

Table 4.1: Location of Climatological Stations

Station name	Latitude	Longitude	Altitude (above MSL)
Barisal	22.75˚ N	90.36˚ E	4 m
Khulna	22.78˚ N	89.53˚ E	4 m

The models were constructed by importing the available climate data of these two stations from CLIMWAT 2.0 to CROPWAT 8.0. The database for each station contains two files. They are the ET_o file (.pem) and rain file (.cli) which corresponds to evapotranspiration and rainfall data respectively. The other required parameters for calculating CWR and IR are soil data and crop pattern which includes the type of crop, planting and harvesting date and the percentage of area that is occupied by each crop.

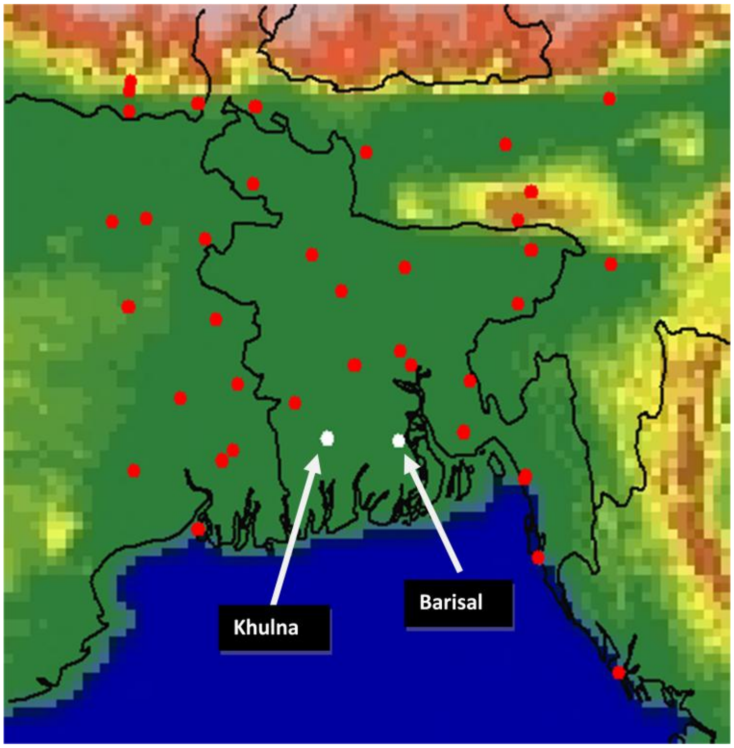

Figure 4.1: The Location of Two Climatological Stations Barisal and Khulna (shown in white dots).

4.2.1 Calculation of CWR and IR

Rainfall and evapotranspiration data for both the stations differ slightly for different month of the year but exhibit a similar yearly trend (Figure 4.2). There is high rainfall in the middle part of the year from May to October with the maximum rainfall during June and July. About 80% of the annual rainfall occurs due to the southwest monsoon and the remaining occurs during pre and post monsoon periods (Rana, et al., 2007). The winter season (November to February) is very dry. Evapotranspiration is the lowest during the winter (November to February). From March, it starts to increase with the longer duration of available sunlight. But as the monsoon starts, in spite of longer day length, it reduces mainly due to cloudy weather.

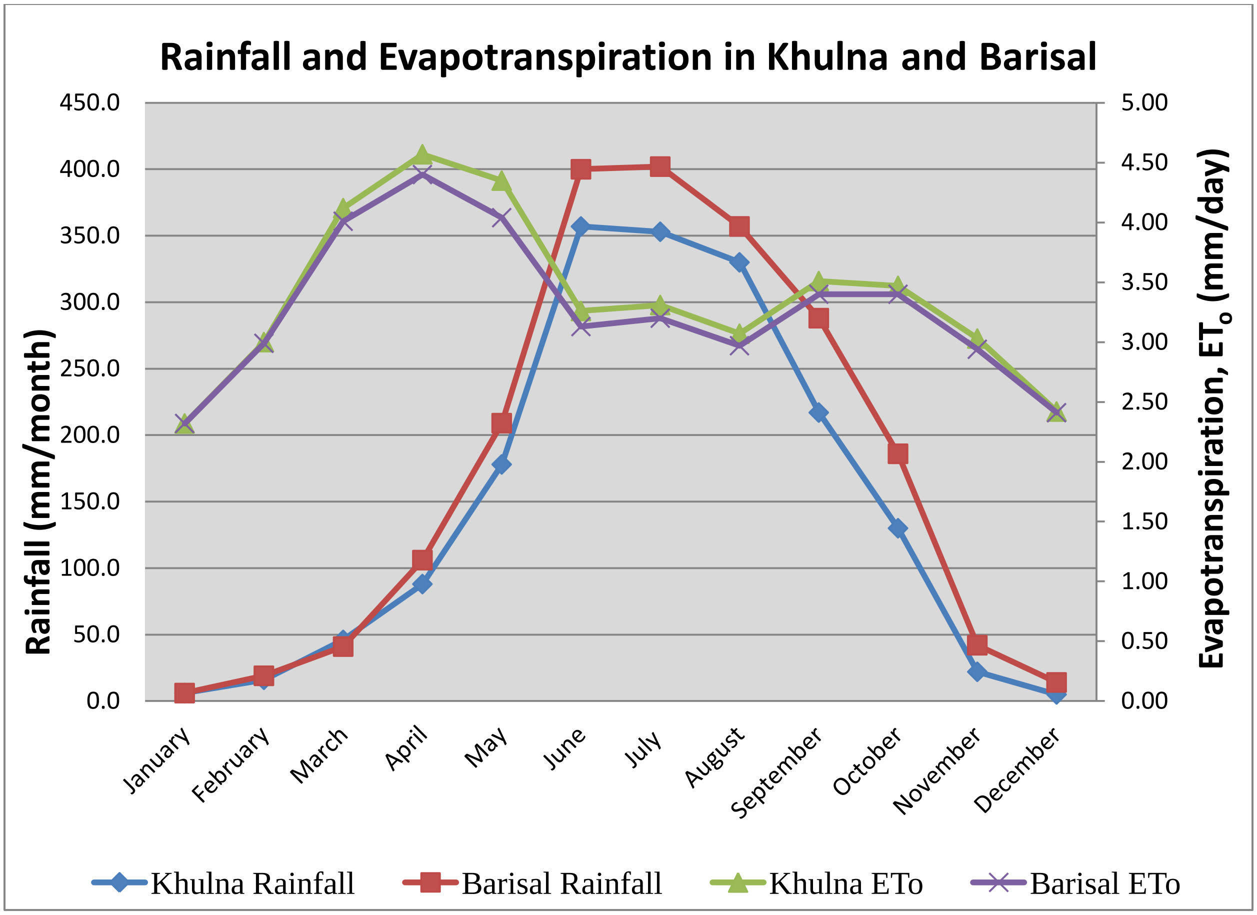

Figure 4.2: Comparison of Rainfall and ET_o of Between Khulna and Barisal

The majority part of the area has sedimentary soils and the sediments are mainly non-calcareous clays but are silty and slight calcareous on riverbanks (Banglapedia, 2006). This area faces soil salinity problem especially during dry seasons (November to March) when rainfall is very low. Among the classification of the soils available in CROPWAT, "medium soil" was selected to represent the mixture of clay, silt and humus found in the soil of the floodplain. This type of soil ("loam") contains roughly equal concentration of sand, silt and clay (Wikipedia , 2012). A medium soil contains the necessary nutrients for plants, holds sufficient water to make them available to the root and allows good drainage and considered very fertile (Soil, 2012). The soil data that was used is shown in Table 4.2.

Table 4.2: Properties of Medium (Loam) Soil [Source: CROPWAT 8.0]

Soil Type	Medium (loam)
Total available soil moisture (TAM)	290.0 mm/meter
Maximum rain infiltration rate	40 mm/day
Maximum rooting depth	900 cm
Initial soil moisture depletion (as % of TAM)	0%
Initial available soil moisture	290 mm/meter

Two cropping models for each climatological station were constructed. In the first model, only rice was planted and harvested three times in a year. In the second model, vegetables and rice both are used and it was assumed that rice is planted and harvested twice in a year with vegetables grown during the dry season in the months of December to March (Table 4.3).

Table 4.3: Cropping Pattern for both Models

Model 1 (Rice only)			Model 2 (Rice and vegetables)		
Crop name	Planting date	Harvesting date	Crop name	Planting date	Harvesting date
Rice (Aman)	25/08	22/12	Rice (Aman)	25/08	22/12
Rice (Boro)	25/12	23/04	Vegetables	25/12	29/03
Rice (Aush)	25/04	22/08	Rice (Aush)	25/04	22/08
Turf grass	25/04	24/04	Turf grass	25/04	24/04

Farmers do not cultivate crops on the entire land area. It is assumed that uncultivated area is covered with vegetation that is modelled as turf grass. These areas are not to be irrigated. According to (Haque, 2006), out of 2.85 million hectares of the coastal and offshore areas about 0.83 million hectares are arable lands. This is approximately 30% of the total area. Among this arable land rice is produced in 74% of the cropped area (Islam, 2000). The three cropping system is prevalent in southwest region that includes three major rice types namely, Aman, Boro and Aush that covers 51%, 39% and 10% of the rice cultivation area (Oryza, 2011). So, Aman occupies $51\times0.74 = 37\%$ of total arable land.

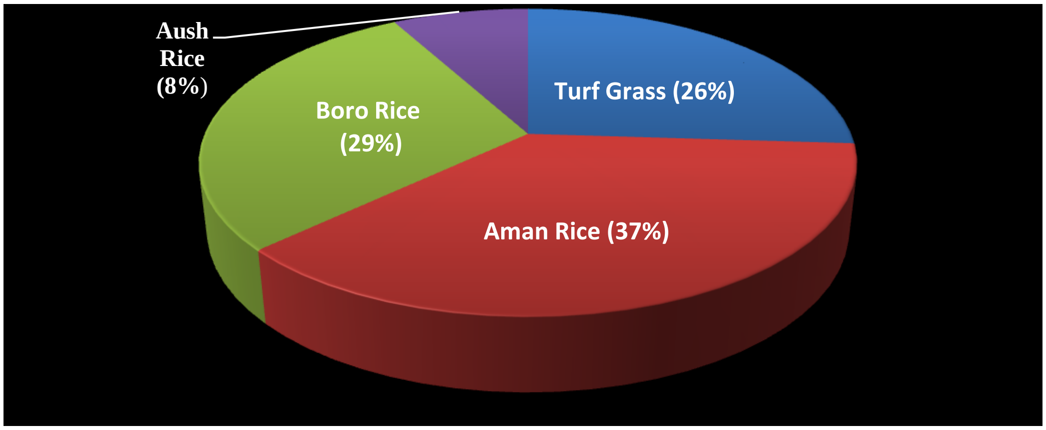

Figure 4.3: Cropping Pattern in the Arable Land Area

The crop properties that will eventually influence the CWR and IR in different stages of plant growth include crop coefficient (K_c), number of days for different growth stages, rooting depth, puddling depth during land preparation, percent of nursery area required during nursery period, critical depletion and yield response factor. The usual duration for rice from transplanting time to the harvesting time is four months and it was set 150 days in the model. For small vegetables this duration is 95 days.

Table 4.4: Crop Properties of Rice in Different Stages [Source: CROPWAT 8.0].

				Transplantation to Harvesting Period				
Stage	Nursery	Land Preparation		Growth Stage				
		total	puddling	initial	develop	mid season	late season	total
Length (days)	30	20	5	20	30	40	30	150
K_c (dry)	0.70	0.30		0.50		1.05	0.70	
K_c (wet)	1.20	1.05		1.10		1.20	1.05	
Rooting depth(m)				0.10		0.60	0.60	
Puddling depth(m)			0.40					
Nursery area (%)	10.0							
Critical depletion (m)	0.20			0.20		0.20	0.20	
yield response factor				1.00	1.09	1.09	1.09	
Crop height (m)						1.00		

Table 4.5: Crop Properties of Small Vegetables in Different Stages [Source: CROPWAT 8.0].

	Transplantation to Harvesting Period				
stage	initial	develop	mid season	late season	total
Length (days)	20	30	30	15	95
Kc	0.70		1.05	0.95	
Rooting depth(m)	0.25		0.60	0.60	
Critical depletion (m)	0.30		0.45	0.50	
yield response factor	0.80	0.40	1.20	1.00	
Crop height (m)			0.30		

4.2.2 Irrigation Model and Discussion of Results

Figure 4.4 shows the calculated IR and ET_c in Barisal for Aman Rice (Planting on 25/08 and harvesting on 22/12). The planting date is 25th of August, but the maximum amount of irrigation is required before the planting date. This is because the nursery and the land preparation (including puddling) starts 30 days before the planting date and this period needs significant volume of water. Even the presence of high amount of rainfall is not enough to reduce the amount of irrigation at this time. Farmers provide this water using surface water irrigation. After the planting, there is enough rainfall and no irrigation is required.

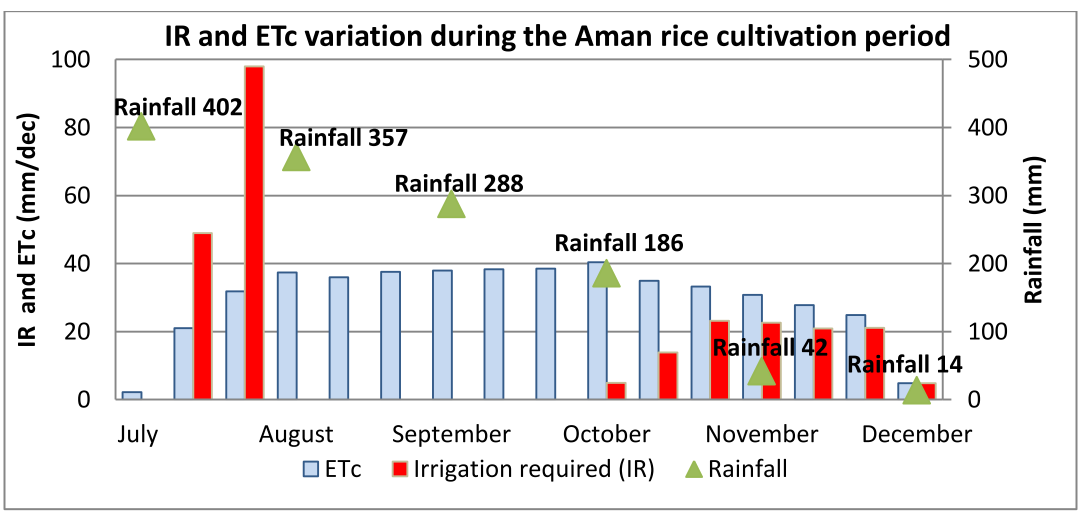

Figure 4.4: Variation of Evapotranspiration and Irrigation Required for Aman Rice Cultivation Period in Barisal

The results generated in CROPWAT 8.0 for other rice cultivation periods are included in Appendix A. The variation of irrigation required over the year for rice only and rice and vegetables combination is shown in Figure 4.5 and Figure 4.6. The unit of IR mm/dec means millimeters per 10 days.

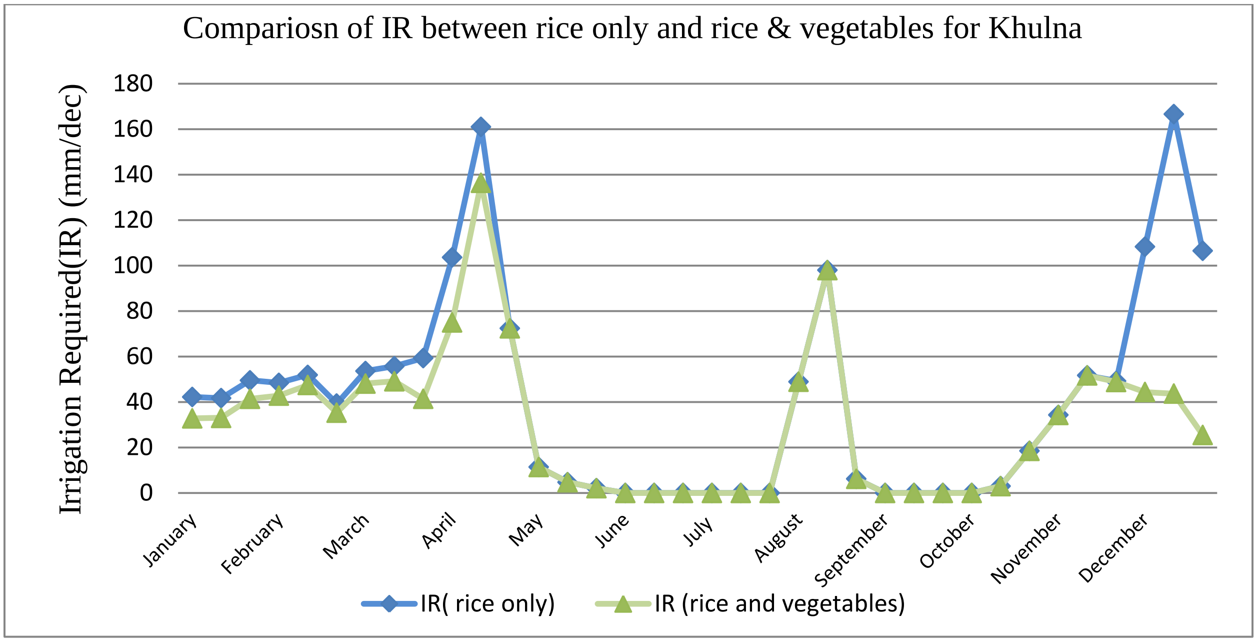

Figure 4.5: Variations of Irrigation Requirement for Two Different Cropping Patterns in Khulna.

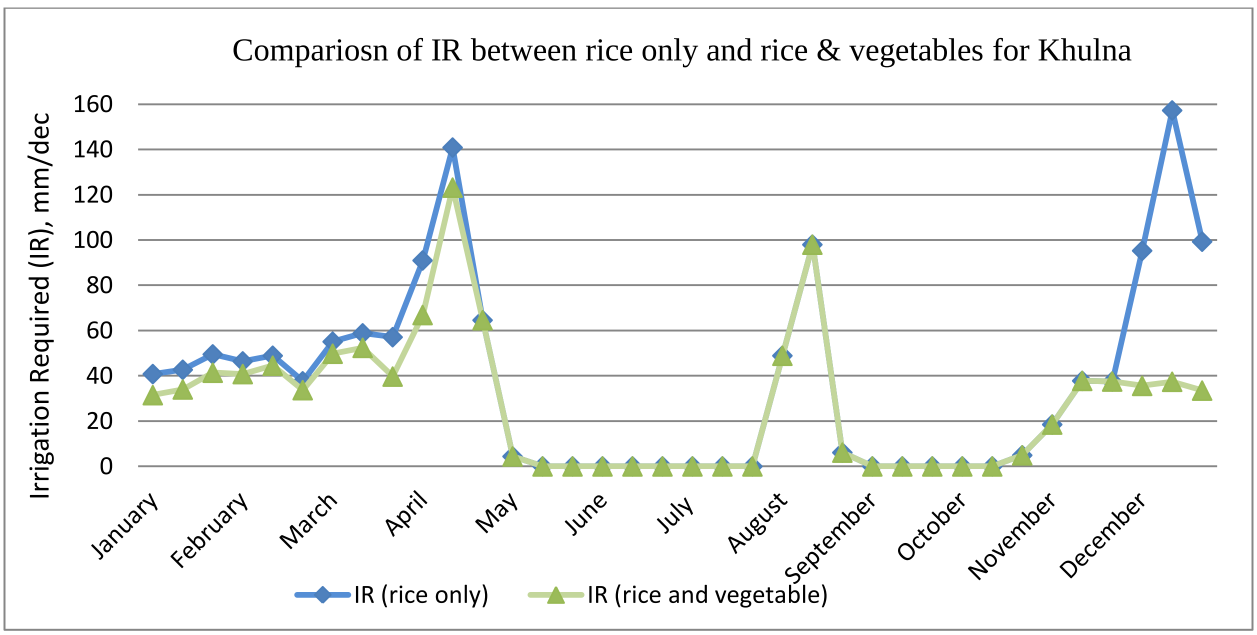

Figure 4.6: Variations of Irrigation Requirements for Two Different Cropping Patterns in Barisal.

Cultivating only rice throughout the whole year demands much irrigation than cultivating the combination of rice and vegetables. The peaks in the graphs represent the large amount of water requirement during the nursery and land preparation period for rice cultivation. If vegetables are cultivated during winter period (December to February), these peaks are absent. As rainfall is low during this time, irrigation is dependent on groundwater extraction. In order to reduce the demand on groundwater, it may be logical to switch to different crop types during the dry period. The economic value of the alternative crop needs to be considered. In addition, crop that can withstand increased salinity should be given more priority, because groundwater and soil salinity is prevalent in this cultivation period.

4.2.3 Groundwater Recharge Calculation

Groundwater recharge is calculated as the difference between total rainfall and actual evapotranspiration. It can be calculated from the climate data for each station.

Table 4.6: Monthly Rainfall and Evapotranspiration for Khulna and Barisal

	Khulna		Barisal	
Month	Rainfall (mm)	ET_o (mm/day)	Rainfall (mm)	ET_o (mm/day)
January	6	2.32	6	2.32
February	16	3	19	2.99
March	46	4.12	41	4.01
April	88	4.57	106	4.4
May	178	4.35	209	4.04
June	357	3.26	400	3.13
July	353	3.31	402	3.2
August	330	3.07	357	2.97
September	217	3.51	288	3.4
October	130	3.47	186	3.4
November	22	3.03	42	2.94
December	5	2.42	14	2.41
	Total 1748.0 mm	Average 3.37 mm/day	Total 2070.0 mm	Average 3.27 mm/day

Table 4.7: Crop Evapotranspiration (ET_c) Data from CROPWAT

Crop Type	Crop Evapotranspiration, ET_c (mm)			
	Khulna		Barisal	
		Total		Total
Aman Rice	490.2	1581.8	477.4	1535.1
Boro Rice	518.9		509.6	
Aush Rice	572.7		548.1	
Turf Grass		1006.2		976.4

In the CROPWAT model, rice is cultivated on 74% of the total land and rest 26% is covered with turf grass.

$$Recharge = Rainfall - \sum ET_c \times \%\ of\ land\ area$$

Using Table 4.6 and 4.7, recharge can be calculated for rice cultivation throughout the year.

For Khulna, Annual Recharge = 1748 – (1581.8×0.74 + 1006.2×0.26) = 316 mm

For Barisal, Annual Recharge = 2070 – (1535.1×0.74 + 976.4×0.26) = 680 mm

4.3 Groundwater Modelling

A rectangular model and a trapezoidal groundwater model were created to analyze the change in groundwater level due to yearly recharge calculated in the previous section.

4.3.1 Model Construction in Visual MODFLOW

Steady state flow was used for the simulations. This approximation was made because the objective of the project was to develop a simplified generic model and it can be assumed that the groundwater properties (i.e. density, temperature, mineral contents, velocity, pressure etc.) do not change with time within the model domain. Another approximation was considered that if the aquifer has recharging boundary condition a steady-state may be reached (Igboekwe & Achi, 2011). The steady state simulation time was set as 3650 days (10 years). A 10 km×10km area was taken as a representative of the land blocks. This model was initially constructed without the internal drains/canals and in later case these were included. To replicate the situation that sea on one side and canal/drain in other side, another 1km×1km model was developed. Both the models were 100m deep and had a resolution of 50 rows by 50 columns.

The aquifer was assumed to be a single layer homogenous soil stratum with impermeable rock strata beneath it. The properties of the soil were hydraulic conductivity, specific storage, specific yield and porosity. Soil type was considered as medium which is a mixture of sand and silt. The range of hydraulic conductivity for loess (aeolian sediment formed by the accumulation of wind-blown silt) is approximately from 10^{-9} to 10^{-5} m/s whereas, for silty sand it is approximately from 10^{-7} to 10^{-3} m/s (Freezy & Cherry, 1979). The overlapping range is between 10^{-7} to 10^{-5} (0.0086 to 0.86 m/day). The range for silty sand and clean sand is 10^{-6} to 10^{-5} m/s (0.086 to 0.86 m/day). Comparing the two ranges it was decided to select the average hydraulic conductivity of 0.086 and 0.86, which is 0.47 m/day (≈ 0.5 m/day). This is equivalent to 5.8×10^{-6} m/s. The corresponding Figure of the ranges is given in Figure B1 in Appendix B.

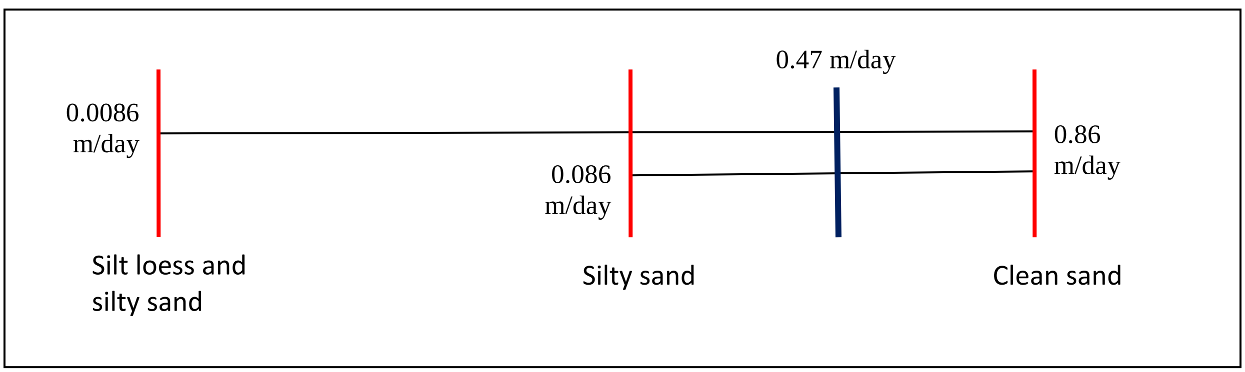

Figure 4.7: Selection of Hydraulic Conductivity.

The specific yield for silt ranges from 0.03 to 0.19 with an average of 0.18 (Johnson, 1967). This value was used in the model. For silt with fine sand, specific storage is 9.82×10^{-4} m^{-1} (Younger, 1993). The ranges of values of total porosity of sand and silt are 25-50% and 35-50% respectively (Freezy & Cherry, 1979). In the model 40% total porosity was considered. Effective porosity was taken as 15%.

The model assumed that the aquifer was 100m thick. The thickness ranges from 10m above MSL to 90m below MSL. This was achieved by setting the groundwater head to be +90m relative to the base of the model. The recharge boundary condition was applied on the whole model domain, set at 500 mm/year recharge which is the average of annual recharges for Khulna and Barisal that were calculated in section 4.2.3. To model the conditions of groundwater extraction during the dry period, it was assumed that groundwater had been recharged in the previous year and then the negative recharge (rainfall < ET_o) of the dry season is applied.

The area has many internal drains and canals (Figure 4.8). So, it is assumed that the 10km×10km area is divided into smaller blocks of lands. Another model was developed which contains drains within the 10km×10km area (Figure 4.9). It was assumed that the drains carried partially full flow and the water surface elevation in the drains was set to +95m (5m below ground surface). Conductance per unit length was 0.5 m/day assuming that same hydraulic conductivity of aquifer near the drains.

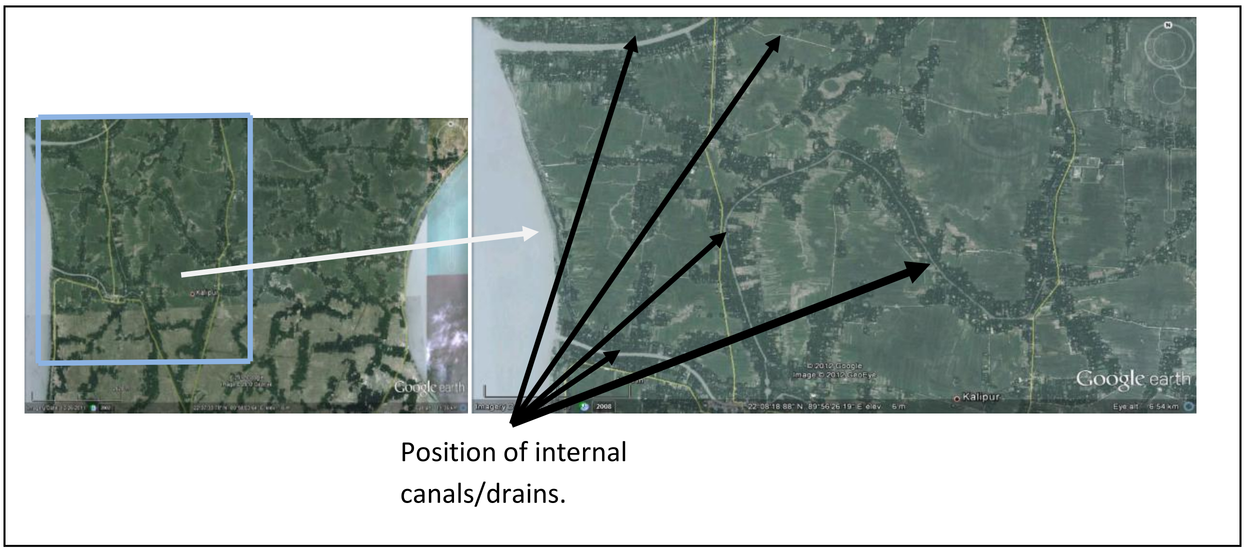

Figure 4.8: Position of Internal Canals and Drains in the Area

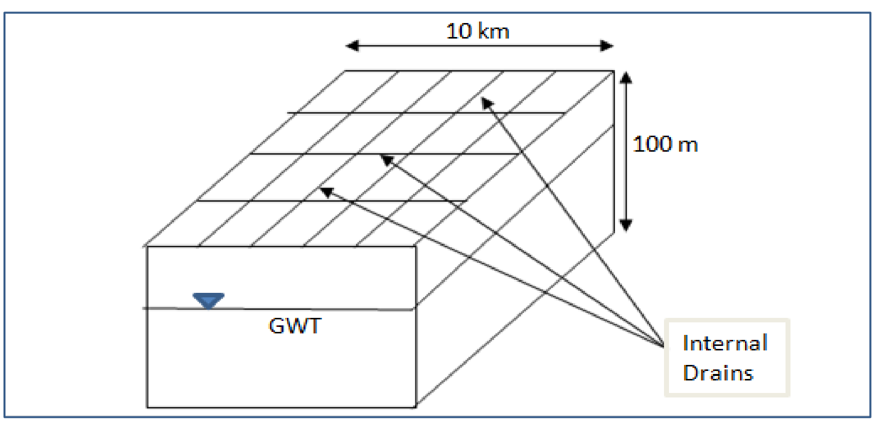

Figure 4.9: 10 km × 10km Model with Internal Drains

4.3.2 Model Testing and Discussion

The square10km×10km model was run using the SOR (successive over-relaxation) solver and the water Table heads were calculated. The groundwater table was approximately horizontal in the middle part with a gradual decrease in the edges of both sides of the model (Figure 4.10).

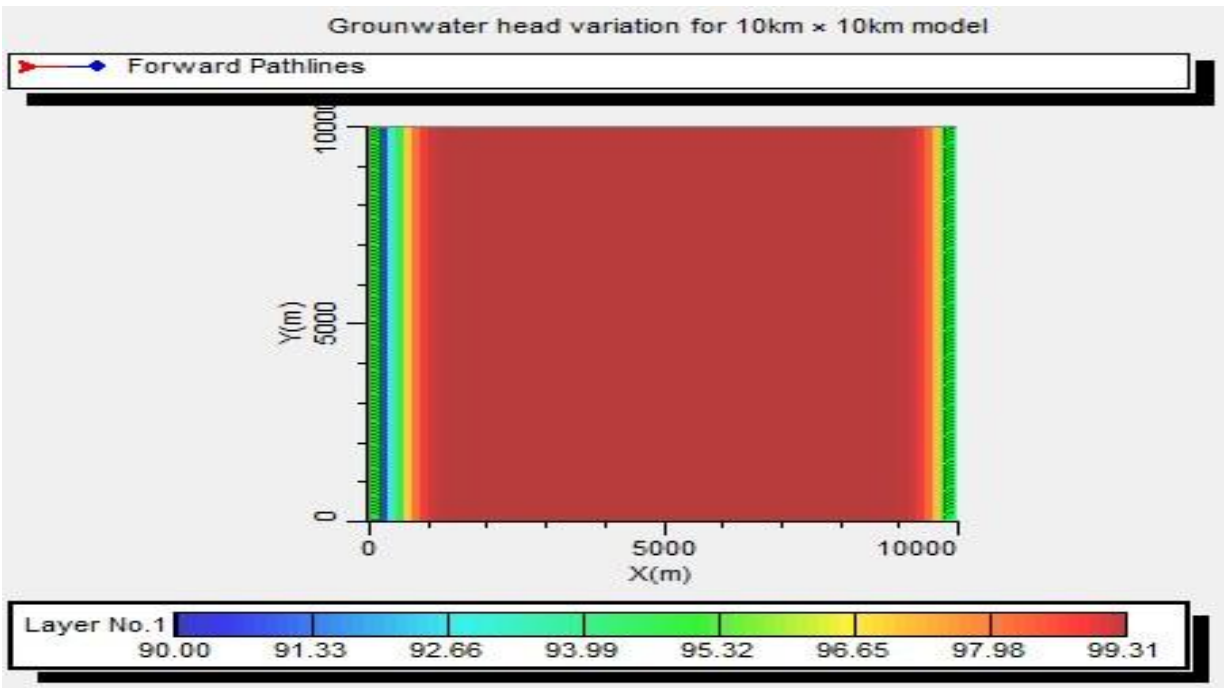

Figure 4.10: Variation of Groundwater Head (in meters) across the 10km × 10km Model.

The initial groundwater head over the entire model area was 90m from the bottom of the model (10m below the ground surface) and due to the presence of annual recharge of 500mm/year, at the middle it rises up to 99.31 m (100 - 99.31 = 0.69 m below ground surface).

For the trapezoidal model, two cases were considered (i) land surrounded by sea on two sides and (ii) land surrounded by sea on three sides. There are slight variations in the calculated groundwater head contours (Figure 4.11). The maximum head of 99.31m exists in the middle part of the model domain and this value is similar to that of rectangular model. No internal drain was considered here.

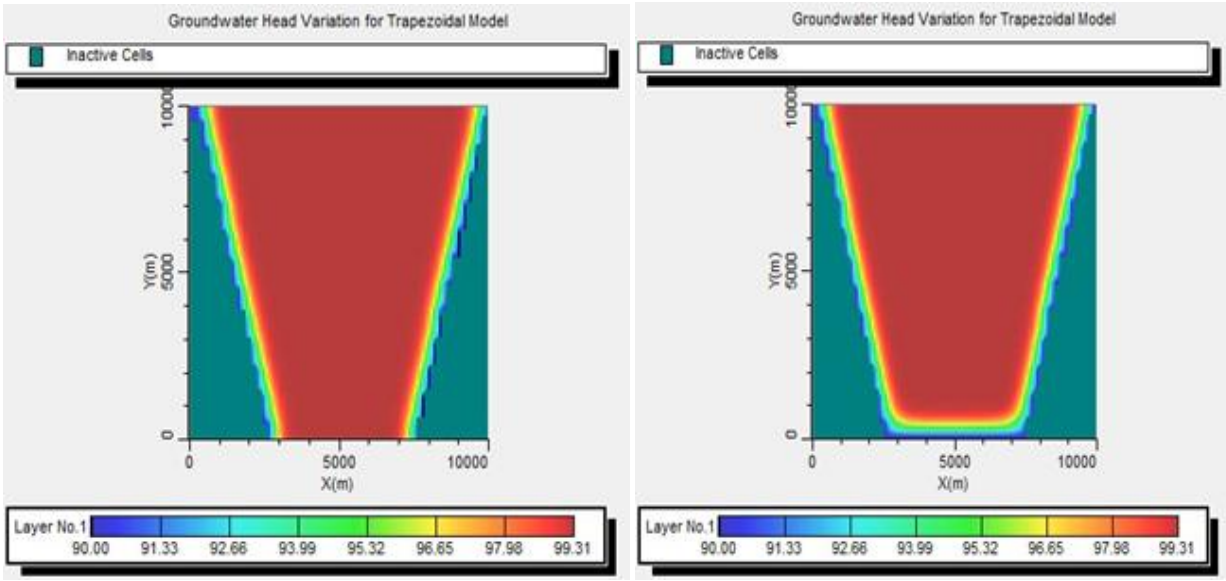

Figure 4.11: Variation of Groundwater Head (in meters) across the Trapezoidal Models- (i) Sea on two sides (left Figure) and (ii) Sea on three sides (right Figure).

Now if the internal drains/canals are considered in 10km×10km square model, the entire area is divided into smaller grids and each grid shows a repeated pattern of groundwater head contours (Figure 4.12). The smaller blocks within this model can be represented by a 1km×1km square model. The pattern of groundwater head contours for 1km×1km model is similar to that of 10km×10km model (Figure 4.13).

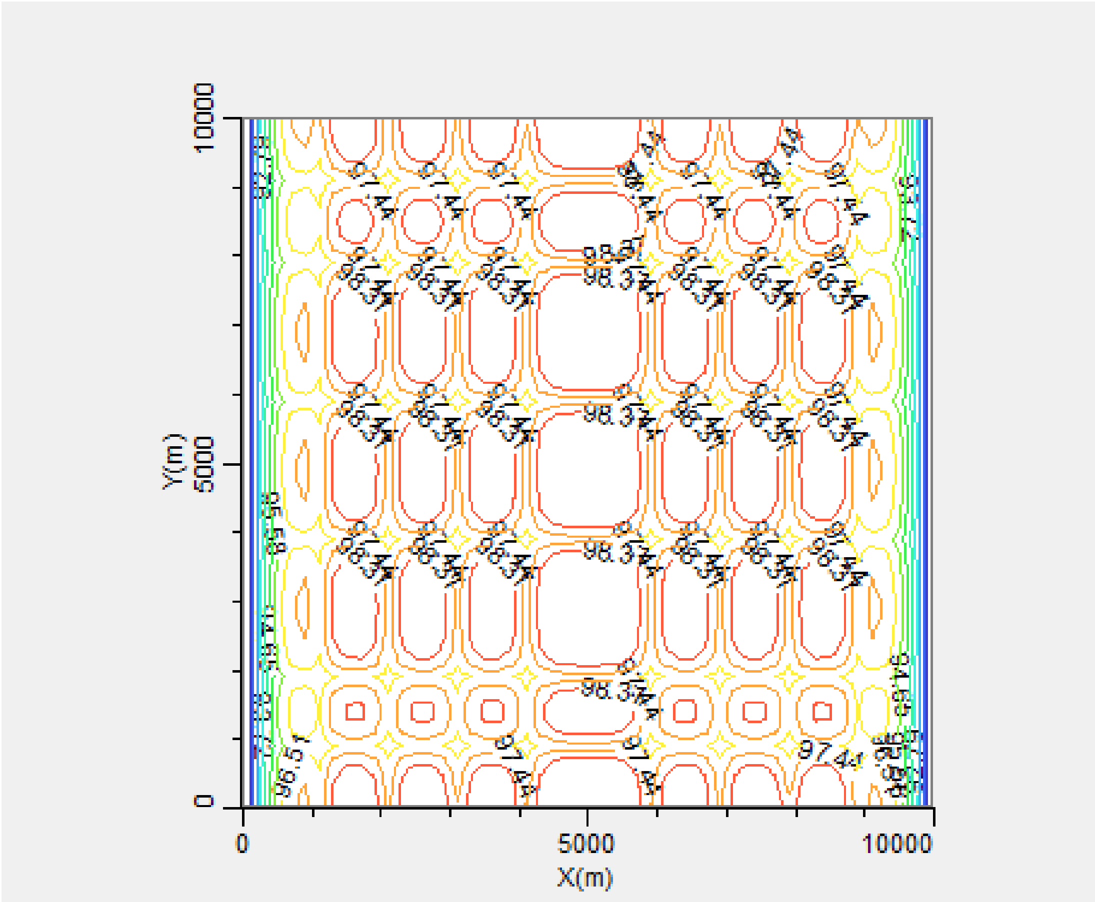

Figure 4.12: Groundwater Head Contours with Presence of Internal Drains/ Canals.

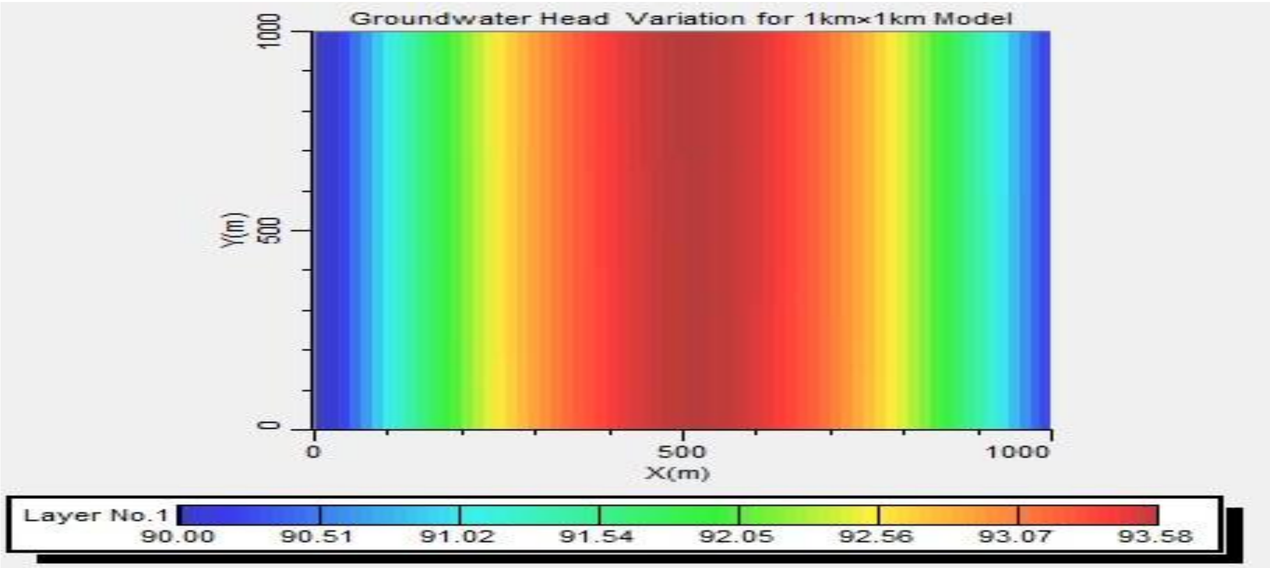

Figure 4.13: Variation of Groundwater Head (in meters) across the 1km × 1km Model.

In case of 1km×1km model, the maximum groundwater head in the middle part was 93.58m (6.42 m below the ground surface) which is lower than that of 10km×10km model. This is because the total amount of recharged water over the entire area ($1\times1 = 1$ km^2) is reduced here and hence the amount of bulging of groundwater table is less.

1km × 1km land block model closely represents the local conditions. The model can be tested using Dupuit's formula (Todd & Mays, 2005),

$$h = \sqrt{(h_o^2 + (h_L^2 - h_o^2)\frac{x}{L} + \frac{q_R}{K_x}(L-x)x)}$$

This gives h_{max} = 93.71m at x = 500m which is almost similar to the obtained result from the MODFLOW model (93.58m).

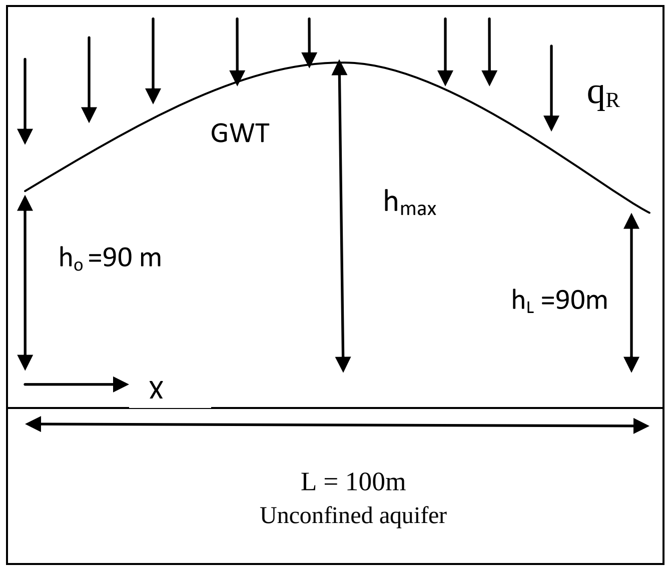

Figure 4.14: Calculation of Groundwater Head Using Dupuit's Formula.

4.4 Particle Tracking and Appropriate Location of Pumping Wells

To analyze the possibility of salt water intrusion caused by groundwater pumping, a model of 1km×1km land block with sea at one side and a fresh water drain at other side was considered. It will be calculated that how much land is affected by salt water intrusion during the dry period when wells are being pumped to irrigate with groundwater.

4.4.1 Dry Period Recharge Calculation

November to April are the months when groundwater is used for irrigation. It was assumed that the aquifer was recharged in the previous year and then the negative recharge was included to simulate the groundwater pumping during this period.

Dry Period Recharge = Annual Recharge of Previous Year + Rainfall (November to April)

$- \Sigma$ {ET_c (November to April)× % of land area}.

The following dry period recharge calculations were done using Table 4.6 and Table A1 to A7 in Appendix A. The data from November to April is considered.

Dry Period Recharge for Khulna (Rice only)

= 316 + 183 – (518.9×0.29 + 160.2×0.37 + 480.2×0.26) = 165 mm

Dry Period Recharge for Khulna (Rice and Vegetables)

= 316 + 183 – (273.4×0.29 + 160.2×0.37 + 480.2×0.26) = 236 mm

Dry Period Recharge for Barisal (Rice only)

= 680 + 228 – (509.6×0.29 + 156.4×0.37 + 469.9×0.26) = 580 mm

Dry Period Recharge for Barisal (Rice and Vegetables)

= 680 + 228 – (270.0×0.29 + 156.4×0.37 + 469.9×0.26) = 650 mm

4.4.2 Estimation of Pumping Rate

From November to April, the groundwater pumping rate can be estimated by considering the maximum irrigation required for actual area.

For Khulna, considering rice cultivation throughout the year, maximum irrigation required is 0.46 l/s/hectare in December (from Table A9 in Appendix A).

Total area to be irrigated = 1 km^2 = 100 hectare

So, pumping rate = 0.46×100 = 46 l/s = (46/1000) × (3600×24) m^3/day = 3975 m^3/day

If shallow tubewell (average discharge rate 10 l/s or 864 m^3/day) is used then the required number of tubewells to irrigate a 1km×1km area will be = 3975 / 864 = 4.6 (i.e. 5 shallow tubewells)

The pumping rate estimation is summarized below in Table 4.8. The maximum irrigation required during the dry season (from November to April) for each crop pattern was obtained from Table A9 to A12 in Appendix A. The assumed irrigation efficiency was 70%.

Table 4.8: Pumping Rate for Different Cropping Patterns in Differnt Locations for 1km×1km Land.

	Rice cultivation throughout the year				Rice and vegetables mixed cultivation			
	Maximum irrigation required (l/s/hec)	Month	Pumping rate (m^3/day)	Required no. of shallow tubewells	Maximum irrigation required (l/s/hec)	Month	Pumping rate (m^3/day)	Required no. of shallow tubewells
Khulna	0.46	December	3975	5	0.32	April	2765	4
Barisal	0.42	December	3629	5	0.27	April	2333	3

4.4.3 MODFLOW Model to Study the Effects of Pumping Wells

The required numbers of pumping wells were placed in different orientations and layouts over the 1km×1km cultivable land block in the MODFLOW model. The aim was to find out the safe distance of wells from the sea in order to avoid salt water intrusion into the aquifer. Almost 80% of the rice field irrigation in Bangladesh is done using low capacity shallow tubewells (average discharge 10 l/s) and these tubewells' usual depth is less than 80m below ground level (Shamsudduha, et al., 2011). The average depth of shallow tubewells in Bangladesh is approximately 100 feet or 30 meters (iminweb, 2012). The well screen bottom and screen top was chosen as 70m and 75m respectively above the bottom of the model; i.e. 25-30m below ground level. The pumping rate of each well was set to -864 m^3/day (a negative sign indicates groundwater extraction). To represent the dry season scenario in Barisal, 5 shallow tubewells were placed in different layouts. For rice cultivation throughout the year, the dry season recharge was set to 580 mm as calculated in section 4.4.1. For Khulna the dry season recharge is 165 mm. If the farmers choose to cultivate both rice and vegetables in a year, then the required number of pumps would be 4 and 3 for Khulna and Barisal respectively. The dry season recharge in that case will be 650 mm and 236 mm for Barisal and Khulna respectively.

4.4.4 Model Testing with Pumping Wells and Discussion

Different layout of wells and corresponding outputs for Barisal is shown in Figures 4.15 to 4.21. The details of the location of the well are given in Table 4.9. In Layout 4, well 2 and well 3 were turned off to predict the approach of the next probable layout.

Table 4.9: (x,y) Co-ordinates (in meter) of Different Wells in Various Layout.

	well 1	well 2	well 3	well 4	well 5
Layout 1	(200, 200)	(800, 200)	(800, 800)	(200, 800)	(500, 500)
Layout 2	(200, 200)	(800, 200)	(800, 800)	(200, 800)	(200, 500)
Layout 3	(200, 200)	(500, 200)	(500, 800)	(200, 800)	(200, 500)
Layout 4	(200, 200)	OFF	OFF	(200, 800)	(200, 500)
Layout 5	(200, 200)	(300, 200)	(300, 800)	(200, 800)	(200, 500)
Layout 6	(200, 100)	(200, 300)	(200, 500)	(200, 700)	(200, 900)
Layout 7	(150, 100)	(150, 300)	(150, 500)	(150, 700)	(150, 900)

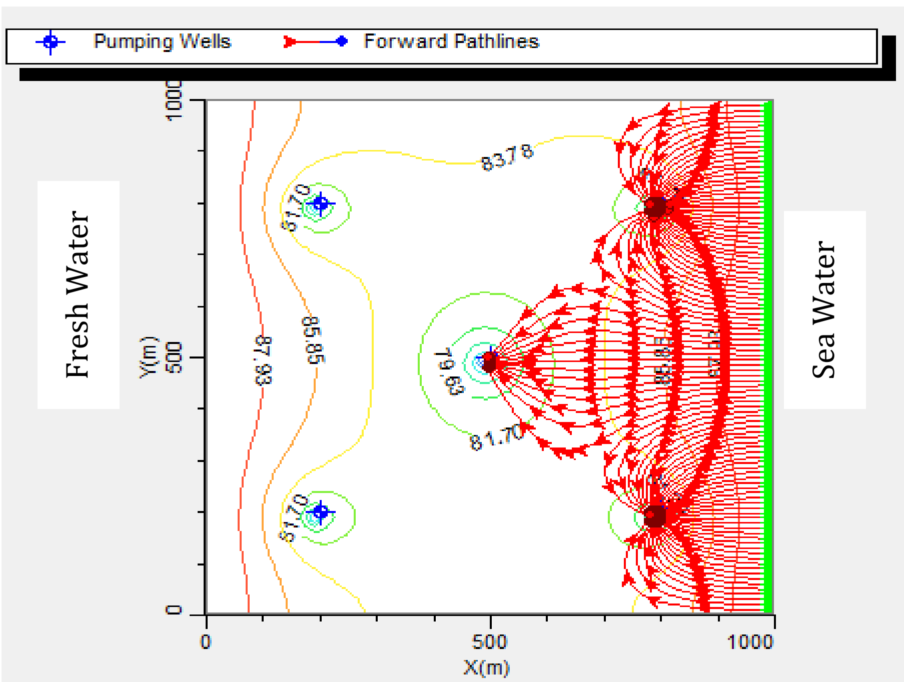

Figure 4.15: Groundwater Head Contours and Pathlines of Saltwater Intrusion for Layout 1(for Barisal)

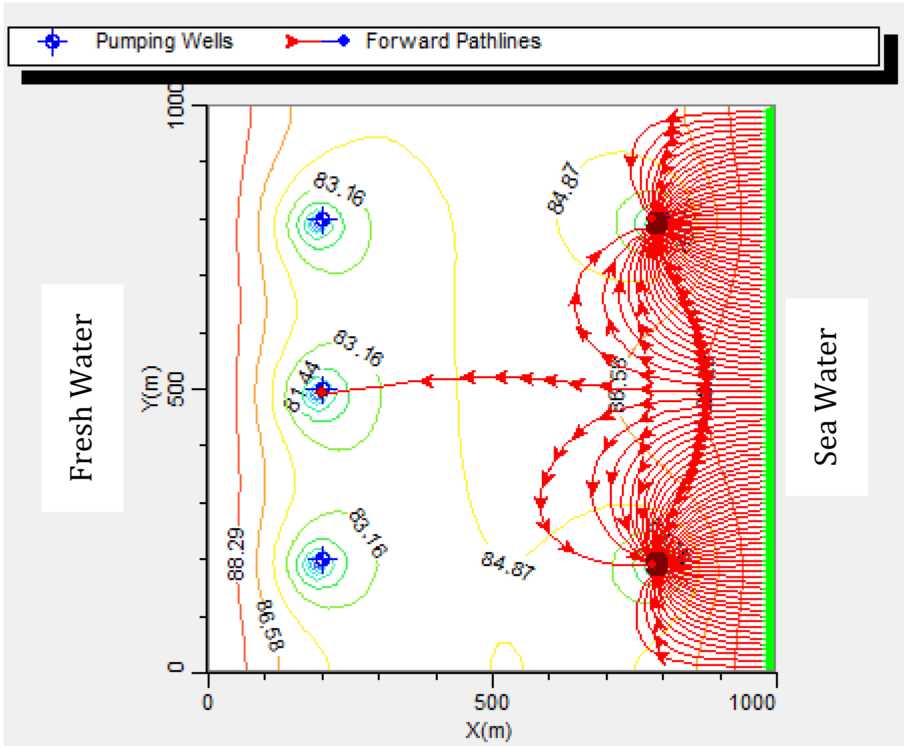

Figure 4.16: Groundwater Head Contours and Pathlines of Saltwater Intrusion for Layout 2(for Barisal)

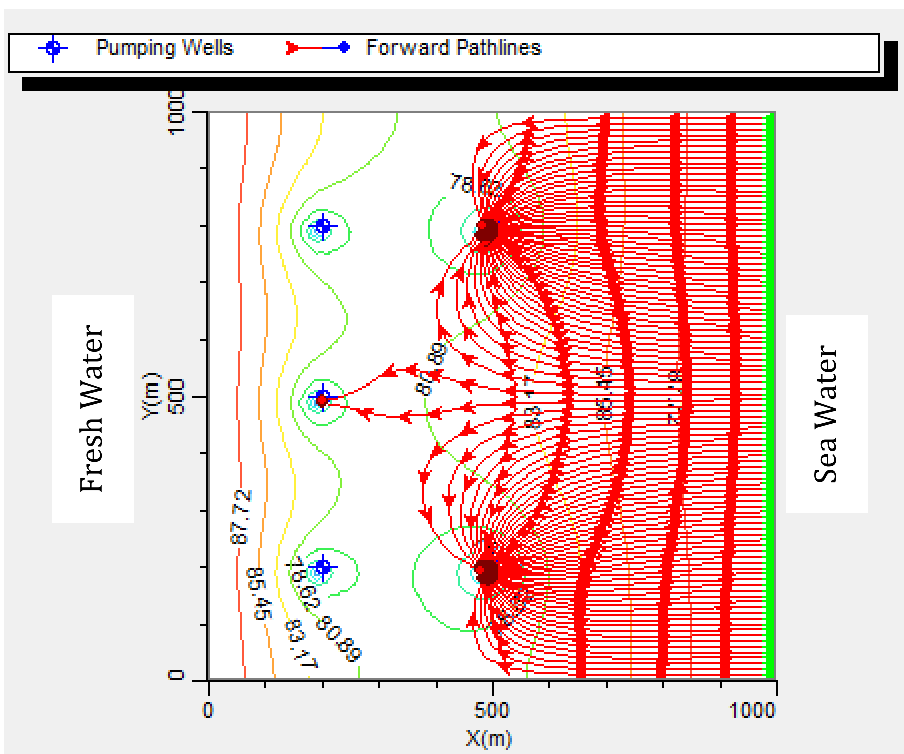

Figure 4.17: Groundwater Head Contours and Pathlines of Saltwater Intrusion for Layout 3(for Barisal)

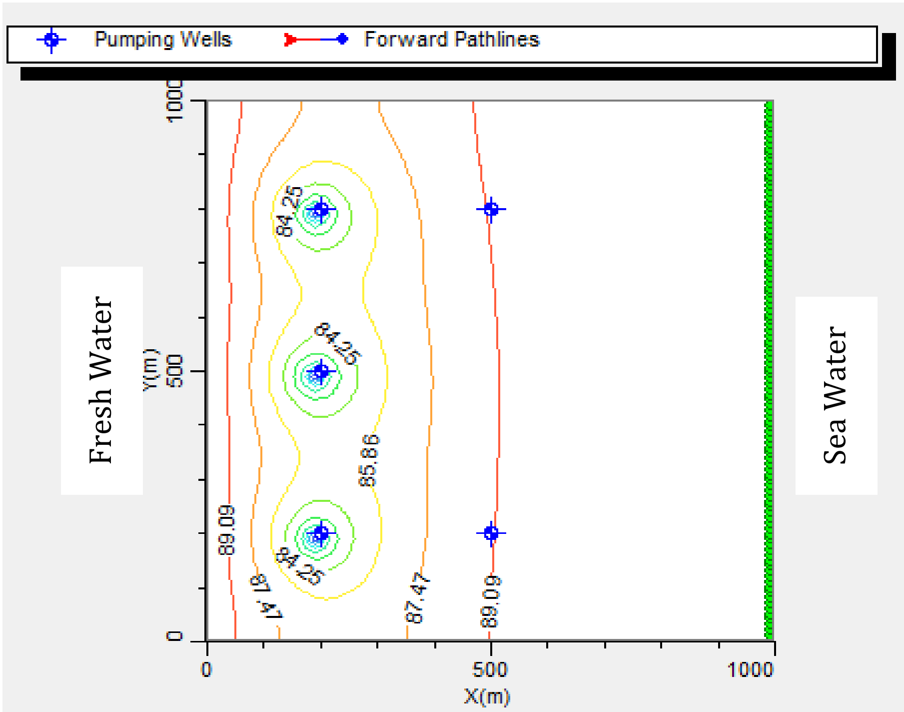

Figure 4.18: Groundwater Head Contours and Pathlines of Saltwater Intrusion for Layout 4 ; well 2 and 3 turned OFF (for Barisal)

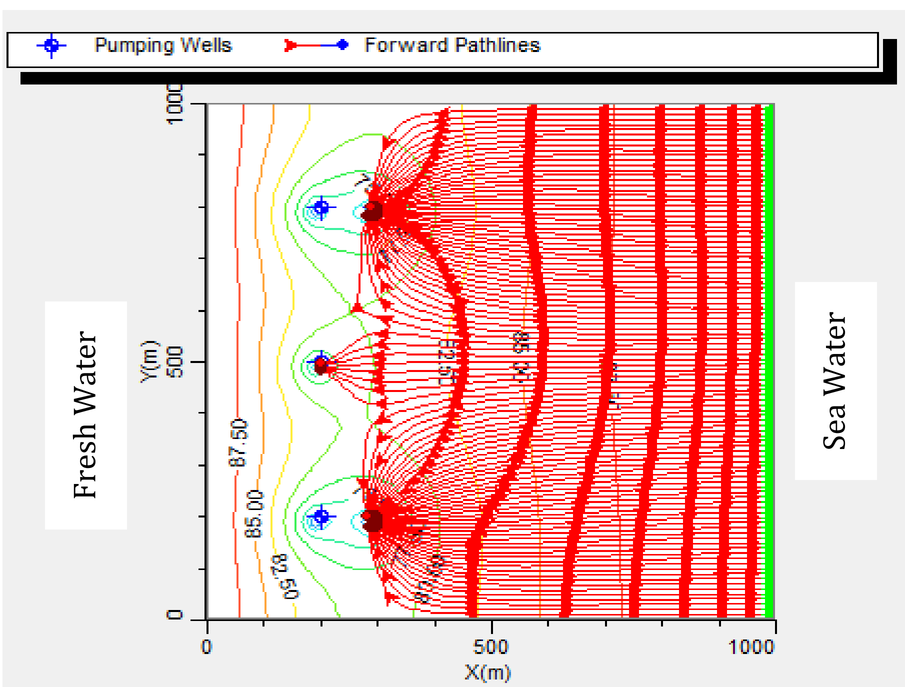

Figure 4.19: Groundwater Head Contours and Pathlines of Saltwater Intrusion for Layout 5(for Barisal)

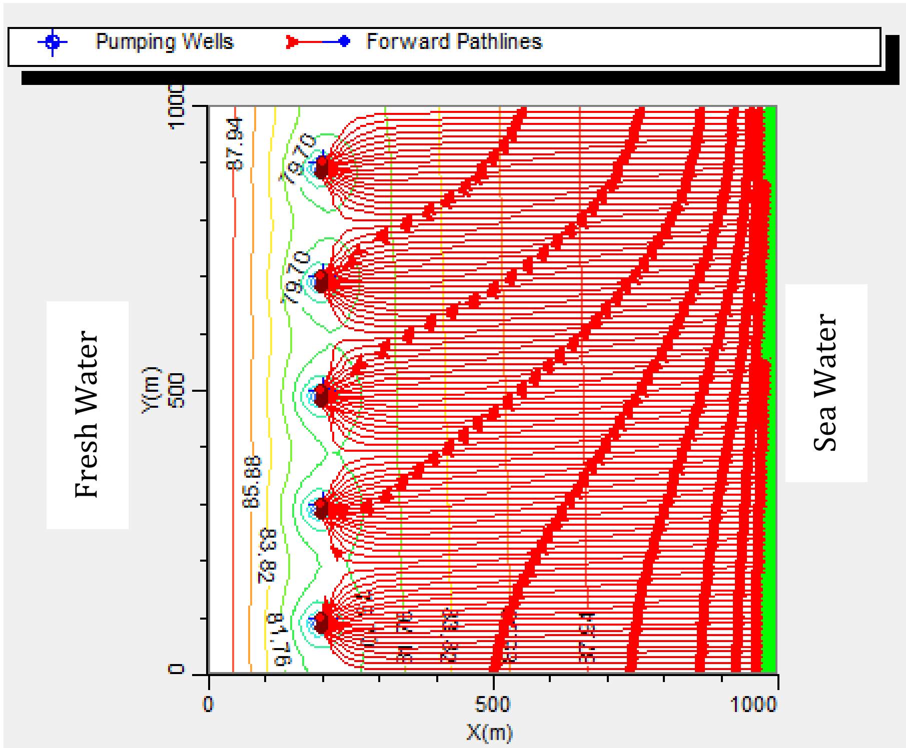

Figure 4.20: Groundwater Head Contours and Pathlines of Saltwater Intrusion for Layout 6(for Barisal)

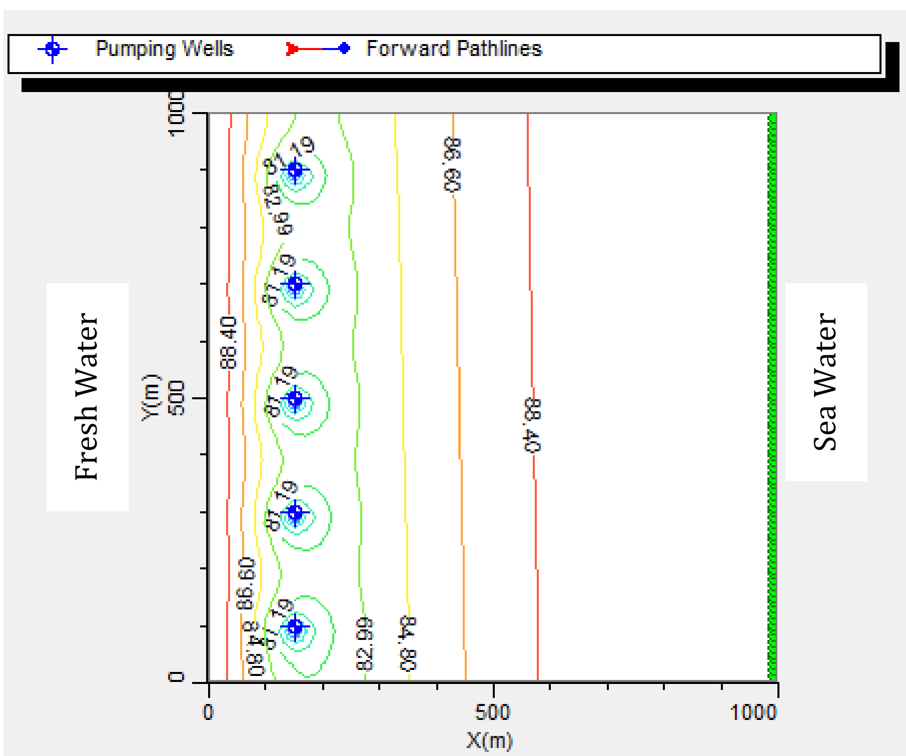

Figure 4.21: Groundwater Head Contours for Layout 7(for Barisal)

From the above Figures it is evident that for Barisal region, if rice is cultivated throughout the year under present dry conditions, the safe distance to install pumps 850 m in order to avoid salt water intrusion. For mixed cultivation of vegetables and rice, where 3 wells are required to irrigate the whole area, the safe distance is 700m away from sea (Figure 4.22).

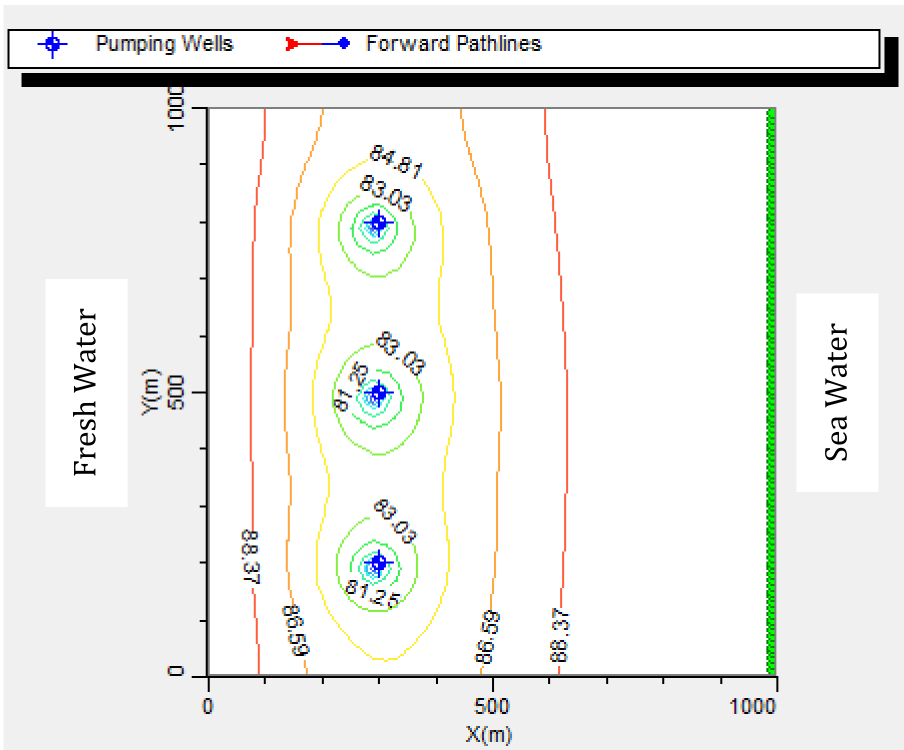

Figure 4.22: Groundwater Head Contours for Barisal for Mixed Cultivation of Rice and Vegetables.

In Khulna, where the recharge during the month of November to April is 165 mm, rice cultivation throughout the year will cause some saltwater intrusion in the pumping wells for any location of the wells (Figure 4.23). This represents the common scenario of salinity problem in that region at the current time. If vegetables are cultivated during the dry season, the same salinity problem prevails (Figure 4.24). From the MODFLOW analysis, the safe distance in this case is 900 m from the sea (Figure 4.25).

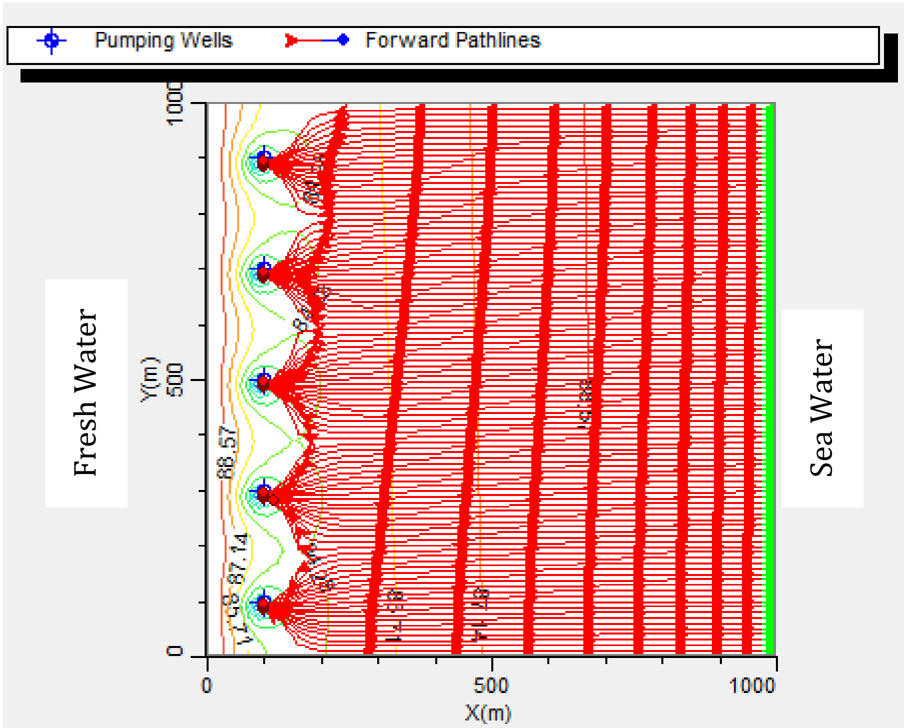

Figure 4.23: Groundwater Head Contours and Pathlines of Saltwater Intrusion for Rice Cultivation Throughout the year (for Khulna)

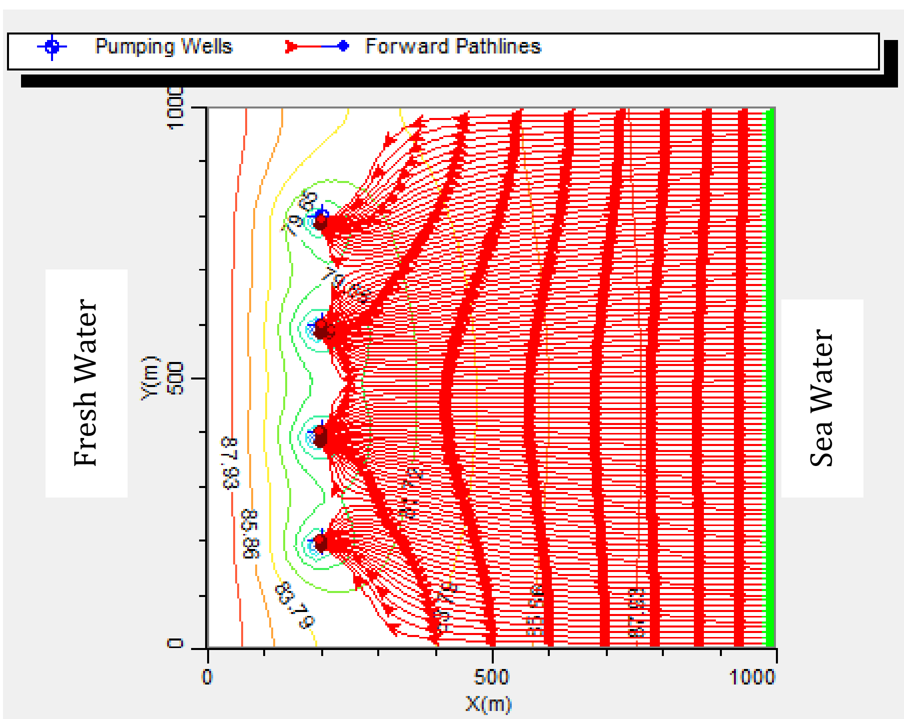

Figure 4.24: Groundwater Head Contours and Pathlines of Saltwater Intrusion for Mixed Cultivation of Rice and Vegetables (for Khulna)

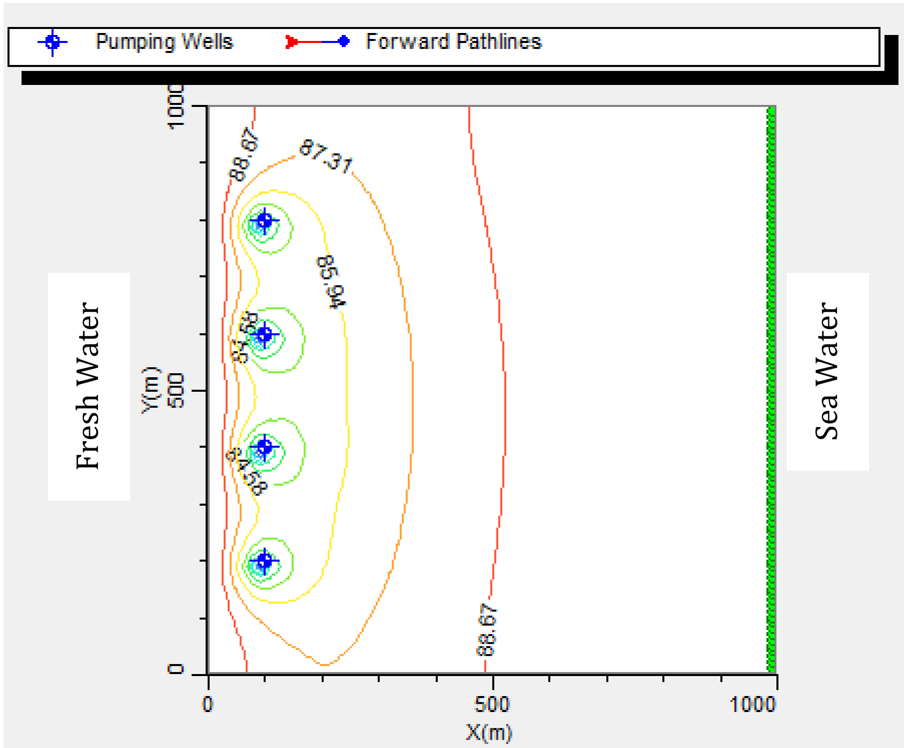

Figure 4.25: Groundwater Head Contours for Mixed Cultivation of Rice and Vegetables (for Khulna)

The results and findings of the previous discussions are summarized below.

Table 4.10: Comparison of Safe Locations of Pumping Wells in Present Time for 1km × 1km Coastal Agricultural Land.

Location	Cropping pattern	Dry season recharge	No of shallow tube wells needed	Safe distance from the sea
Barisal	rice only	580 mm	5	850 m
	rice and vegetables	650 mm	3	700 m
Khulna	rice only	165 mm	5	No safe distance
	rice and vegetables	236 mm	4	900 m

Another MODFLOW model was considered of 2km×1km dimension with sea at one side and fresh water drain at the other side. It was assumed that no cultivation was done within the buffer zone at seaward side that was mentioned in Table 4.10. Figure 4.26 shows the layout of the model.

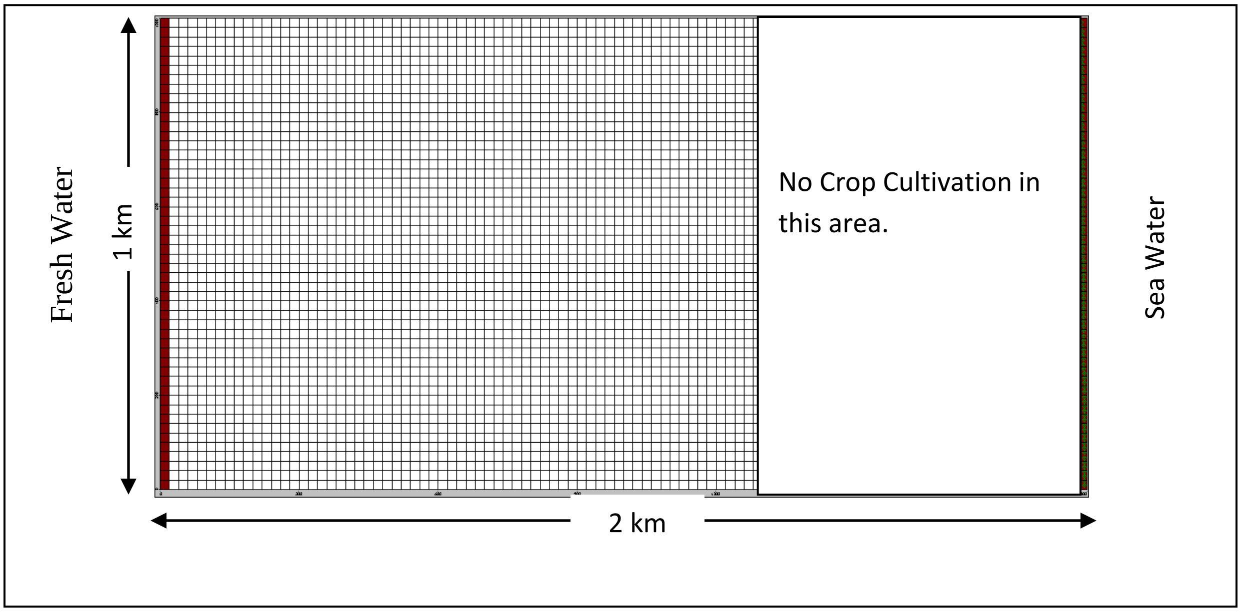

Figure 4.26: Layout of the 2km × 1km Model

The extent of the "no cultivation area" shown in Figure 4.26 varies with different places and different cropping patterns as shown in Table 4.10. For instance, for mixed cultivation of rice and vegetables in Barisal, 700m from the sea will be within this zone. In that case total irrigation area will be 1.3km×1km. To irrigate this area, the number of shallow tubewells will be 4. If the tubewells are placed 1000 m away from the sea the area can be irrigated without the possible hazard of sea water intrusion (Figure 4.27).

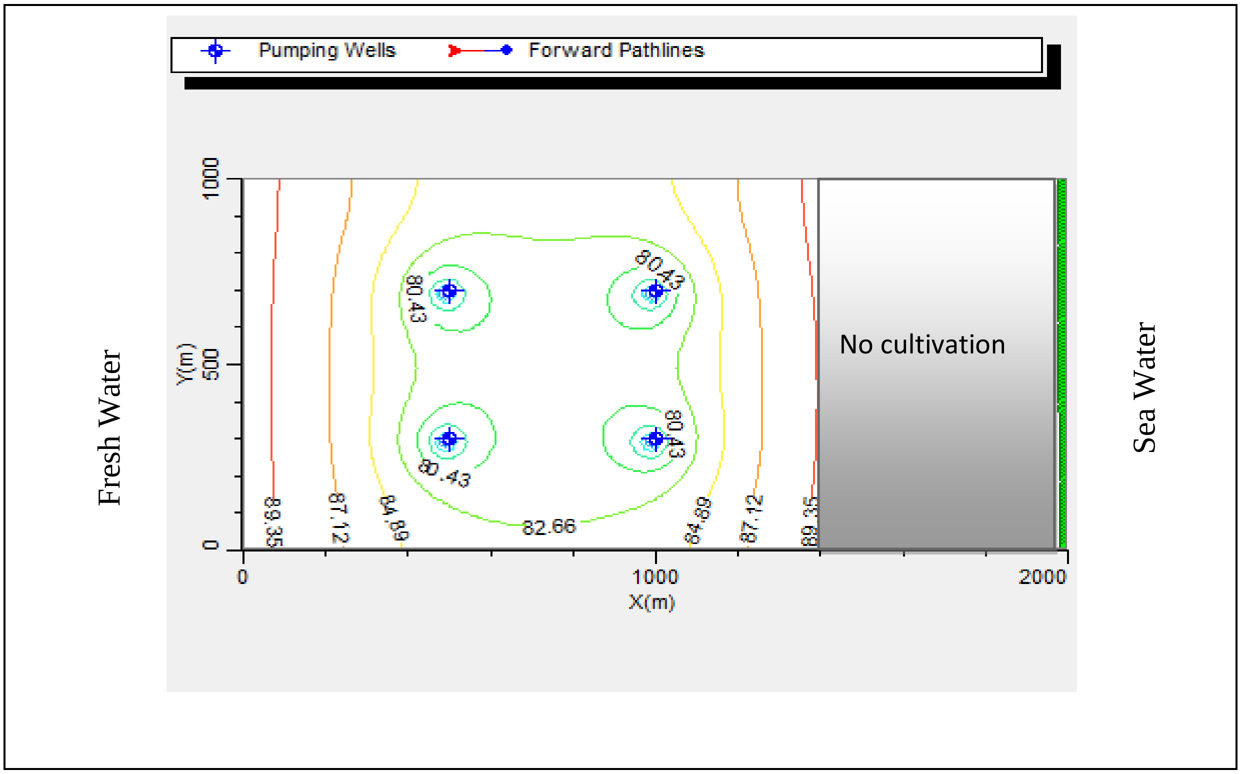

Figure 4.27: Groundwater Head Contours for Mixed Cultivation of Rice and Vegetables (for Barisal) the 2km×1km Model

4.4 Summary

Chapter 4 discussed the model construction using CROPWAT 8.0 and Visual MODFLOW. The models were run for current scenario and the existing salinity problems in Khulna and Barisal region were found from the results.

The models were based on some assumptions such as (i) Constant rate of recharge over the entire area (ii) Soil parameters were same in both horizontal and vertical directions and (iii) The aquifer consisted of one layer and there was no aquitard.

The major findings of the analysis are (i) Cultivation of vegetables instead of rice from December to March will reduce the demand of groundwater extraction (ii) Mixed cultivation of rice and vegetables will render higher groundwater recharge. This will occur because vegetables have lower crop evapotranspiration (K_c) than that of rice. (iii) Salt water intrusion occurs during the dry period of the year (November to April) and it causes loss of cultivable lands that are adjacent to the sea. The limitation of the model is that the analysis does not provide information about the quantity of salt water intrusion in a well.

In chapter 5, these models will be used to simulate future scenarios in response to climate change and sea level rise.

Chapter 5

EFFECTS OF CLIMATE CHANGE AND SEA LEVEL RISE ON GROUNDWATER

5.1 Introduction

The coastal region of Bangladesh is a disaster prone area and every year occurrence of tropical cyclones, storm surges and coastal erosions jeopardize the development here. The south west region of the country is already experiencing the hazard of salt water intrusion which is severely affecting the agricultural sector. From the discussion of chapter 4, it is evident that farmers may already have to give away some lands adjacent to the sea due to salinity problem. There is a possibility of worsening this hazard in the future due to the consequences of climate change. The salt water intrusion phenomenon may be increased in two ways: (i) the change of rainfall and temperature will affect the groundwater recharge and (ii) the sea level rise will cause higher head on the seaward side.

5.2 Effects of Climate Change

To use the existing CROPWAT models for future prediction, crop evapotranspiration and irrigation requirements were recalculated using new climate data. This changed the calculated recharge of the aquifer. In MODFLOW, the newly calculated recharge was used as a boundary condition. In addition, the effect of sea level rise was imposed by setting a higher constant head in the seaward side.

5.2.1 Change of Rainfall and Temperature

Future climate change projections show that rainfall will increase during monsoon season (June to September) and will decrease in winter months (December to February) (Ramamasy & Baas, 2007). Global Climate Models suggest that the average temperature of Bangladesh will increase by 1.4˚ C by 2050 (Ramamasy & Baas, 2007). Figure 5.1 shows this increasing trend of temperature and Table 5.1 shows the values of the estimation of both temperature and rainfall along with standard deviations.

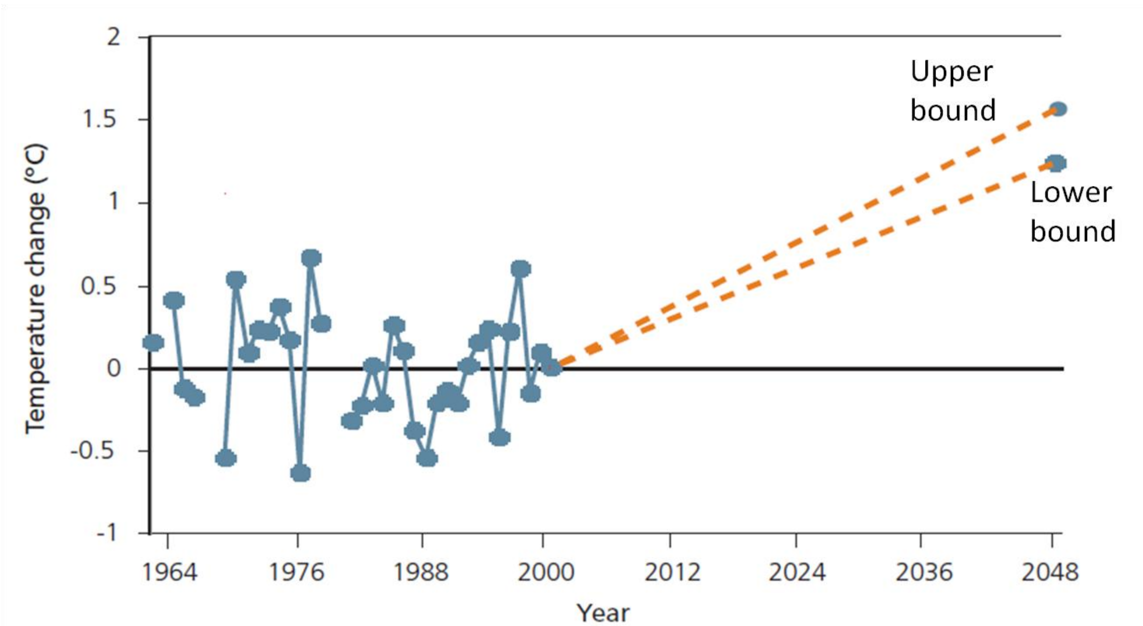

Figure 5.1: Annual average maximum temperature variations (1964-2003) and temperature projected to 2050 of Bangladesh. [Image source: (Ramamasy & Baas, 2007)]

Table 5.1: Estimates of Temperature and Precipitation Changes for Bangladesh
(Data source: Ramamasy & Baas, 2007)

Year	Mean Temperature Change (˚C) (standard deviation)			Mean Precipitation Change (%) (standard deviation)		
	Annual	Winter	Monsoon	Annual	Winter	Monsoon
Baseline average (1964-2003)				2278 mm	33.7 mm	1343.7 mm
2030	+1.0 (0.11)	+1.0 (0.18)	+0.8 (0.16)	+3.8 (2.30)	-1.2 (12.56)	+4.7 (3.17)
2050	+1.4 (0.16)	+1.6 (0.26)	+1.1 (0.23)	+5.6 (3.33)	-1.7 (18.15)	+6.8 (4.58)
2100	+2.4 (0.28)	+2.7 (0.46)	+1.9 (0.40)	+9.7 (5.80)	-3.0 (31.60)	+11.8 (7.97)

Rainfall and temperature changes in Barisal and Khulna were calculated for year 2030, 2050 and 2100 by adjusting the baseline data in the CLIMWAT database.

For the winter period (December to February),

Maximum average temperature in January of 2050 = maximum temperature in January of present time + mean temperature change in winter of 2050 (from the 'winter' column of the table).

Rainfall in January 2050 = rainfall in present time + [rainfall in present time × (% of mean precipitation change in winter 2050 / 100)]

For the monsoon period (June to September) same procedure was followed using the data from 'monsoon' column from Table 5.1. For other months of the year, the 'annual' column was used to estimate the future temperature and rainfall. The estimated values of temperature and rainfall in Barisal and Khulna for the year 2030, 2050 and 2100 are given in Table C1 to C3 in Appendix C.

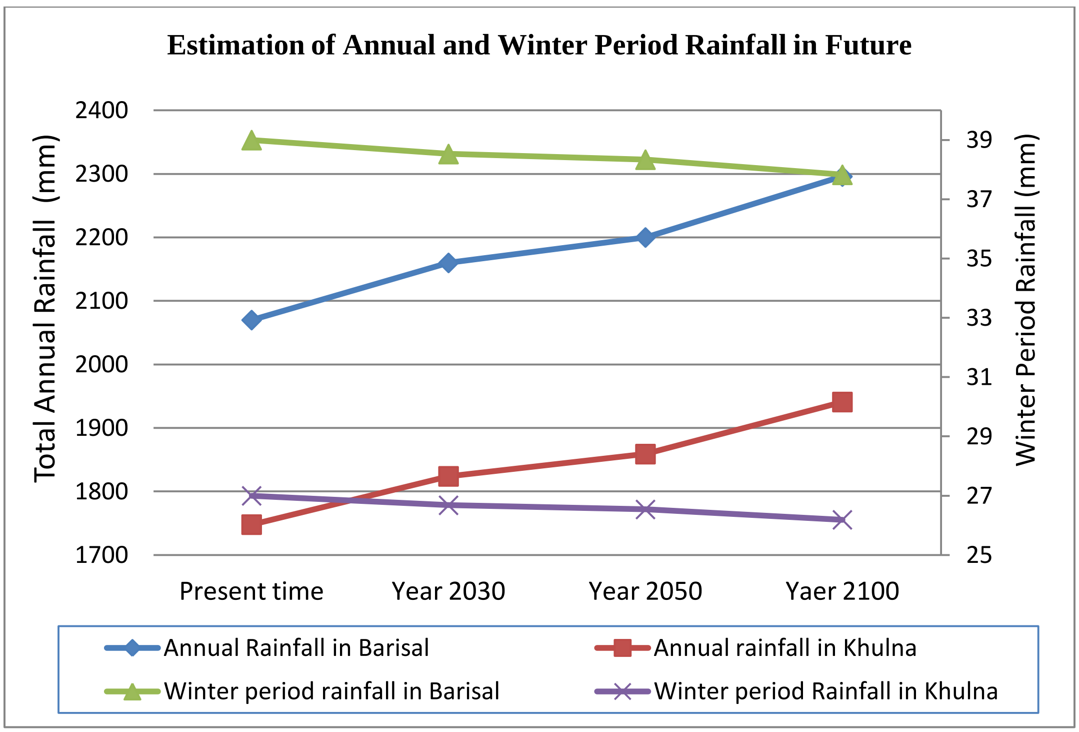

Figure 5.2: Comparison of Future Trends of Annual Rainfall and Winter Period (December to February) Rainfall in Barisal and Khulna.

From Figure 5.2, it is evident that total annual rainfall will increase in the future, but winter period rainfall shows a declining trend. Because of the increasing trend of temperature, the yearly average evapotranspiration (ET_o) also expected to increase in future years (Figure 5.3).

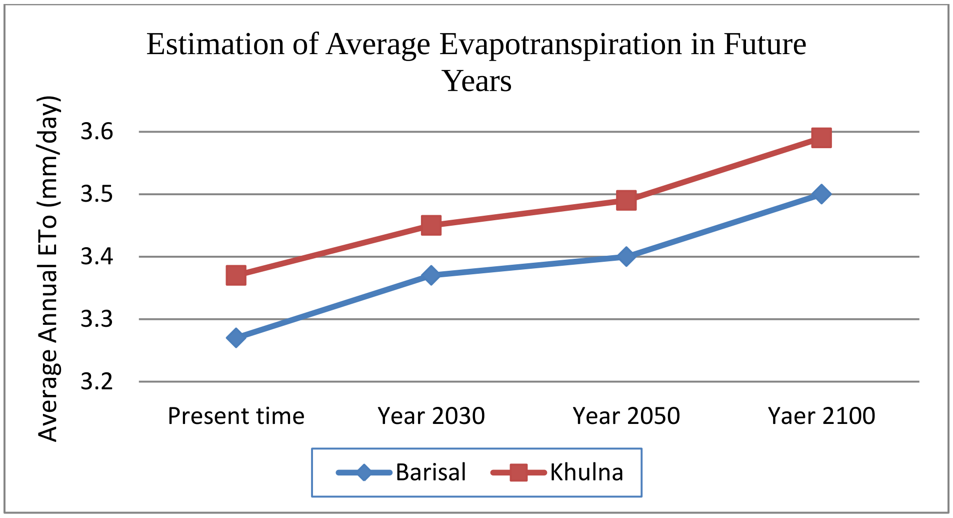

Figure 5.3: Increasing Trend of Average Annual Evapotranspiration (ET_o)

5.2.2 Change of Groundwater Recharge in Future Years

Yearly and dry period recharge of groundwater in the years 2030, 2050 and 2100 were estimated. In the dry season (November to April) recharge was calculated for two cropping patterns (i.e. rice only and mixed cultivation of rice and vegetables). The calculation is shown in Tables C3 to C9 in Appendix C.

Table 5.2: Prediction of Annual Groundwater Recharge in Khulna and Barisal

	Annual Groundwater Recharge (mm)							
Cropping pattern	Khulna				Barisal			
	Present time	Year 2030	Year 2050	Year 2100	Present time	Year 2030	Year 2050	Year 2100
Rice only	316	357	375	416	680	736	756	812
Rice and vegetables	-	986	1013	1078	-	1348	1376	1449

The annual groundwater recharge is expected to increase due to the increase of annual rainfall. It was anticipated that groundwater recharge may be lower in future than that of present time in the dry period. However, the analysis revealed that even in the dry period, recharge may increase (Table 5.3). This is because in calculating dry period (November to April) recharge at first it was considered that the aquifer has been recharged in the previous year and then the dry period negative recharge is included there. Because of higher annual rainfall in the future, the dry period recharged also may increase although the rainfall will be less in the winter season. The groundwater recharge will be higher if the farmers cultivate both rice and vegetables.

Table 5.3: Prediction of Dry Period (November to April) Groundwater Recharge in Khulna and Barisal

	Dry Period Groundwater Recharge (mm)							
Cropping pattern	Khulna				Barisal			
	Present time	Year 2030	Year 2050	Year 2100	Present time	Year 2030	Year 2050	Year 2100
Rice only	165	197	213	258	580	637	653	701
Rice and vegetables	236	900	925	988	650	1320	1348	1412

In present time dry period recharge calculation, for mixed cultivation of rice and vegetables, it was assumed that farmers had been cultivating rice only for the past years. Then they switched to the mixed cultivation. But for Year 2030, the assumption is that they will continue mixed cultivation from present time to 2030. This causes a higher rate of increase in dry period recharge in the year 2030 for mixed cultivation.

5.3 Effects of Sea Level Rise

The effect of sea level rise was included in the MODFLOW model by setting higher constant heads on the seaward side. The higher heads were applied on the model in addition of the existing constant head (+90 m above the base of the model). The head at the freshwater side was left unchanged at +90m above the model base (10m below the ground surface). Values for SLR in coastal area of Bangladesh for future years are given in Table 5.4.

Table 5.4: Predicted Sea Level Rise in Bangladesh (MOEF, 2005) and the Change in the Model.

Year	Predicted Sea Level Rise (cm)	Sea side Head in the Model (above the model base)
2030	14	+90.14 m
2050	32	+90.32 m
2100	88	+90.88 m

5.4 Estimation of Groundwater Pumping Rate in Future Years

From November to April, the maximum pumping rate for different crop patterns (i.e. rice only and mixed cultivation of rice and vegetables) was estimated using CROPWAT and is summarized in Table 5.5.

Table 5.5: Estimation of Maximum Irrigation Required During the Dry Period in Future Years

	Rice cultivation throughout the year			Rice and vegetables mixed cultivation		
	Maximum irrigation required (l/s/hectare)		Month	Maximum irrigation required (l/s/hectare)		Month
	Khulna	Barisal		Khulna	Barisal	
Present time	0.46	0.42	December	0.32	0.27	April
Year 2030	0.47	0.43	December	0.32	0.27	April
Year 2050	0.48	0.44	December	0.32	0.27	April
Year 2100	0.49	0.45	December	0.33	0.28	April

Using Table 5.5 and following the calculation method described in section 4.4.2, the required number of shallow tubewells (average pumping rate 864 m^3/day) in a 1km×1km agricultural area was estimated for future years and given in Table 5.6.

Table 5.6: Pumping Rate for Different Cropping Patterns in Different Locations in Future Years for 1km×1km Land.

		Rice cultivation throughout the year			Rice and vegetables mixed cultivation		
		Maximum pumping rate (m^3/day)	Month	Required no of shallow tubewells	Maximum pumping rate (m^3/day)	Month	Required no of shallow tubewells
Khulna	Present time	3975	December	5	2765	April	4
	Year 2030	4061	December	5	2765	April	4
	Year 2050	4147	December	5	2765	April	4
	Year 2100	4234	December	5	2851	April	4
Barisal	Present time	3629	December	5	2333	April	3
	Year 2030	3715	December	5	2333	April	3
	Year 2050	3802	December	5	2333	April	3
	Year 2100	3888	December	5	2419	April	3

From Table 5.6 it is evident that, although the maximum pumping rate required will increase in the future, same number of shallow tubewell can serve the area. The wells were simulated in MODFLOW along with the changed recharge and higher constant head at the seaward side. The changes of groundwater head and extent saltwater intrusion in future years will be discussed in the next section.

5.5 Results of Groundwater Modelling for Future Years and Discussion

The future SLR and the estimated annual and dry period recharge from Tables 5.2 and 5.3 were run in the 1km×1km model. The calculated maximum groundwater head is predicted to increase in future years. This increasing trend is because of higher rainfall and the increased constant boundary head at the seaward side of the model due to SLR. The results are summarized in Table 5.7.

Table 5.7: Maximum Values of Groundwater Head in the 1km×1km MODFLOW Model

		Maximum Groundwater Head (m) above the Model Base Considering Annual Recharge		Maximum Groundwater Head (m) above the Model Base Considering Dry period Recharge from November to April	
		Rice cultivation throughout the year	Rice and Vegetables mixed cultivation	Rice cultivation throughout the year	Rice and Vegetables mixed cultivation
Khulna	At present	92.29	-	91.21	91.72
	Year 2030	92.65	97.00	91.51	96.41
	Year 2050	92.87	97.26	91.72	96.66
	Year 2100	93.44	97.96	92.33	97.36
Barisal	At Present	94.84	-	94.14	94.63
	Year 2030	95.29	99.40	94.61	97.01
	Year 2050	95.51	99.67	94.80	99.48
	Year 2100	96.16	100.41	95.40	100.16

The maximum elevation of groundwater head is higher for the mixed cultivation of rice and vegetables than that of cultivation of rice only. Cultivating vegetables during the dry period will increase the groundwater recharge and the groundwater table will be higher. This will help the farmers to install pumps at lesser depths. From Table 5.7 it can be found that the groundwater will rise in year 2100 over the ground surface (> 100 m) for mixed cultivation. This will cause flooding. In Khulna, for the year 2030 and 2050, it seems to rise very close to the ground surface (>90 m). This will cause water logging in the area and sluice gates and drains will be needed to mitigate the problem. But for cultivation of rice only this problem will not arise.

In Barisal, for rice cultivation throughout the year, the safe distance from the seaward side to install pumping is 850 m in 2030 which is similar to that of present time (Figure 5.4). Even in 2050 and 2100 for sea level rises of 32cm and 88cm respectively, for Barisal, the safe distance remains the same as present time (Figure 5.5 and Figure 5.6).However, in Khulna, where the total rainfall and recharge is less than that of Barisal, in year 2100, the existing safe distance of wells will increase from 900 m to 950 m from sea side (Figure 5.8). The results and findings are summarized in Table 5.8.

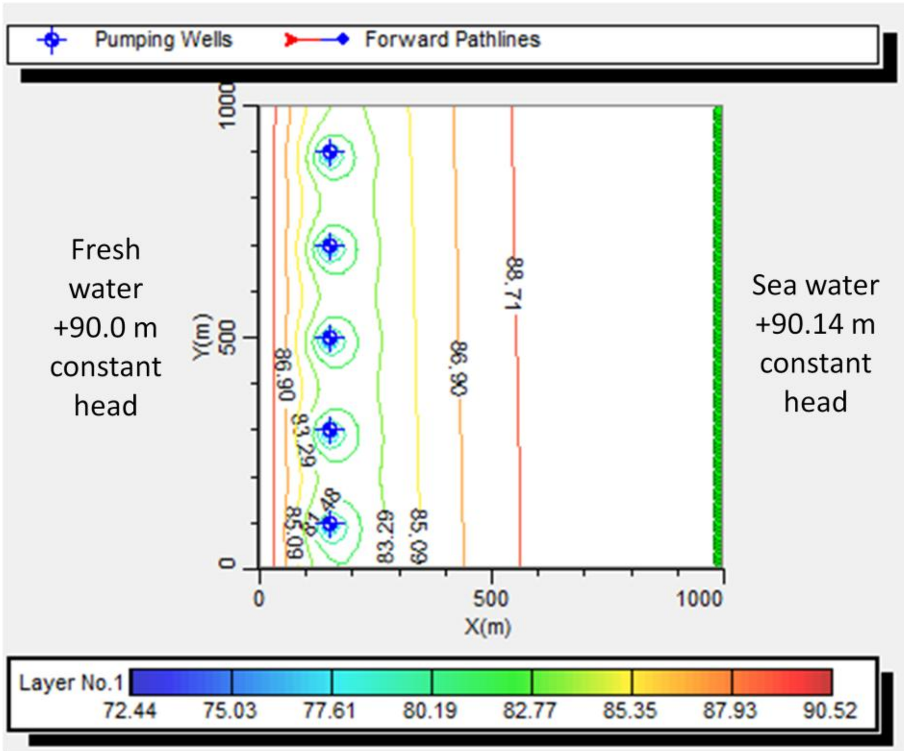

Figure 5.4: Groundwater Head Contours for Rice Cultivation in Barisal in Year 2030.

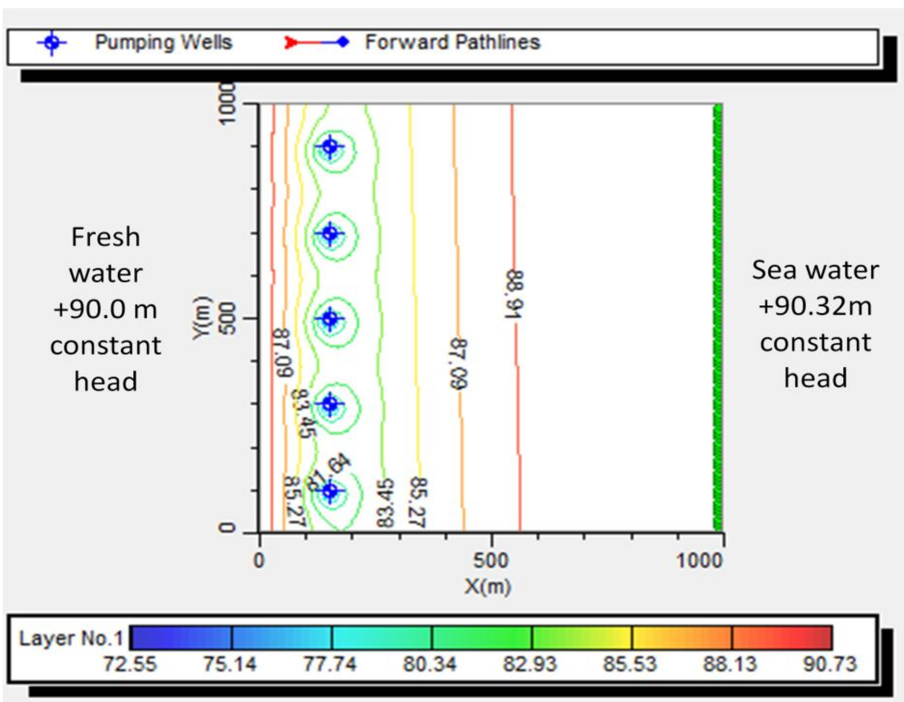

Figure 5.5: Groundwater Head Contours for Rice Cultivation in Barisal in Year 2050.

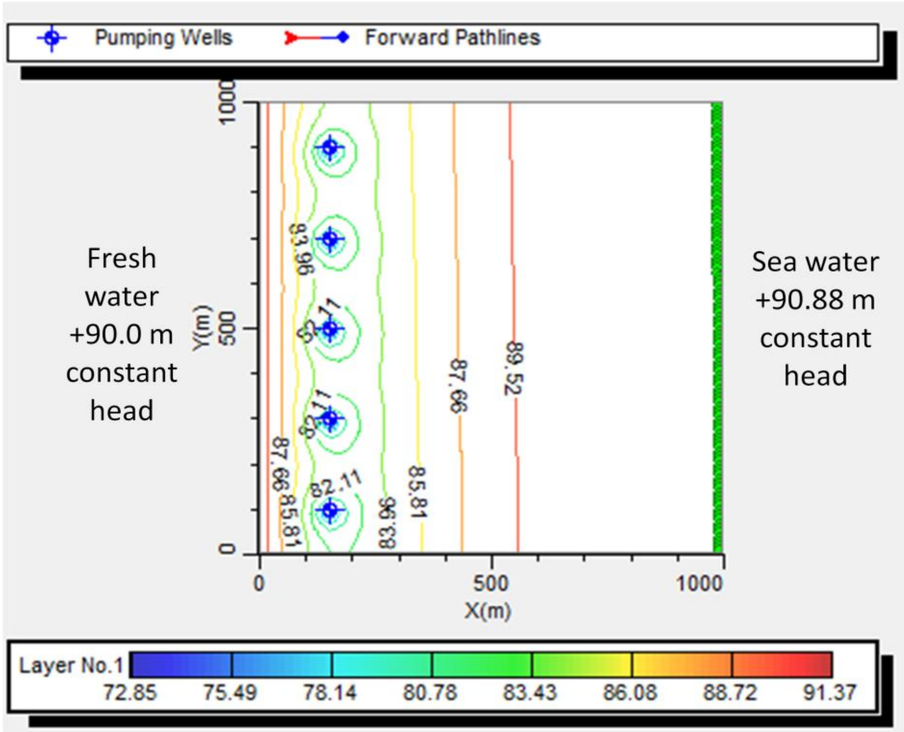

Figure 5.6: Groundwater Head Contours for Rice Cultivation in Barisal in Year 2100.

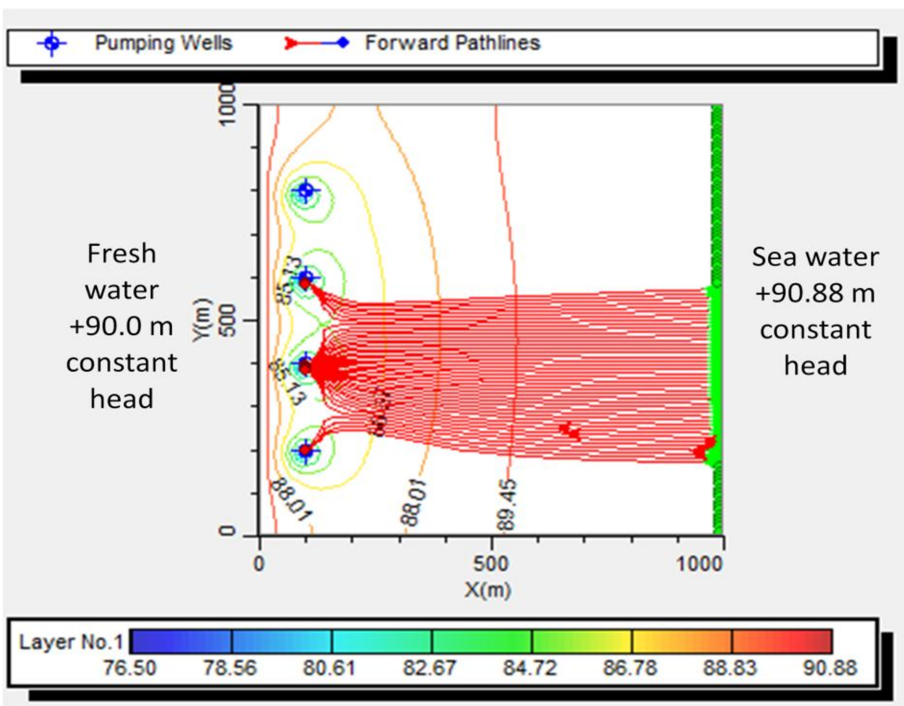

Figure 5.7: Groundwater Head Contours and Pathlines of Saltwater Intrusion for Mixed Cultivation of Rice and Vegetables in Khulna in Year 2100 (wells are 900 m from the sea).

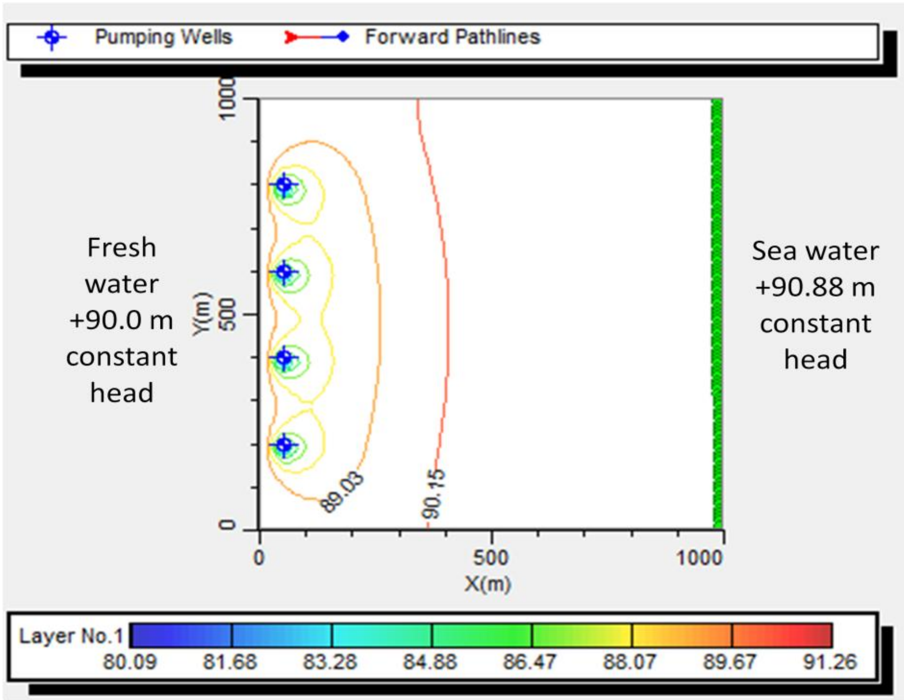

Figure 5.8: Groundwater Head Contours and Pathlines of Saltwater Intrusion for Mixed Cultivation of Rice and Vegetables in Khulna in Year 2100 (wells are 950 m from the sea).

Table 5.8: Comparison of Safe Locations of Pumping Wells in Future Time for 1km × 1km Coastal Agricultural Land.

Location	Cropping Pattern	No of shallow tubewells	Safe distance from the sea			
			Present time	Year 2030	Year 2050	Year 2100
Barisal	rice only	5	850 m	850 m	850 m	850 m
	rice and vegetables	3	700 m	700 m	700 m	700 m
Khulna	rice only	5	No safe distance	No safe distance	No safe distance	No safe distance
	rice and vegetables	4	900 m	900 m	900 m	950 m

5.6 Summary

From the model runs of chapter 5, it can be said that climate change will result in higher annual rainfall and higher average evapotranspiration in the future. Rainfall will be intense during the monsoon period but it will decrease in the winter period (December to February). But the increase of rainfall will cause higher annual recharge. From the analysis, it shows that the total recharge in the dry period (November to April) will also increase over time. This increase will be higher if the farmers cultivate both rice and vegetables jointly over the year.

The sea level rise phenomenon may expand the problem of salt water intrusion at the end of 21st century. From the analysis it was found that the groundwater in Barisal region will not be significantly affected by the sea level rise of 88 cm in the year 2100. But Khulna region appears to face higher salinity at the end of this century and farmers may have to shift their pumps further inland. This will also cause loss of cultivable land in the future.

Chapter 6

CONCLUSION AND RECOMMENDATIONS

6.1 General Comments on the Study

The study established a linkage between irrigation practice and groundwater in the south-west coastal region of Bangladesh. It focused on the interrelationships among different cropping patterns, groundwater pumping in dry seasons (November to April) and saltwater intrusion in the coastal aquifers. The probable consequences of future climate change and corresponding sea level rise on the current scenario were also evaluated. The analysis was done by developing and using generic models for the area. Two types of generic model were established. Crop Irrigation model was developed in CROPWAT and MODFLOW was used for groundwater modelling. Climate data of two climatological stations (Khulna and Barisal) was used for the analysis.

6.2 Conclusion

The findings and conclusions from the study are summarized below:

- In south-west coastal region of Bangladesh, during the dry season (November to April), irrigation is dependent on groundwater. Farmers extract groundwater from upper unconfined aquifers by pumping with shallow tubewells. Producing rice throughout the year had been the general cultivation practice in the past years. Recently, farmers are switching to the mixed cultivation of rice and vegetables. These two cropping patterns significantly influence the groundwater recharge. It also affects the total amount of irrigation required in the dry season.

- Extraction of groundwater from the coastal aquifers causes saltwater intrusion. Excessive presence of salinity in the soil and the irrigation wells compel the farmers to give away the cultivable lands adjacent to the sea. The analysis revealed that the pumping wells near the shoreline are affected by saltwater intrusion. The extent of this problem is higher for rice cultivation throughout the year in comparison to the mixed cultivation of rice and vegetables. Saltwater intrusion is higher in Khulna than that of Barisal. In Khulna, for rice cultivation only, no pumping well is safe from salinity problem within 1km distance from the sea.

- Increase of annual rainfall due to climate change will cause higher groundwater recharge in the future which will raise the groundwater table higher. This will be conducive for pumping because groundwater will be extracted from lesser depth. However, the sea level rise is expected to increase the saltwater intrusion. It was found from the analysis that for Khulna, the current safe distance of wells from the sea will not remain safe from saltwater intrusion in the year 2100.

6.3 Limitation of the Study

- Typical representative values for the study area were used for aquifer properties in the MODFLOW models considering a uniform model domain. In real world, these values may vary from place to place within a very short distance.
- From the outputs, it is evident that the models show the problem of saltwater intrusion. But it does not provide information about the quantity of saltwater intrusion in a particular well.
- To ensure the reliability of the models, they need to be validated by comparing with field data.

6.4 Recommendations for Further Research

- The crop irrigation models can be generated for the combination of different other cropping patterns to find out the best alternative. Apart from the irrigation requirements and groundwater recharge, the economic values of the cultivated crops should be emphasized while selecting the best option.

- Similar MODFLOW models can be developed for every coastal district or even for every coastal upazilla (sub-divisions of district in Bangladesh) by considering the local aquifer properties. This will provide the information of saltwater intrusion scenario in local basis.
- Different predictions were made for future climate change and sea level rise in different literatures. By using different model results from different literatures, a comparison of the expected extent of saltwater intrusion can be made for future years.

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APPENDICES

APPENDIX A

TABLES FROM CROPWAT

Table A1: Irrigation Required (IR) Calculations for Boro Rice in Khulna (Plantation 25/12, Harvest 23/04)

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Nov	3	Nurs	1.2	0.34	2	1.9	0.4
Dec	1	Nurs/LPr	1.12	1.8	18	2.9	63.9
Dec	2	Nurs/LPr	1.06	2.58	25.8	0.9	122.9
Dec	3	Init	1.09	2.6	28.5	1.2	81
Jan	1	Init	1.1	2.59	25.9	1.6	24.2
Jan	2	Deve	1.11	2.57	25.7	1.6	24
Jan	3	Deve	1.14	2.89	31.8	2.8	29
Feb	1	Deve	1.17	3.24	32.4	3.6	28.8
Feb	2	Mid	1.19	3.56	35.6	4.4	31.2
Feb	3	Mid	1.19	4	32	7.7	24.4
Mar	1	Mid	1.19	4.45	44.5	11	33.4
Mar	2	Mid	1.19	4.89	48.9	14	34.9
Mar	3	Late	1.17	5.01	55.1	17.7	37.4
Apr	1	Late	1.12	4.96	49.6	21	28.6
Apr	2	Late	1.07	4.9	49	24.4	24.6
Apr	3	Late	1.04	4.67	14	9.1	0
Total					518.9	125.8	589

Table A2: Irrigation Required (IR) Calculations for Small Vegetables in Khulna (Plantation 25/12, Harvest 29/03)

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Dec	3	Init	0.7	1.67	11.7	0.8	11.1
Jan	1	Init	0.7	1.65	16.5	1.6	14.8
Jan	2	Deve	0.73	1.69	16.9	1.6	15.3
Jan	3	Deve	0.85	2.16	23.7	2.8	20.9
Feb	1	Deve	0.97	2.68	26.8	3.6	23.2
Feb	2	Mid	1.04	3.12	31.2	4.4	26.8
Feb	3	Mid	1.04	3.51	28.1	7.7	20.4
Mar	1	Mid	1.04	3.9	39	11	27.9
Mar	2	Late	1.03	4.23	42.3	14	28.3
Mar	3	Late	0.97	4.13	37.2	14.5	19.5
Total					273.4	62	208.3

Table A3: Irrigation Required (IR) Calculations for Boro Rice in Barisal (Plantation 25/12, Harvest 23/04)

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Nov	3	Nurs	1.2	0.33	2	4.9	0
Dec	1	Nurs/LPr	1.12	1.78	17.8	6.9	59.7
Dec	2	Nurs/LPr	1.06	2.57	25.7	3.8	119.9
Dec	3	Init	1.09	2.58	28.4	3.2	75.9
Jan	1	Init	1.1	2.58	25.8	2.2	23.5
Jan	2	Deve	1.11	2.56	25.6	1.1	24.5
Jan	3	Deve	1.14	2.89	31.8	2.8	29
Feb	1	Deve	1.17	3.23	32.3	4.6	27.8
Feb	2	Mid	1.19	3.56	35.6	5.8	29.7
Feb	3	Mid	1.19	3.96	31.7	8.2	23.5
Mar	1	Mid	1.19	4.37	43.7	9.6	34
Mar	2	Mid	1.19	4.77	47.7	11.4	36.3
Mar	3	Late	1.17	4.86	53.5	17.4	36.1
Apr	1	Late	1.12	4.79	47.9	23.8	24.1
Apr	2	Late	1.07	4.7	47	29.3	17.7
Apr	3	Late	1.04	4.43	13.3	10.5	0
Total					509.6	145.3	561.8

Table A4: Irrigation Required (IR) Calculations for Small Vegetable in Barisal (Plantation 25/12, Harvest 29/03)

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Dec	3	Init	0.7	1.66	11.6	2	10.1
Jan	1	Init	0.7	1.64	16.4	2.2	14.2
Jan	2	Deve	0.73	1.69	16.9	1.1	15.8
Jan	3	Deve	0.85	2.15	23.7	2.8	20.9
Feb	1	Deve	0.97	2.68	26.8	4.6	22.2
Feb	2	Mid	1.04	3.12	31.2	5.8	25.3
Feb	3	Mid	1.04	3.47	27.8	8.2	19.6
Mar	1	Mid	1.04	3.83	38.3	9.6	28.7
Mar	2	Late	1.03	4.13	41.3	11.4	29.9
Mar	3	Late	0.97	4.01	36.1	14.2	18.7
Total					270	61.9	205.4

Table A5: Irrigation Required (IR) Calculations for Aman Rice in Khulna (Plantation 25/08, Harvest 22/12)

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jul	3	Nurs	1.2	0.39	2.3	29	0
Aug	1	Nurs/LPr	1.12	2.17	21.7	53.4	48.9
Aug	2	Nurs/LPr	1.06	3.27	32.7	53.3	98
Aug	3	Init	1.09	3.5	38.5	51.3	0
Sep	1	Init	1.1	3.7	37	49.7	0
Sep	2	Deve	1.1	3.88	38.8	48.3	0
Sep	3	Deve	1.11	3.9	39	43.6	0
Oct	1	Deve	1.13	3.92	39.2	40	0
Oct	2	Mid	1.13	3.93	39.3	36.3	3
Oct	3	Mid	1.13	3.77	41.4	26.6	14.8
Nov	1	Mid	1.13	3.6	36	14.1	21.9
Nov	2	Mid	1.13	3.44	34.4	4	30.4
Nov	3	Late	1.12	3.16	31.6	3.2	28.4
Dec	1	Late	1.08	2.83	28.3	2.9	25.4
Dec	2	Late	1.04	2.51	25.1	0.9	24.3
Dec	3	Late	1.01	2.42	4.8	0.2	4.8
Total					490.2	456.7	300

Table A6: Irrigation Required (IR) Calculations for Aman Rice in Barisal (Plantation 25/08, Harvest 22/12)

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jul	3	Nurs	1.2	0.37	2.2	29.8	0
Aug	1	Nurs/LPr	1.12	2.1	21	54.1	48.9
Aug	2	Nurs/LPr	1.06	3.18	31.8	53.7	98
Aug	3	Init	1.09	3.4	37.4	52.9	0
Sep	1	Init	1.1	3.6	36	52.5	0
Sep	2	Deve	1.1	3.76	37.6	52	0
Sep	3	Deve	1.11	3.79	37.9	49.2	0
Oct	1	Deve	1.12	3.83	38.3	48.3	0
Oct	2	Mid	1.13	3.85	38.5	46.7	0
Oct	3	Mid	1.13	3.67	40.4	35.5	4.9
Nov	1	Mid	1.13	3.49	34.9	21.2	13.8
Nov	2	Mid	1.13	3.32	33.2	10	23.2
Nov	3	Late	1.11	3.08	30.8	8.2	22.6
Dec	1	Late	1.07	2.78	27.8	6.9	20.9
Dec	2	Late	1.03	2.49	24.9	3.8	21.1
Dec	3	Late	1.01	2.4	4.8	0.6	4.8
Total					477.4	525.2	258.1

Table A7: Irrigation Required (IR) Calculations for Turf Grass in Khulna (Plantation 25/04, Harvest 24/04)

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Aug	3	Init	0.81	2.61	18.3	32.6	0
Sep	1	Init	0.8	2.69	26.9	49.7	0
Sep	2	Init	0.8	2.81	28.1	48.3	0
Sep	3	Init	0.8	2.8	28	43.6	0
Oct	1	Init	0.8	2.79	27.9	40	0
Oct	2	Init	0.8	2.77	27.7	36.3	0
Oct	3	Init	0.8	2.66	29.2	26.6	2.7
Nov	1	Init	0.8	2.54	25.4	14.1	11.3
Nov	2	Init	0.8	2.43	24.3	4	20.3
Nov	3	Init	0.8	2.26	22.6	3.2	19.4
Dec	1	Init	0.8	2.1	21	2.9	18.1
Dec	2	Init	0.8	1.94	19.4	0.9	18.5
Dec	3	Init	0.8	1.91	21	1.2	19.8
Jan	1	Init	0.8	1.88	18.8	1.6	17.2
Jan	2	Init	0.8	1.85	18.5	1.6	16.9
Jan	3	Deve	0.8	2.05	22.5	2.8	19.7
Feb	1	Deve	0.81	2.26	22.6	3.6	19
Feb	2	Deve	0.82	2.47	24.7	4.4	20.3
Feb	3	Deve	0.83	2.8	22.4	7.7	14.7
Mar	1	Mid	0.83	3.12	31.2	11	20.2
Mar	2	Mid	0.83	3.44	34.4	14	20.4
Mar	3	Mid	0.83	3.56	39.1	17.7	21.4
Apr	1	Mid	0.83	3.68	36.8	21	15.8
Apr	2	Mid	0.83	3.8	38	24.4	13.7
Apr	3	Mid	0.83	3.75	37.5	30.4	7.1
May	1	Mid	0.83	3.69	36.9	37.3	0
May	2	Mid	0.83	3.63	36.3	43.3	0
May	3	Mid	0.83	3.32	36.6	46.7	0
Jun	1	Mid	0.83	2.97	29.7	50.9	0
Jun	2	Mid	0.83	2.64	26.4	55.1	0
Jun	3	Mid	0.83	2.68	26.8	54.6	0
Jul	1	Mid	0.83	2.75	27.5	53.5	0
Jul	2	Late	0.83	2.75	27.5	53.5	0
Jul	3	Late	0.82	2.67	29.3	53.2	0
Aug	1	Late	0.82	2.58	25.8	53.4	0
Aug	2	Late	0.81	2.5	25	53.3	0
Aug	3	Late	0.81	2.61	10.4	18.6	0
Total					1004.5	1016.9	316.4

Table A8: Irrigation Required (IR) Calculations for Turf Grass in Barisal (Plantation 25/04, Harvest 24/04)

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Aug	3	Init	0.81	2.54	17.8	33.6	0
Sep	1	Init	0.8	2.62	26.2	52.5	0
Sep	2	Init	0.8	2.73	27.3	52	0
Sep	3	Init	0.8	2.73	27.3	49.2	0
Oct	1	Init	0.8	2.73	27.3	48.3	0
Oct	2	Init	0.8	2.73	27.3	46.7	0
Oct	3	Init	0.8	2.6	28.6	35.5	0
Nov	1	Init	0.8	2.48	24.8	21.2	3.6
Nov	2	Init	0.8	2.35	23.5	10	13.6
Nov	3	Init	0.8	2.21	22.1	8.2	13.9
Dec	1	Init	0.8	2.07	20.7	6.9	13.8
Dec	2	Init	0.8	1.93	19.3	3.8	15.5
Dec	3	Init	0.8	1.9	20.9	3.2	17.7
Jan	1	Init	0.8	1.87	18.7	2.2	16.5
Jan	2	Init	0.8	1.85	18.5	1.1	17.4
Jan	3	Deve	0.8	2.04	22.5	2.8	19.7
Feb	1	Deve	0.81	2.25	22.5	4.6	17.9
Feb	2	Deve	0.82	2.46	24.6	5.8	18.8
Feb	3	Deve	0.83	2.76	22.1	8.2	14
Mar	1	Mid	0.83	3.06	30.6	9.6	21
Mar	2	Mid	0.83	3.35	33.5	11.4	22.1
Mar	3	Mid	0.83	3.45	37.9	17.4	20.6
Apr	1	Mid	0.83	3.55	35.5	23.8	11.7
Apr	2	Mid	0.83	3.66	36.6	29.3	7.3
Apr	3	Mid	0.83	3.56	35.6	35	0.6
May	1	Mid	0.83	3.47	34.7	41.5	0
May	2	Mid	0.83	3.37	33.7	47.5	0
May	3	Mid	0.83	3.11	34.2	50	0
Jun	1	Mid	0.83	2.8	28	52.9	0
Jun	2	Mid	0.83	2.52	25.2	56.2	0
Jun	3	Mid	0.83	2.56	25.6	55.8	0
Jul	1	Mid	0.83	2.64	26.4	55.2	0
Jul	2	Late	0.83	2.65	26.5	55.3	0
Jul	3	Late	0.82	2.58	28.4	54.7	0
Aug	1	Late	0.82	2.51	25.1	54.1	0
Aug	2	Late	0.82	2.44	24.4	53.7	0
Aug	3	Late	0.81	2.54	10.2	19.2	0
Total					974	1118.1	265.8

Table A9: Irrigation Scheme for Khulna (Rice cultivation throughout the year)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Precipitation deficit												
1. Rice	0	0	0	0	0	0	0	146.9	0	22.1	85.4	56.4
2. Rice	77.3	84.4	105.8	53.3	0	0	0	0	0	0	0.4	267.8
3. Rice	0	0	0	253.3	19.3	0	0	6.7	0	0	0	0
4. Turf grass warm	54.4	53	60.7	29.1	0	0	0	0	0	3	51.9	57.1
Net scheme irr.req.												
in mm/day	1.2	1.4	1.5	1.4	0	0	0	1.8	0	0.3	1.5	3.7
in mm/month	36.6	38.3	46.5	43.3	1.5	0	0	54.9	0	9	45.2	113.4
in l/s/h	0.14	0.16	0.17	0.17	0.01	0	0	0.2	0	0.03	0.17	0.42
Irrigated area	55	55	55	63	8	0	0	45	0	63	92	92
(% of total area)												
Irr.req. for actual area	0.25	0.29	0.32	0.26	0.07	0	0	0.46	0	0.05	0.19	0.46
(l/s/h)												

Table A10: Irrigation Scheme for Khulna (Rice and vegetable mixed cultivation)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Precipitation deficit												
1. Rice	0	0	0	0	0	0	0	146.9	0	22.1	85.4	56.4
2. Small Vegetables	51	70.4	75.8	0	0	0	0	0	0	0	0	11.1
3. Rice	0	0	0	253.3	19.3	0	0	6.7	0	0	0	0
4. Turf grass warm	54.4	53	60.7	29.1	0	0	0	0	0	3	51.9	57.1
Net scheme irr.req.												
in mm/day	0.9	1.2	1.2	0.9	0	0	0	1.8	0	0.3	1.5	1.3
in mm/month	28.9	34.2	37.8	27.8	1.5	0	0	54.9	0	9	45.1	38.9
in l/s/h	0.11	0.14	0.14	0.11	0.01	0	0	0.2	0	0.03	0.17	0.15
Irrigated area	55	55	55	34	8	0	0	45	0	63	63	92
(% of total area)												
Irr.req. for actual area	0.2	0.26	0.26	0.32	0.07	0	0	0.46	0	0.05	0.28	0.16
(l/s/h)												

Table A11: Irrigation Scheme for Barisal (Rice cultivation throughout the year)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Precipitation deficit												
1. Rice	0	0	0	0	0	0	0	146.9	0	6.9	64.6	48.8
2. Rice	77.1	81	106.5	41.8	0	0	0	0	0	0	0	255.4
3. Rice	0	0	0	234.9	4.4	0	0	6.5	0	0	0	0
4. Turf grass warm	54.3	49.8	62.4	18.5	0	0	0	0	0	0	32	47.9
Net scheme irr.req.												
in mm/day	1.2	1.3	1.5	1.2	0	0	0	1.8	0	0.1	1.1	3.4
in mm/month	36.5	36.5	47.1	35.7	0.3	0	0	54.9	0	2.6	32.2	104.6
in l/s/h	0.14	0.15	0.18	0.14	0	0	0	0.2	0	0.01	0.12	0.39
Irrigated area	55	55	55	63	8	0	0	45	0	37	63	92
(% of total area)												
Irr.req. for actual area	0.25	0.27	0.32	0.22	0.02	0	0	0.46	0	0.03	0.2	0.42
(l/s/h)												

Table A12: Irrigation Scheme for Barisal (Rice and vegetable mixed cultivation)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Precipitation deficit												
1. Rice	0	0	0	0	0	0	0	146.9	0	6.9	64.6	48.8
2. Small Vegetables	50.9	67.2	77.3	0	0	0	0	0	0	0	0	10.1
3. Rice	0	0	0	234.9	4.4	0	0	6.5	0	0	0	0
4. Turf grass warm	54.3	49.8	62.4	18.5	0	0	0	0	0	0	32	47.9
Net scheme irr.req.												
in mm/day	0.9	1.2	1.2	0.8	0	0	0	1.8	0	0.1	1.1	1.1
in mm/month	28.9	32.4	38.6	23.6	0.3	0	0	54.9	0	2.6	32.2	33.4
in l/s/h	0.11	0.13	0.14	0.09	0	0	0	0.2	0	0.01	0.12	0.12
Irrigated area	55	55	55	34	8	0	0	45	0	37	63	92
(% of total area)												
Irr.req. for actual area	0.2	0.24	0.26	0.27	0.02	0	0	0.46	0	0.03	0.2	0.14
(l/s/h)												

APPENDIX B

TABLES AND FIGURES USED TO DETERMINE THE AQUIFER PROPERTIES

Table B1: Values of Specific Yield (Johnson, 1967)

Material	Specific Yield (%)		
	min	avg	max
Unconsolidated deposits			
Clay	0	2	5
Sandy clay (mud)	3	7	12
Silt	3	18	19
Fine Sand	10	21	28
Medium sand	15	26	32
Coarse sand	20	27	35
Gravelly Sand	20	25	35
Fine gravel	21	25	35
Medium gravel	13	23	26
Coasrse gravel	12	22	26

Table B2: Ranges of Values of Porosity (Freezy & Cherry, 1979)

Material	Porosity, n (%)
Uncosolidated deposits	
Gravel	25-40
Sand	25-50
Silt	35-50
Clay	40-70
Rocks	
Fractured basalt	5-50
Karst limestone	5-50
Sandstone	5-30
Limestone, dolomite	0-20
Shale	0-10
Fractured crystalline rock	0-10
Dense crystalline rock	0-5

Table B3: Values of Specific Storage (Younger, 1993)

Typical Lithologies	Specific storage (m^{-1})
Clay	9.81 x 10-3
Silt, fine sand	9.82 x 10-4
Medium sand, fine	9.87 x 10-5
Coarse sand, medium gravel, highly fissured	1.05 x 10-5
Coarse gravel, moderately fissured rock	1.63 x 10-6
Unfissured rock	7.46 x 10-7

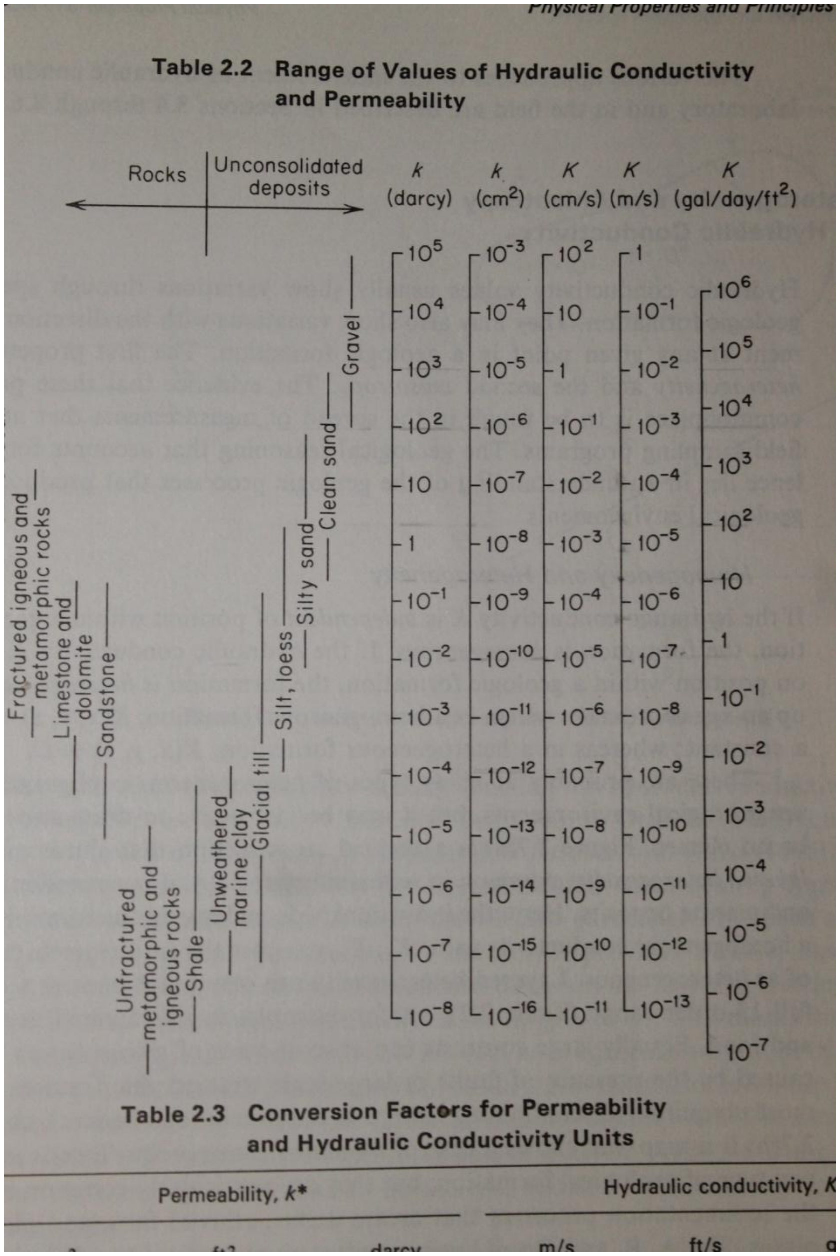

Figure B1: Range of Values of Hydraulic Conductivity for Different Class of Soils.

[Collected from: (Freezy & Cherry, 1979)]

APPENDIX C

TABLES FROM CROPWAT TO ESTIMATE FUTURE SCENARIO

Table C1: Estimation of Temperature for Barisal in Year 2030, 2050 and 2100

Month	Minimum Temperature (˚C)				Maximum Temperature (˚C)			
	Present time	Year 2030	Year 2050	Year 2100	Present time	Year 2030	Year 2050	Year 2100
January	11.3	12.1	12.9	14.0	25.6	26.4	27.2	28.3
February	14.1	14.9	15.7	16.8	28.3	29.1	29.9	31.0
March	19.6	20.6	21.0	22.0	32.1	33.1	33.5	34.5
April	23.3	24.3	24.7	25.7	33.3	34.3	34.7	35.7
May	24.6	25.6	26.0	27.0	32.9	33.9	34.3	35.3
June	25.6	26.6	26.7	27.5	31.3	32.3	32.4	33.2
July	25.5	26.5	26.6	27.4	30.6	31.6	31.7	32.5
August	25.5	26.5	26.6	27.4	30.6	31.6	31.7	32.5
September	25.3	26.3	26.4	27.2	31.2	32.2	32.3	33.1
October	23.5	24.5	24.9	25.9	31.2	32.2	32.6	33.6
November	18.2	19.2	19.6	20.6	29.1	30.1	30.5	31.5
December	12.7	13.5	14.3	15.4	26.1	26.9	27.7	28.8
Average	20.8	21.7	22.1	23.1	30.2	31.1	31.5	32.5

Table C2: Estimation of Temperature for Khulna in Year 2030, 2050 and 2100

Month	Minimum Temperature (˚C)				Maximum Temperature (˚C)			
	Present time	Year 2030	Year 2050	Year 2100	Present time	Year 2030	Year 2050	Year 2100
January	12.2	13.0	13.8	14.9	26.1	26.9	27.7	28.8
February	14.7	15.5	16.3	17.4	28.8	29.6	30.4	31.5
March	19.9	20.9	21.3	22.3	33.5	34.5	34.9	35.9
April	23.4	24.4	24.8	25.8	34.6	35.6	36.0	37.0
May	25	26.0	26.4	27.4	34.4	35.4	35.8	36.8
June	25.9	26.9	27.0	27.8	32.4	33.4	33.5	34.3
July	26	27.0	27.1	27.9	31.6	32.6	32.7	33.5
August	26.2	27.2	27.3	28.1	31.4	32.4	32.5	33.3
September	26	27.0	27.1	27.9	32.1	33.1	33.2	34.0
October	24.2	25.2	25.6	26.6	31.9	32.9	33.3	34.3
November	19.2	20.2	20.6	21.6	29.9	30.9	31.3	32.3
December	13.6	14.4	15.2	16.3	26.5	27.3	28.1	29.2
Average	21.4	22.3	22.7	23.7	31.1	32.1	32.5	33.4

Table C3: Estimation of Rainfall for Barisal and Khulna in Year 2030, 2050 and 2100

Month	Rainfall in Barisal (mm)				Rainfall in Khulna (mm)			
	Present time	Year 2030	Year 2050	Year 2100	Present time	Year 2030	Year 2050	Year 2100
January	6.00	5.93	5.90	5.82	6.00	5.93	5.90	5.82
February	19.00	18.77	18.68	18.43	16.00	15.81	15.73	15.52
March	41.00	42.56	43.30	44.98	46.00	47.75	48.58	50.46
April	106.00	110.03	111.94	116.28	88.00	91.34	92.93	96.54
May	209.00	216.94	220.70	229.27	178.00	184.76	187.97	195.27
June	400.00	418.80	427.20	447.20	357.00	373.78	381.28	399.13
July	402.00	420.89	429.34	449.44	353.00	369.59	377.00	394.65
August	357.00	373.78	381.28	399.13	330.00	345.51	352.44	368.94
September	288.00	301.54	307.58	321.98	217.00	227.20	231.76	242.61
October	186.00	193.07	196.42	204.04	130.00	134.94	137.28	142.61
November	42.00	43.60	44.35	46.07	22.00	22.84	23.23	24.13
December	14.00	13.83	13.76	13.58	5.00	4.94	4.92	4.85
Total	2070	2160	2200	2296	1748	1824	1859	1941

Table C4: Crop Evapotranspiration (ET_c) Data for Year 2030 (Rice cultivation throughout the year)

Crop Type	Crop Evapotranspiration, ET_c (mm)			
	Khulna		Barisal	
		Total		Total
Aman Rice	500.3	1621.3	489.7	1577.5
Boro Rice	537.8		522.9	
Aush Rice	583.2		564.9	
Turf Grass		1030.2		988.2

Table C5: Crop Evapotranspiration (ETc) Data for Year 2050 (Rice cultivation throughout the year)

Crop Type	Crop Evapotranspiration, ET_c (mm)			
	Khulna		Barisal	
		Total		Total
Aman Rice	504.2	1639.3	493.6	1595.2
Boro Rice	547.6		532.5	
Aush Rice	587.5		569.1	
Turf Grass		1041.7		1015.0

Table C6: Crop Evapotranspiration (ETc) Data for Year 2100 (Rice cultivation throughout the year)

Crop Type	Crop Evapotranspiration, ET_c (mm)			
	Khulna		Barisal	
		Total		Total
Aman Rice	517.6	1684.0	506.7	1639.0
Boro Rice	564.4		548.9	
Aush Rice	602.0		583.4	
Turf Grass		1070.3		1043.0

Table C7: Crop Evapotranspiration (ETc) Data for Year 2030 (Rice and vegetable mixed cultivation)

Crop Type	Crop Evapotranspiration, ET_c (mm)			
	Khulna		Barisal	
		Total		Total
Aman Rice	500.3	1083.5	489.7	1054.6
Aush Rice	583.2		564.9	
Vegetables		283.6		276.5
Turf Grass		1030.2		988.2

Table C8: Crop Evapotranspiration (ETc) Data for Year 2050 (Rice and vegetable mixed cultivation)

Crop Type	Crop Evapotranspiration, ET_c (mm)			
	Khulna		Barisal	
		Total		Total
Aman Rice	504.2	1091.7	493.6	1062.7
Aush Rice	587.5		569.1	
Vegetables		289.3		282.0
Turf Grass		1041.7		1015.0

Table C9: Crop Evapotranspiration (ETc) Data for Year 2100 (Rice and vegetable mixed cultivation)

Crop Type	Crop Evapotranspiration, ET_c (mm)			
	Khulna		Barisal	
		Total		Total
Aman Rice	517.6	1196.6	506.7	1090.1
Aush Rice	602.0		583.4	
Vegetables		298.2		290.8
Turf Grass		1070.3		1043.0