EFFECT OF DIFFERENT CROPPING PATTERN ON GROUNDWATER OF NAOGAON DISTRICT USING MATHEMATICAL MODELLING

S. M. SAHABUDDIN

DEPARTMENT OF WATER RESOURCES ENGINEERING
BANGLADESH UNIVERSITY OF ENGINEERING & TECHNOLOGY
DHAKA-1000, BANGLADESH

SEPTEMBER 2018

Effect of Different Cropping Pattern on Groundwater of Naogaon District Using Mathematical Modelling

by

S. M. Sahabuddin

Student No: 0412162043 (P)

In Partial fulfillment of the requirement for the degree

of

MASTER OF ENGINEERING IN WATER RESOURCES

Department of Water Resources Engineering,

BANGLADESH UNIVERSITY OF ENGINEERING & TECHNOLOGY,

BUET, DHAKA

September 2018

CERTIFICATION OF APPROVAL

The project work titled **" Effect of Different Cropping Pattern on Groundwater of Naogaon District Using Mathematical Modelling"**, submitted by S. M. Sahabuddin, Student ID: 0412162043 P, Session April 2012, has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Engineering in Water Resources Engineering on 29th September, 2018.

Dr. A T M Hasan Zobeyer
Associate Professor
Department of Water Resources Engineering
BUET, Dhaka-1000, Bangladesh

Chairman of the Committee (Supervisor)

Dr. Md. Sabbir Mostafa Khan
Professor
Department of Water Resources Engineering
BUET, Dhaka-1000, Bangladesh

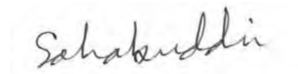
Member

Dr. K. M. Ahtesham Hossain
Assistant Professor
Department of Water Resources Engineering
BUET, Dhaka-1000, Bangladesh

Member

DECLARATION

It is hereby declared that this project work or any part of it has not been submitted elsewhere for the award of any degree or diploma.



Signature of the Author

S. M. Sahabuddin

ACKNOWLEDGEMENT

I am using this opportunity to express my gratitude to everyone who supported me throughout the project work. I am thankful for their aspiring guidance, invaluably constructive criticism and friendly advice during the work. I am sincerely grateful to them for sharing their truthful and illuminating views on several issues related to the work.

I wish to express my gratitude to my project supervisor Dr. A T M Hasan Zobeyer, Associate Professor, Department of Water Resources Engineering, BUET for his constant guidance, inspiration and valuable advice at all stages of the study.

I wish also to thank Dr. Md. Sabbir Mostafa Khan, Professor, Department of WRE, BUET and Dr. K. M. Ahtesham Hossain, Assistant Professor, Department of WRE, BUET who were the members of the Board of Examiners. Their valuable comments on this project are duly acknowledged.

I am very grateful to Prof. Dr. M. Monowar Hossain, Executive Director, IWM, Mr. Abu Saleh Khan, Deputy Executive Director (Opn.), IWM and Dr. A.F.M Afzal Hossain, PEng, Deputy Executive Director (P&D), IWM for granting me with necessary data, information and modelling tools of IWM to carry out this research work.

I am thankful to Mr. Goutam Chandra Mridha, Senior Specialist, Irrigation Management Division, IWM and Mr. Md. Salahuddin, Senior Specialist, Irrigation Management Division, IWM for their constant guidance, support and valuable advice during the study.

Finally, I am grateful to almighty Allah.

ABSTRACT

Bangladesh is an agricultural based and densely populated country of south Asia. It relies heavily on the domestic crop production. Her economy rolls upon the agricultural production across the country. Naogaon district located in the north west region of the country lacks industrialization. Crop production is the main profession of the people which is rice based. Dry period rice covers the maximum area and needs higher irrigation. Surface water sources like rivers are limited and cannot meet the demand of irrigation. For these reasons the irrigation is dependent on groundwater. To meet the irrigation demand in dry period huge numbers of STW and DTW are used. Due to over abstraction and less in recharge the extent of area with lowered groundwater level is increasing. Therefore, in this study the effect of change in cropping pattern with low water consuming crop has been investigated to maintain sustainability of the agriculture in Naogaon district.

In this study MIKE SHE model has been simulated from year 2002 to 2015. The model has been calibrated for the period 2011 to 2014 and validated for 2015. An analysis of temporal and spatial variation of groundwater level indicates that in this district dry period area coverage of groundwater level of 0 to -7 m has been reduced from forty seven percent in year 2002 to twenty six percent in year 2015. In year 2002, groundwater level in this upazila Patnitola, Niamatpur was -7 to -14 m for ninety percent which also indicates stress condition. In year 2015, groundwater level in this two upazilas was bellow -20m. Groundwater level in Mohadevpur upazila was within -7 to -14 m for 50% area in 2002. But in year 2015 groundwater level in this upazila reduced significantly and went bellow -20 m for ninety percent area.

In order to improve the groundwater condition in Naogaon district three different cropping pattern such as (50% boro & 50% wheat) [Option-1], (100% wheat) [Option-2] and (50% boro & 50% vegetable) [Option-3] have been investigated by simulating groundwater level using MIKE SHE model from year 2011 to 2015. The result shows that cultivating wheat instead of Boro improve the groundwater level significantly in year 2015. This groundwater level is almost same as the dry period groundwater level in 2005.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

1-D	1-Dimensional
2-D	2-Dimensional
AEZ	Agro-Ecological Zone
BBS	Bangladesh Bureau of Statistics
BIWTA	Bangladesh Inland Water Transport Authority
BM	Bench Mark
BMDA	Barind Multipurpose Development Authority
BOD	Biological Oxygen demand
BRAC	Bangladesh Rural Advancement Committee
BTM	Bangladesh Transverse Mercator
BWDB	Bangladesh Water Development Board
CA	Catchment Area
CBN	Cost of Basic Need
CWR	Crop Water Requirement
DAE	Department of Agriculture Extension
DEM	Digital Elevation Model
DHI	Danish Hydraulic Institute
DOE	Department of Environment
DOF	Department of Fisheries
DPHE	Department of Public Health Engineering
DTW	Deep Tube Well
EGL	Existing Ground Level
EIA	Environmental Impact Assessment
ETO	Potential Evapotranspiration
FAO	Food and Agricultural Organization
FAP	Flood Action Plan
FCDI	Flood Control, Drainage & Irrigation
FGD	Focal Group Discussion
GIS	Geographical Information System
GOB	Government of Bangladesh
GPS	Global Positioning System
HD	Hydro dynamic
HH	Household
HYV	High Yielding Variety
IECs	Important Environmental Components
IUCN	International Union for Conservation of Nature
IWM	Institute of Water Modelling
LAP	Land Acquisition Plan
LGED	Local Government Engineering Department
LLP	Low Lift Pump
LRP	Land Requisition Plan
LV	Local Variety
MPO	Master Plan Organization
MSL	Mean Sea Level

ABBREVIATIONS

NAM	Nedbør-Afstrømnings-Model (meaning precipitation-runoff-model).
NAP	National Agricultural Plan
NCA	Net Cultivable Area
NEMAP	National Environmental Management Action Plan
NWMP	National Water Management Plan
OL	Overland Flow
PWD	Public Works Datum
Q	Discharge
RAP	Resettlement Action Plan
SAAO	Sub Assistant Agricultural Officer
SLWL	Standard Low Water Level
SMonP	Social Monitoring Plan
SMP	Social Mitigation Plan
SoB	Survey of Bangladesh
SoL	Start of Line
SRDI	Soil Resource Development Institute
STW	Shallow Tube Well
SW	Surface Water
SWR	Scheme Water Requirement
SZ	Saturated Zone
T. Aman	Transplanted Aman
TBM	Temporary Bench Mark
UZ	Unsaturated Zone
WARPO	Water Resources Planning Organization
WGS 84	World Geodetic System-1984
WL	Water Level

CHAPTER 1

INTRODUCTION

1.1 General

Bangladesh is an agricultural and densely populated country of south Asia. It relies heavily on the domestic crop production to feed her 160 million inhabitants. Her economy rolls upon the agricultural production across the country. Irrigation is an important aspect for crop yield. Bangladesh has a land area of about 14.4 million ha of which 9.03 million ha (64%) are under cultivation. Irrigation is currently available to less than 50% of the land that can be irrigated in the Rabi season. Irrigation has revolutionized rice production in Bangladesh. However, limited irrigation is used for non-rice crops. The rice crop alone occupies 90-95% of the irrigated area and only 5-10% is left for other crops. Cultivation of High Yield Varieties (HYV) rice (boro) during the dry season is almost entirely dependent on irrigation water. The contribution of groundwater has increased from 41% in 1982-83 to 77% in 2006-07 and surface water has declined accordingly. The ratio of groundwater to surface water use is much higher in northwestern districts of Bangladesh compared to other parts of the country. All the rivers and channels of the area become dry during the dry season and make the people completely dependent on groundwater.

Water is a renewable resource and the availability of water is complicated because of its uneven distribution over the localities (FAO, 2012). Evaporation and precipitation are work together to replenish our fresh water supply constantly and quickly (Altaner, 2012). Groundwater is the largest source of usable, fresh water in the world (Subramanya, 1994; Chow, Maidment and Mays, 1988). In many parts of the world, domestic, agricultural and industrial water needs are being met using groundwater; where surface water supplies are not available (Siebert and D"oll, 2010). In Bangladesh, contribution of groundwater has increased from 38% to 79% and surface water has declined from 62% to 21% during 1985 to 2008 (Shaw et. al., 2011). The ratio of groundwater to surface water use is much higher in north-western districts of Bangladesh compared to other parts of the country (Shahid and Behrawan, 2008). More than 90% of the population in Bangladesh relies on groundwater; about 97 percent rural people are using over 10 million hand tube wells to fulfill their drinking water needs (Amin, 2009).

This groundwater based irrigation system of the country is now threatened due to lowering of groundwater table. In recent years, due to over abstraction, the groundwater in north-western region of Bangladesh is lowering at an alarming rate. Lowering of groundwater table during dry months is a serious issue to operate shallow tubewell, hand tubewell and dug wells. In addition, many ponds and tanks become derelict due to lowering of groundwater table which creates water shortage for domestic use as well as for the livestock population (NWMP, 2001). The ground water level declined substantially during the last decade causing threat to the sustainability of water use for irrigation in the region and also affecting other sectors (Jahan et. al., 2010). In greater Rajshahi area, extraction exceeds recharge and groundwater table declined 3 meters between 2004 and 2010 (Luby, 2013). Declination of water table affects water quality; specially arsenic is a function of water depth (Harvey et.al., 2006).

In the north-west region of Bangladesh, tubewell intensity is increased from 6.9 to 36 per square kilometer, deep tubewell almost doubled, shallow tubewell reached more than five times higher and irrigated land increased 1.6 times between 1984-85 and 2010-2011 (Dey et.al., 2013). According to Bangladesh Bureau of Statistics, population of Bangladesh increased from 28.93 million in 1901 to 149.77 million in 2011. More use of irrigation water especially groundwater has contributed to increase in crop productivity in Bangladesh. Rice yield for example, increased from 1.0 MT/ha in 1971/72 to 2.8 MT/ha in 2008/09. Much of this increase in yield was due to an increase in the share of rice area especially during the boro season which increased from 10% in 1971/72 to 44% in 2006/07. Rajshahi division reported the highest percentage (27.22%) of households with Hybrid boro cultivation. In the next 25 years, food demand of the country is expected to increase by 29% (NWMP, 2001). Uses of land and water resources particularly ground water that have evolved overtime to sustain agricultural production and meet the growing demand of increased population. In addition of major surface water diversion, added pressure on groundwater will lead to further depletion of sources. The National Water Management Plan considered an expected increase in irrigation demands by at least a quarter over the next 25 years (NWMP, 2001).

Now, it is becoming an alarming issue to fulfill irrigation and domestic water demand that will gradually increase in future. Change in crop pattern could be the probable option to sustain water level within limit. In Bangladesh, wheat ranks second position in respect to land having an annual production of 0.976 million tons and total area of 0.56 million hectares (BBS, 2005). The water requirement for boro rice is much higher than that of wheat. The water requirement of wheat is only 25-33% of boro rice (BARI, 1990). The production cost of wheat is also less than that of boro rice. (Dey N.C. et.al 2013) claims that, in the context of sustainability of groundwater use for irrigation, wheat production has to be emphasized in north-west region of Bangladesh.

Naogaon district is selected as the study area, a north-western district which is characterized for groundwater depletion in the recent years due to increasing trend of water use. The current study is attempted to identify the stress on groundwater table both at spatial and temporal scale and change in crop pattern to reduce the stress of groundwater Naogaon district.

The model area has an area of 4787 sq.km. extending over Atrai, Badalgachi, Dhamoirhat, Manda, Mahadebpur, Naogaon Sadar, Niamatpur, Patnitala, Porsha, Raninagar and Sapahar Upazilas of Naogaon District, partly of Tanore, Mohonpur, Puthia, Natore Sadar upazila of Rajshahi district and Gomostapur, Nachole upazila of Chapai Nawabganj district. It lies in the Barind tract. A base map of the study area shown in Figure 1.1. The area is located in the north-western region of Bangladesh which is very different from other part of the country. The area is the driest part of Bangladesh where mean monthly average rainfall from November to April varies only from 12 mm to 20 mm, although the annual rainfall varies from minimum of 1250 mm to a maximum of 2000 mm (IWM 2012).

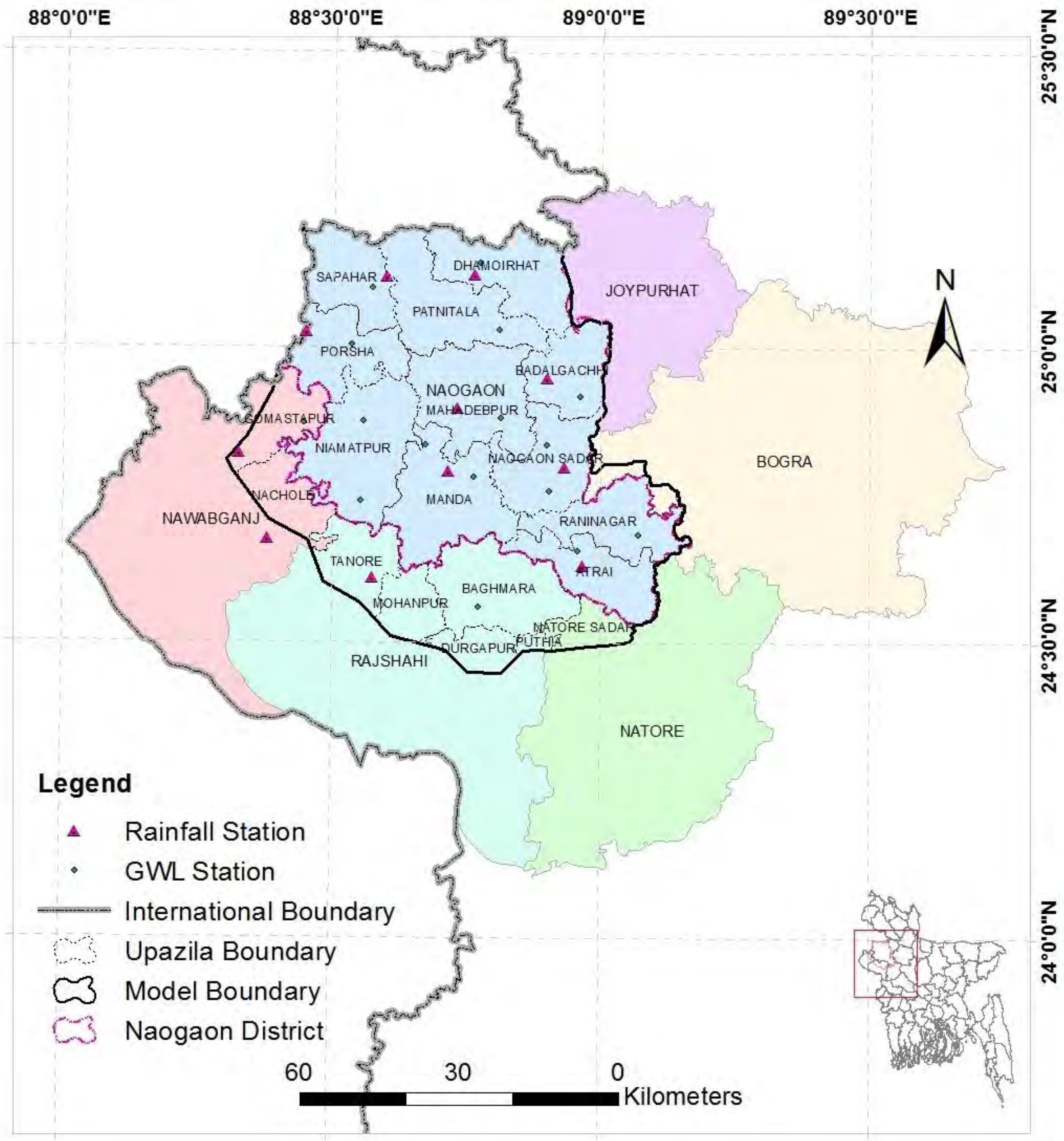


Figure 1.1: Base Map of the Study Area

1.2 Objectives of the Study

The study is conducted to understand the groundwater resources and impact of different cropping pattern on groundwater of Naogaon district. Objectives of the study are as follows:

1. To simulate groundwater level for 2011 to 2015 using calibrated MIKE SHE model.
2. To identify the over stressed zones for groundwater through spatial and temporal groundwater level variation for dry and wet period during 2002 to 2015.
3. To simulate the MIKE SHE model for different cropping pattern.

4. To investigate the effect of different crop pattern on groundwater level.

1.3 Structure of the Report

This report represents the total achievement carried out under the study. It is comprised of six chapters including a list of references in the report.

Chapter 1 focuses on the report background, brief description of the existing problems and bottlenecks, justification of the study and study objectives.

Chapter 2 present the brief summary of the modelling background, MIKE SHE hydrologic model simulation and previous studies related to this study.

Chapter 3 contains the data requirements for MIKE SHE groundwater model.

Chapter 4 presents the general approach and methodology that has been applied during the modelling works. It includes development of model, calibration and validation of the model.

Chapter 5 reflects the result and analysis of the modelling works from simulated data. It includes different output of the study such as groundwater level spatial and temporal variation, crop pattern change and effect of different cropping pattern on groundwater levels.

Chapter 6 presents the conclusions and recommendations.

CHAPTER 2

LITERATURE REVIEW

2.1 Researches Related to Groundwater Resources of the Study Area

In the surrounding of the study area, a significant number of studies on groundwater resources, water demand, land use for crop pattern, extension of crop intensity and their effects on groundwater level were done. The available study reports, project documents, published scientific articles have collected and reviewed to get information on the study area & corresponding groundwater resources prior to this study. Some of the important studies are briefly described below.

UNDP-BWDB, 1982 investigated the hydrogeologic conditions of Bangladesh. During this study, countrywide general groundwater survey has been carried out. Observation wells were set up, test, shallow and deep borings were drilled and aquifer tests were conducted. Specific study areas were selected to collect more intensive hydro geological data. Based on these data, and existing data of geology and climate, hydro-geological conditions of the country on broad basis were studied. Geologic cross-sections were drowned, hydraulic properties were determined, water quality except arsenic was studied and minimum and maximum groundwater recharge were determined from climatic data and assumed value of runoff and field capacity of soil profile. Contour map of transmissivity of main aquifer was prepared. Potential groundwater development areas were identified based on 1) annual volume of recharge, 2) capacity of the system to act as a long term storage reservoir, 3) energy source for the pumping lift and 4) water quality. According to this report the study area has limited thick sandy aquifer especially in the high Barind area and transmissivity-value ranges 500m^2/day to 1500m^2/day. Annual recharge varied from a minimum of 80 mm to a maximum of 190 mm. This study was based on limited data for generalized appraisal of hydro-geologic condition of the country and therefore, needed a detailed study of available ground resources of the area for formulation of the project for groundwater resource development.

MacDonald, (1983) described brief geological description, infiltration rate, permeability range, storage range, water level fluctuations and development potential of the study area. The study was based on data analysis and water balance study. The study was based on existing data analysis and water balance study. The study area consists of mainly three aquifer units namely Sibganj of 1200 sq km, High Barind Area of 3634 sq km and Little Jamuna of 980 sq km.

Aquifer at Sibganj has been classified as semi-confined. Infiltration rate is 1.7 mm/day in wetland and 12 mm/day in dry land. Permeability ranges from 30 to 60 m/day with an average of 40 m/day. Specific yield of upper layer is 6%. Drilling of DTW is no constraints except deep flooded areas. At High Barind area, aquifer has been classified as semi confined and multi-layered. Infiltration rate is 1.5 mm/day in wetland and 7.5mm/day in dry land. Permeability ranges from 25 to 40 m/day with an average of 30 m/day. Specific yield of upper layer is approximately 4%. Semi-confined, most water derived from leakage. Drilling of DTW is not promising because of large depth to poor aquifer and fine material will require special designs. Recharge could also be a limiting factor; trial borings recommended. At Little Jamuna area, aquifer has been classified as unconfined to semi confined. Infiltration rate is 1.5mm/day in wetland and 5mm/day in dry land. Permeability ranges from 50 to 80 m/day with an average of 65 m/day. Specific yield averages 5%. Semi-confined. Good potentials for drilling of DTW in this area. Recharge is unlikely to hinder development.

Asaduzzaman M, 1983 in this report highlighted successes and problems of drilling deep tubewell (DTW) and recommendations for actions to facilitate drilling of DTW. The reports contains a table of thana-wise recommended no of DTW for 45% development level as per "Northwest Bangladesh Groundwater Modelling Report," a table of well fixtures, discharge and draw down of tubewells drilled during 1982-1983, a table of thana-wise fluctuation ground water level (average) in the month of March 1981 and 1983 and comparison, a table of rainfall and bore log and construction sheet of DTW. These information and data are found to be very useful to develop database for model study.

NWMP, 2001 Preparation of National Water Management Plan to monitor activities within all water related sector, to provide information and to advice on best practice on water related issues in Bangladesh. With the estimation and prediction of the water resources in all sectors, water demand in dry period has been estimated and predicted for future 25 years. Study assessed, the main determinant in overall demand for water resources in the future is the growth of irrigation demand. As per study, water supply for urban and rural domestic & commercial use will be more than twice as before and irrigation demand are expected to increase potentially by at least a quarter (1/4) over the next 25 years.

IWM, 2006 studied the overall water resources of the study area for an efficient planning and management of the resources for deep tubewell installation. For the assessment and future development of groundwater resources an integrated hydrological model has been developed describing the condition in the unsaturated and saturated zone of the subsurface together with rainfall, overland flow, evapotranspiration and the condition of flow in the river. The major findings of the study are:

The sources of groundwater recharge in the study area are mainly rainfall; floodwater and return flow of irrigated water. Generally, recharge from rainfall starts in the month of May and continues to the end of October. In low Barind area, there are lots of depressions, where excess rainwater is stored during monsoon. This water is available as vertical recharge for recharging groundwater after meeting the demand of evapotranspiration after October. Thick clay layer at the top in some parts of the study area restricts the percolation of rain and floodwaters. Geological structures up to 80 m depth have been studied.

Maximum depth to groundwater table occurs at the end of April mainly due to irrigation abstraction and natural drainage. In case of average year rainfall condition, this maximum depth to groundwater table remains in the range between 2.0 m to 15.0 m in most of the study area. Some of the places in high Barind areas go below 20.0 m depth. Suction mode tubewells will not operate in these areas where, groundwater table remains below 7.0 m.

It has also been observed that during peak time, groundwater table almost regains to its original positions except some areas of some Upazilas. This indicates that aquifers in those locations have potential of groundwater recharge and further scope for development. However groundwater table does not regain to its original positions in some areas of Tanore, Dhamoirhat, Godagari, Gomastapur, Patnitala, Mahadevpur, Niamatpur and Nachole Upazilas. This is mainly due to substantial use of groundwater in monsoon period and over drainage in the vicinity of the Ganges and Mohananda river during dry period. In these areas, recharge is less compared to the total abstractions and drainage.

The potential recharge of the present study varies from 357 mm to 725 mm. In the present study, total potential recharge in the project area is 13156 mm, while in the MPO study it is 10002 mm and in the NWMP study it is 11855 mm. Potential recharge of IWM study is 10% higher than NWMP study and 24.1% higher than MPO study. Potential recharge of this study is mainly higher in low Barind area compared to NWMP and MPO study. The variation of results is due to variation in approaches and parameters used. IWM considered entire physical processes that exist in the hydrological cycle using distributed modelling approach.

Useable recharge for Barind area has been estimated to a total of 9867 mm, while 7623 mm net irrigation requirement for Boro cultivation has been estimated in this area. The study confirms that in Barind area, total useable recharge is higher than total net irrigation requirement for Boro cultivation. However, Upazila wise comparison shows resource constraints for only Boro cultivation in Dhamoirthat, Mohadebpur and Tanore Upazilas. In addition to these three Upazilas, resource constraints are also observed in Niamatpur and Patnitala Upazilas, if supplementary irrigation from groundwater is considered. In addition to the existing tubewell, total 6533 numbers of 1-cusec capacity of DTW (80% efficiency) can be installed in different Upazilas.

Estimation of spacing between two tubewells depend on recharge conditions, command area of the tubewell, crop water demand and hydraulic properties of the aquifer. Upazila wise spacing of different capacity of tubewells have been estimated and it can be seen that the spacing of 2 cfs to 2 cfs tubewell varies from 446 m to 628 m, 2 cfs to 0.5 cfs varies from 317 m to 447 m and 0.5 cfs to 0.5 cfs varies from 203 m to 266 m in Barind area.

Akram, 2009 MIKE SHE and MODFLOW have been used to simulate the regional groundwater flow in the high Barind area of NW Bangladesh. The study area was about 2236 km^2 which cover 9 upazilas in Rajshahi, Naogaon and Nawabganj Districts. Simulation shows that recharge occurs mainly due to rainfall, while the contribution of irrigation (in the winter) is very negligible. Upazila wise groundwater resources have been assessed based on safe yield criteria, where groundwater table would be replenished every year. The main difference between the two models is that MIKE SHE includes unsaturated zone, so it calculates infiltration, actual evapotranspiration and recharge from their physical laws. On the other hand MODFLOW deals with saturated zones only. So, in case of groundwater flow study where irrigation is not present, MODFLOW can be used. Otherwise MIKE SHE will be more appropriate. Study use only MIKE SHE hydrologic model to assess groundwater resource & MIKE SHE result shows that the available groundwater resources (before irrigation starts) vary in the range of 180 mm in Tanore upazila to 913 mm in Nawabganj Sadar upazila. Usable resources have been assumed as 90% of the available resources as there are some natural losses set out the study area during irrigation season.

Islam, 2009 this study area covered three upazilas of Rajshahi District. It has been observed from the study that, the gain of groundwater from river to aquifer occurs only for a short period from July to September. On the contrary loss of groundwater from aquifer to river occurs for a longer period from October to June. The magnitude and duration of groundwater loss from aquifer to river is higher in upper part than in lower part of the study area. During the study period the yearly average lateral groundwater outflow from aquifer to river was estimated as 0.29 Mm^3 per kilometer varies from 0.20 Mm^3 to 0.45 Mm^3. The trend of lateral outflow from groundwater (aquifer to river) has been increasing over the years.

Dey et. Al,. 2013 this study conducted on Sustainability of Groundwater Use for Irrigation in North-West Bangladesh under National Food Policy Capacity Strengthening Programme implemented by FAO in collaboration with FPMU/Ministry of Food and Disaster Management with financial support of EU and USAID. Objective of the study was to quantitatively assess the trends in water table depths and crop areas in the designated study area for the past 30 years. Financial & economic profitability of different crops along with likely changes over time due to decline of water tables. Recommend policies for sustainable use of irrigation water in northwestern Bangladesh. The study area was five north-western districts of Bangladesh as Rajshahi, Pabna, Bogra, Rangpur and Dinajpur. Sample survey conducted through structured questionnaire, focus group discussion, consultation meeting and workshops have been done for this study. Secondary data have been collected from BWDB, BMDA, BADC and BBS. Study shows, within 10 major crops area, boro alone increased more than 9 times during 1980/81 to 2009/10. Study suggested according to crop pattern and benefit-cost ratio (BCR), wheat, potato, maize, mustard and these types of less irrigation demand crops should be emphasized in future.

IWM, 2013 Deep Tubewell Installation Project Phase II, of Barind Multipurpose Development Authority (BMDA) covers 65 Upazilas of Pabna, Sirajganj, Bogra, Gaibandha, Rangpur, Kurigram, Nilphamari and Lalmonirhat districts having gross area of 17, 455 km^2 and cultivable area of 12, 765 km^2. The objectives of this project was to assess upazila wise groundwater resources and recharge potential; surface water resource assessment; additional number of required DTWs. To fulfill the above objectives an extensive field data collection program was taken which includes test drilling, aquifer test, topographic and cross section survey, water quality test land water level measurement. Accordingly hydrogeological investigation upto 150m depth was conducted at 8 locations and 10 numbers of aquifer test were completed up to interim report. A model up to the depth of 80m was developed and a number of options were simulated to see the impact of irrigation expansion as well as impact due to climate change. It was found that within the study area, groundwater table (GWT) was from 1 to 13m from ground surface in dry period. In some areas of Bogra, Sirajganj & Pabna, groundwater level went below suction limit of Hand Tubewell (HTW) & Deep Tara Set (DTS) and Shallow Tubewell (STW) became inoperable in that period, but in monsoon it was recharged fully. Transmissivity and Hydraulic conductivity of the study area was good and potential for groundwater development. Upazila wise groundwater resources were estimated through water balance analysis. In order to meet the future demand, it would be needed to install additional 14, 184 DTWs. It has been seen that due to climate change, the groundwater level may drop about 0.5 to 1.0m in some study areas. It was also identified that there is no separate aquifer in deeper strata up to 150m depth.

2.2 Developments of Hydrologic Model

Groundwater is an important part of full hydraulic cycle. There for to understand the groundwater movement a good understanding of the full hydraulic cycle is important. The science of hydrology began with the conceptualization of the hydrologic cycle. Some of the Greek philosophers correctly described some aspects of the hydrologic cycle. For example, Anaxagoras of Clazomenae (500-428 B.C.) formed a primitive version of the hydrologic cycle (e.g. the sun lifts water from the sea into the atmosphere). Another Greek philosopher, Theophrastus (circa 372-287 B.C.) gave a sound explanation of the formation of precipitation by condensation and freezing. Meanwhile, independent thinking occurred in ancient Chinese, Indian and Persian civilizations (Essink, 2000).

During the Renaissance, a gradual change occurred from purely philosophical concepts of hydrology toward observational science, e.g. by Leonardo da Vinci (1452-1519). Hydraulic measurements and experiments flourished during the eighteenth century, when Bernoulli's equation and Chezy's formula were discovered. Hydrology advanced more rapidly during the nineteenth century, when Darcy developed his law of porous media flow in 1856 and Manning proposed his open-channel flow formula (1891). However, quantitative hydrology was still immature at the beginning of the twentieth century. Gradually, empiricism was replaced with rational analysis of observed data. For example, Sherman devised the unit hydrograph method to transform effective rainfall to direct runoff (1932) and Gumbel proposed the extreme value law for hydrological studies (1941). Like many sciences, hydrology was recognized only recently as a separate discipline (e.g. in 1965, the US Civil Service Commission recognized a hydrologist as a job classification).

In nineties, the main subject in hydrological study was to recognize about how much water is available, how much can be extracted, what are the effects on piezometric heads, etc. The spectacular boom in computer possibilities during recent times makes hydrologic analysis possible on a larger scale. As a result, hydrologists have analyzed problems in more detail and with shorter computation intervals than before. Complex theories describing hydrologic processes have been applied using computer simulations. Also interactions between surface water systems and groundwater systems in terms of quality and quantity became within the reach of the hydrologist. Huge quantities of observed data have easily been processed for statistical analysis. Moreover, during the past decade, developments in electronics and data transmission have made possible to retrieve instantaneous data from remote recorders (e.g. satellites), which lead to the development of real-time programs for water management.

2.3 Basic Theory of Modelling

"A model is a simplified representation of a complex system." Modelling (also called simulation or imitation) of specific elements of the real world could help, considerably in understanding the hydrological problem. It is an excellent way to organize and synthesize field data. Modelling should contribute to the perception of the reality, yet applied on the right way. In fact, hydrological models should only be applied to help the user with the analysis of a problem, nothing more, nothing less. It is only part of the way to understand or percept a hydrological process.

In general, two main categories of models are widely used:

- A physical model or scale model, being a scaled-down duplicate of a full-scale prototype;
- A mathematical model; MIKE SHE is a mathematical model that is to be used in the current study.

Mathematical Model

A mathematical model is a model in which the behavior of the system is represented by a set of equations, perhaps together with logical statements, expressing relations between variables and parameters.

Classification (Figure 2.1) is based on the way the mathematical model is designed, e.g. how the model domain or problem area is schematized; what the characteristics of the data are (variables and/or parameters) and how they are utilized in the model.

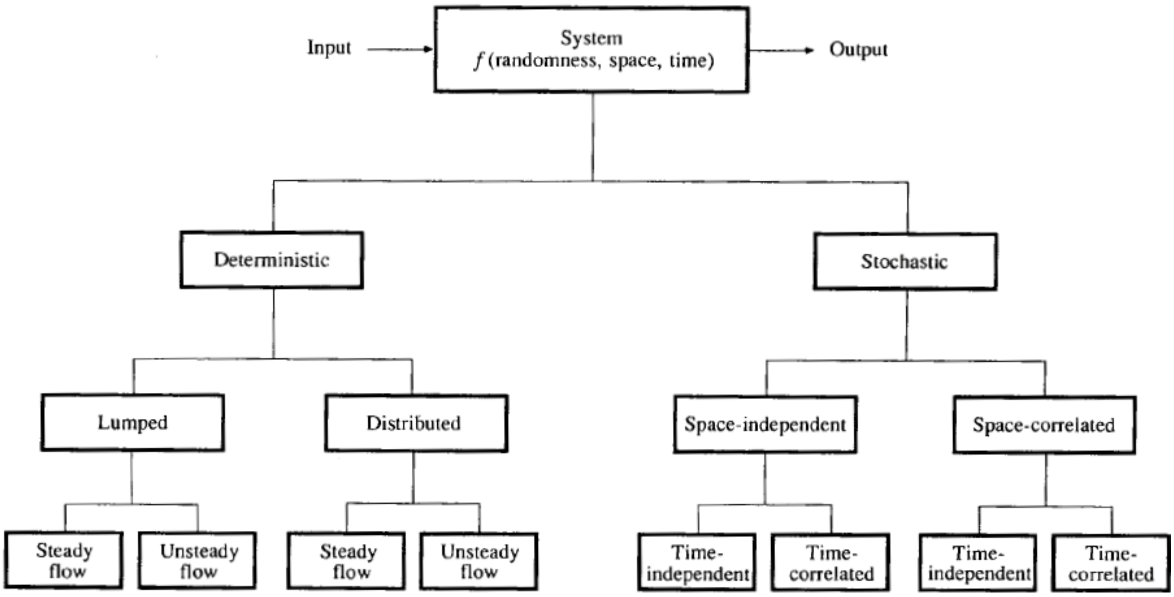


Figure 2.1: Classification of Hydrologic Models According to Chow, Maidment & Mays, 1988

Deterministic and Stochastic Model

A model is regarded deterministic, if all variables are regarded as free from random variation, or, if the chance of occurrence of the variables involved in such a process is ignored and the model is considered to follow a definite law of certainty and thus not any law of probability. A deterministic model is one that is defined by cause-and-effect relations. A deterministic model treats the hydrologic processes in a physical way. MIKE SHE is a deterministic model.

A model is regarded stochastic, if any of the variables are regarded as random variables, having distributions in probability.

Lumped and Distributed Model

A lumped model neglects the spatial distribution in the input variables and the parameters in the model domain. A lumped model is a system with a particular quantity of matter, whereas a distributed model is a system with specified regions of space. For example, a lumped model treats variables, such as natural groundwater recharge, in the area of a catchment surface as a single (1D) unit, whereas a distributed model calculates the variables from one point in the area to another point (2D or 3D). MIKE SHE is a distributed model.

Empirical, Conceptual and Physically Based Model

An empirical model is based on observation and experiment, not on physically sound theory. In the empirical approach, physical laws are not taken into account. These models are often applied in inaccessible (ungauged) areas, where only little is known about the area involved.

A model is regarded as a conceptual model, if physical processes are considered which are acting upon the input variables to produce output variables. In the conceptual approach, an attempt is made to add physical relevance to the variables and parameters used in the mathematical function which represent the interactions between all the processes that affect the system. An example of simple conceptual models is the formulation of Darcy (law of porous media flow). Conceptual models are widely applied, as they are easy to use, apply limited input data, and can always be calibrated.

A physically based model is based on the understanding of the physics of the processes involved. They describe the system by incorporating equations grounded on the laws of conservation of mass, momentum and energy. The parameters of a physically based model are identical with or related to the respective prototype characteristics (e.g. storage capacities, transmissivities). Physically based models often apply deterministic and distributed input data. They can be applied in measured as well as unmeasured systems. Physically based models have the advantage that they have universal applications. The measured or estimated model parameters and hydrologic stresses (e.g. differences in natural groundwater recharge, human impacts such as groundwater extractions) can be adjusted in the input data file, so that the model is geographically and climatically transferable to any other area. MIKE SHE is a physically based model.

Common Physically Based Model

Physically based hydrological model MIKE SHE and MODFLOW, are widely used. The main difference between the two models is that MIKE SHE includes unsaturated zone, so it calculates infiltration, actual Evapotranspiration and recharge from their physical laws. On the other hand MODFLOW deals with saturated zones only. So, in case of groundwater flow study where irrigation is not present, MODFLOW can be used. Otherwise MIKE SHE will be more appropriate.

2.4 MIKE SHE Hydrologic Model

MIKE SHE is an advanced, flexible framework for hydrologic Modelling. From 1977 onwards, a consortium of three European organizations: the Institute of Hydrology in the United Kingdom, SOGREAH in France, and the Danish Hydraulic Institute in Denmark have developed MIKE SHE. The integrated hydrological Modelling system of MIKE SHE is shown in Figure 2.2. MIKE SHE has proven valuable in hundreds of research and consultancy projects covering a wide range of climatological and hydrological regimes (Graham and Butts, 2005).

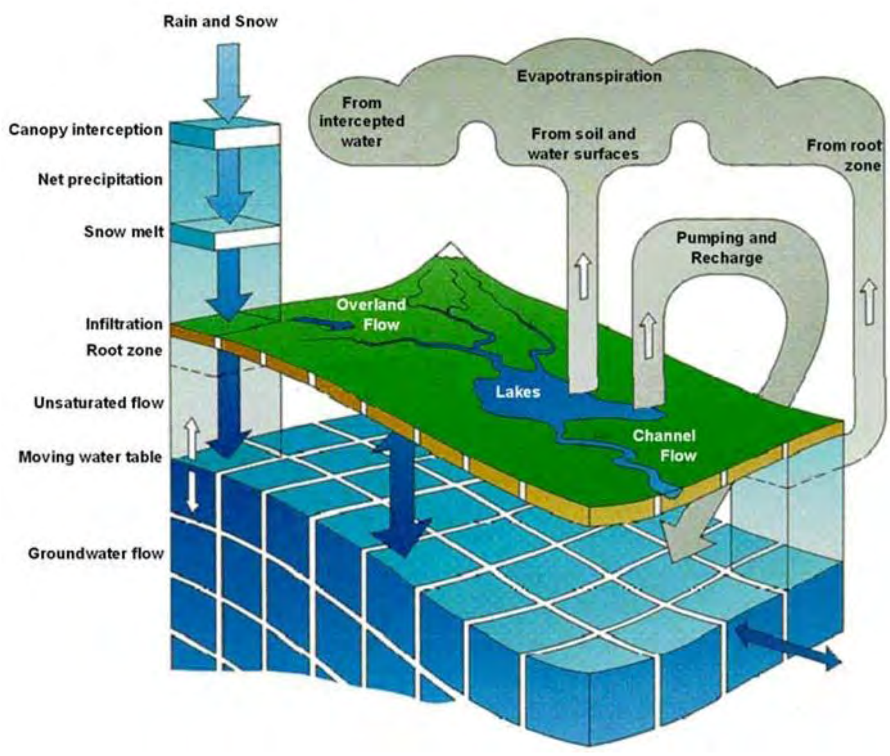


Figure 2.2: Hydrologic Processes Simulation by MIKE SHE Hydrologic Model (DHI, 2016)

MIKE SHE, in its original formulation, could be characterized as a deterministic, physics-based, distributed model code. It was developed as a fully integrated alternative to the more traditional lumped, conceptual rainfall-runoff models. A physics-based code is one that solves the partial differential equations describing mass flow and momentum transfer. The Saint Venant equations (Chow, Maidment and Mays, 1988) for open channel flow and the Darcy equation (Chow, Maidment and Mays, 1988) for saturated flow in porous media are physics-based equations.

The process-based, modular approach implemented in the original SHE code has made it possible to implement multiple descriptions for each of the hydrologic processes. In the simplest case, MIKE SHE can use fully distributed conceptual approaches to model the watershed processes (Figure 2.3). MIKE SHE hydrologic model consider the variables as precipitation and evapotranspiration, unsaturated flow, overland flow and saturated groundwater flow.

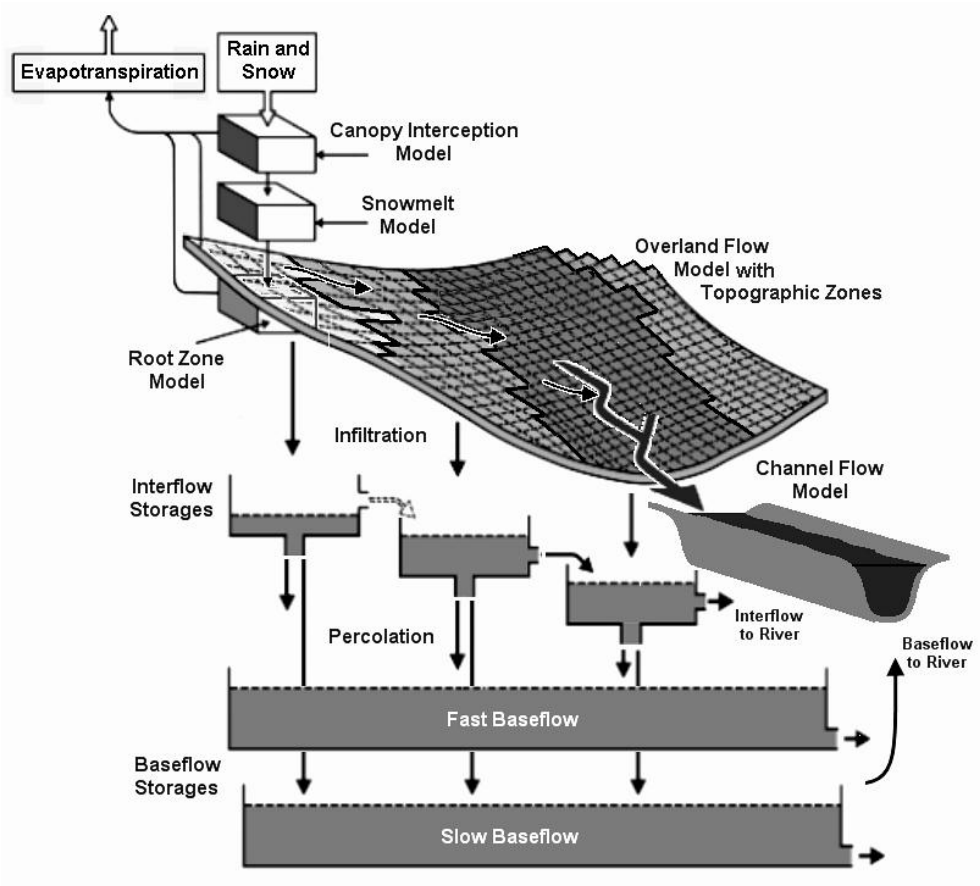


Figure 2.3: Schematic Representation of the Conceptual Components in MIKE SHE Hydrologic Model (DHI, 2011)

Precipitation and Evapotranspiration

Precipitation is usually a direct input in MIKE SHE, whereas radiation and water vapor transport in the atmosphere is typically bound up in Evapotranspiration (ET). Evapotranspiration refers to the sum of the processes of direct evaporation from free water surfaces and transpiration of sub-surface water either directly or via plants. Evapotranspiration is an important component of the water balance. Evapotranspiration can be 70% of rainfall in temperate climates and even exceed annual rainfall in arid areas (Bedient and Huber, 2002).

Unsaturated Flow

The unsaturated zone is usually heterogeneous and characterized by cyclic fluctuations in the soil moisture as soil moisture is replenished by rainfall and removed by evapotranspiration and recharge to the groundwater table. Unsaturated flow is assumed to be primarily vertical, since gravity dominates infiltration. Therefore, to reduce the computational burden, unsaturated flow in MIKE SHE is calculated only vertically.

Overland Flow

Ponded water can occur, for example, when rainfall cannot infiltrate fast enough, when groundwater flows onto the surface (e.g. in wetlands), or when streams flood over their banks. Ponded water is routed downhill as surface runoff. The flow path and quantity is determined by the topography and flow resistance, as well as losses due to evaporation and infiltration along the path it takes. Water flow on the ground surface is calculated using a semi-distributed, slope-zone approach based on the Mannings equation (Chow, Maidment and Mays, 1988).

Saturated Groundwater Flow

Groundwater plays a significant role in the hydrological cycle. During drought periods groundwater discharge sustains stream flow. Irrigation and abstraction can influence natural recharge and discharge, thereby changing the flow regime in a catchment. In MIKE SHE, the spatial and temporal variations of the hydraulic head in the saturated groundwater zone are described mathematically by the 3D Darcy equation (DHI, 2011).

CHAPTER 3

DATA COLLECTION

3.1 General

The study area is Naogaon district consisting of 11 upazilas is shown in Figure 3.1. The study area is bounded on the east by Nawabganj district and partly India, on the west by Joypurhat and Bogra district, on the north by India and on the south east by Rajshahi and Natore district. It lies between 24°32' and 25°13' north latitudes and between 88°20' and 89°10' east longitudes. According to BBS (2011), the total area of the study area is about 3435 sq km.

According to BBS (2011), the annual average temperature of this district varies maximum 37.8°C to minimum 11.2°C. The annual average rainfall is 1862 mm.

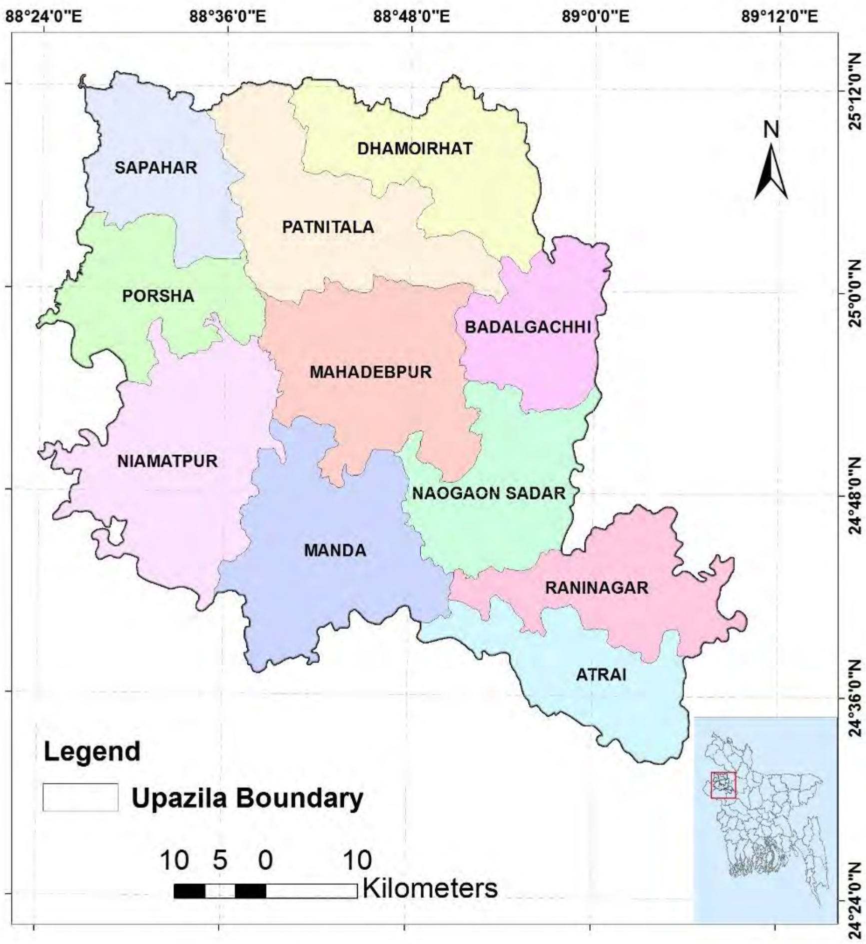


Figure 3.1: Map of the Study Area (Naogaon District)

3.2 Data Requirement for MIKESHE Hydrologic Model

According to the model requirements, significant amount of data have been collected from Institute of Water Modelling (IWM), Bangladesh Bureau of Statistics (BBS), Bangladesh Water Development Board (BWDB) and Bangladesh Agricultural Development Corporation (BADC). Significant numbers of input data have been taken directly from the project titled as "Groundwater Resources Study and Decision Support System Development of Rajshahi, Naogaon, Chapai Nawabganj, Pabna and Natore Districts and also Remaining Districts (Except Thakurgaon, Panchagarh, Dinajpur & Joypurhat Districts) of Rajshahi Division through Mathematical Model Study for Barind Integrated Area Development Project, Phase-III" (IWM, 2012).

Only BWDB stations data has taken to prepare MIKE SHE model in current study; there were available data that were collected from BWDB stations and used in the mentioned project (IWM, 2012). The data has to be used in this study after checking quality & consistency, and then processed as per required format for the model running. In addition to the data quality checking, data analysis has to be carried out for estimation of different model parameters. For the model development of MIKE SHE hydrologic model (Figure 3.2) the following data is required.

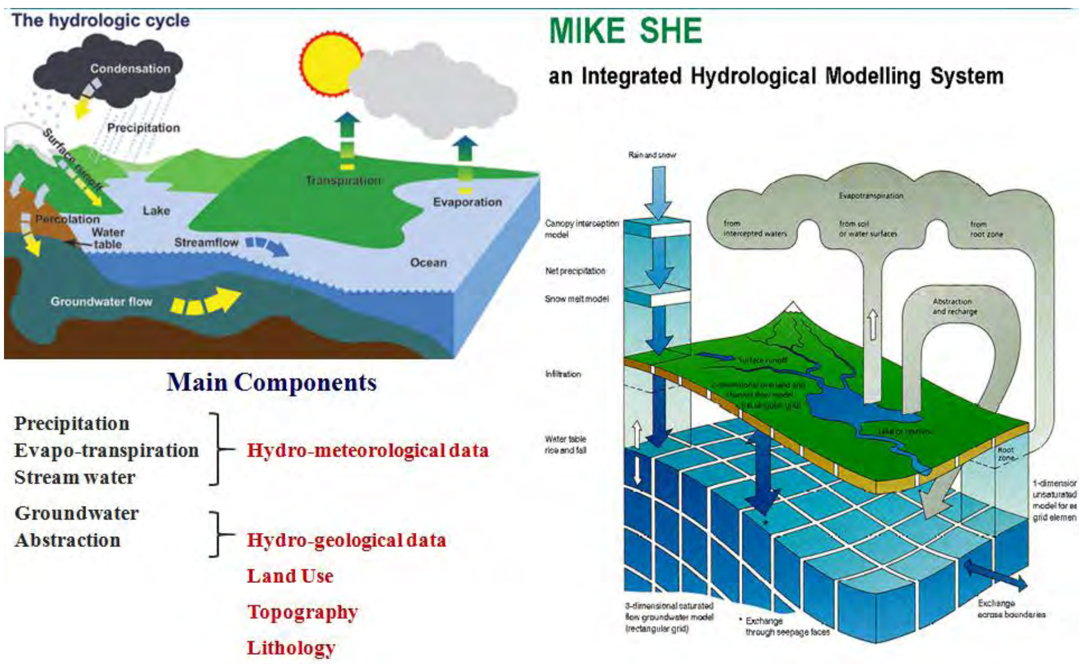


Figure 3.2: Schematic Diagram of MIKE SHE Hydrologic Model (DHI, 2016)

Data Requirements for MIKE SHE Hydrologic Model are as follows:

- Hydrometeorology of the study area i.e. precipitation, Evapotranspiration
- Hydrogeology of the study area i.e. groundwater level & abstraction data
- Land Use of the study area i.e. land use map & crop calendar throughout the year
- Topography of the study area
- Lithology of the study area including hydraulic properties of the aquifer

3.3 Hydrometeorology of the Study Area

Precipitation, Evapotranspiration, stream water level data are the main hydro-meteorological inputs for the groundwater model that is described below.

3.3.1 Precipitation

BWDB maintains 11 rainfall stations in and around the study area. Rainfall data for the period of 1980-2015 of the 11 stations have been collected from BWDB. List of these stations are given in Table 3.1. In general, most of the stations contain long time series data. However, there are certain gaps in the data record, which has been duly filled in using data from adjacent stations after carrying out necessary quality checking. Quality checking of rainfall includes visual observation of plots of rainfall, preparation of double mass curves, estimation of yearly mean values and comparison of monthly values. Double mass analysis reveals that rainfall data for most of the stations are consistent. After necessary consistency and quality checking, Rainfall data has been used in the model. It has been observed from the mean monthly rainfall of all the stations that, in the study area rainfall excess is for the period of May to October and rainfall deficit is for the period of November to April. A comparison of yearly sum of rainfall of Atrai, Badalgachi, Manda, Mohadevpur, Naogaon, Najipur, Nitpur and Sapahar stations has been given in Figure 3.3. There are eleven BWDB rainfall stations (Table 3.1) that have influence in the study area shown in Figure 3.4.

Table 3.1: Details of Rainfall Stations within Model Area (Source: BWDB)

Sl. No.	Station ID	Station Name	Duration
1	R219	Tanore	1980-2015
2	R192	Nitpur	-Do-
3	R211	Shapahar	-Do-
4	R208	Rohanpur	-Do-
5	R194	Nithpur	-Do-
6	R191	Naogaon	-Do-
7	R190	Nachol	-Do-
8	R187	Mohadevpur	-Do-
9	R185	Manda	-Do-
10	R152	Badalgachi	-Do-
11	R003	Atrai (Ashanganj)	-Do-

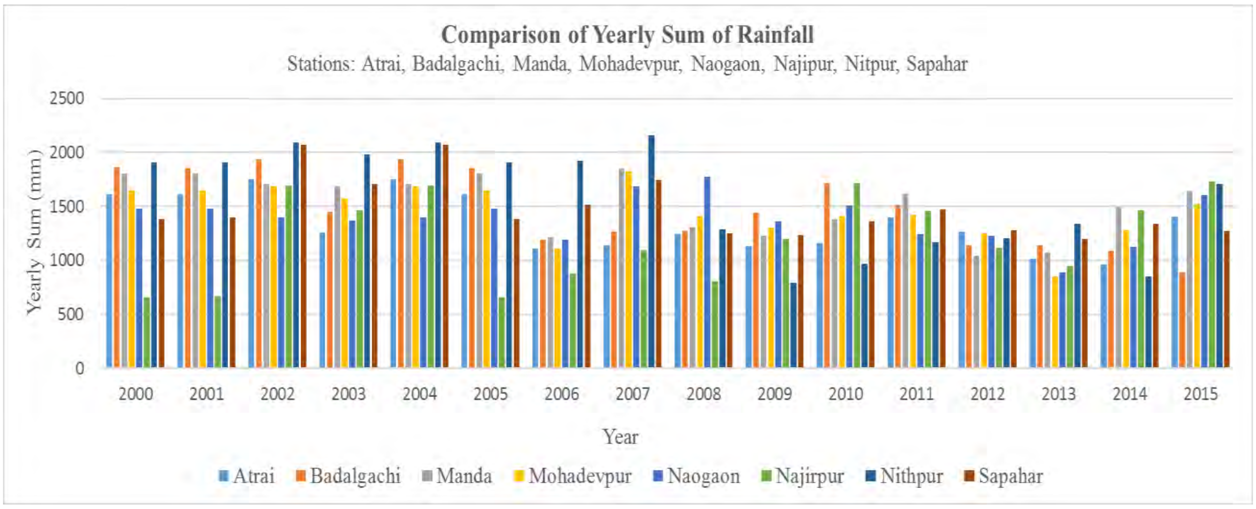


Figure 3.3: Annual Rainfall of Different Upazilas of Naogaon District

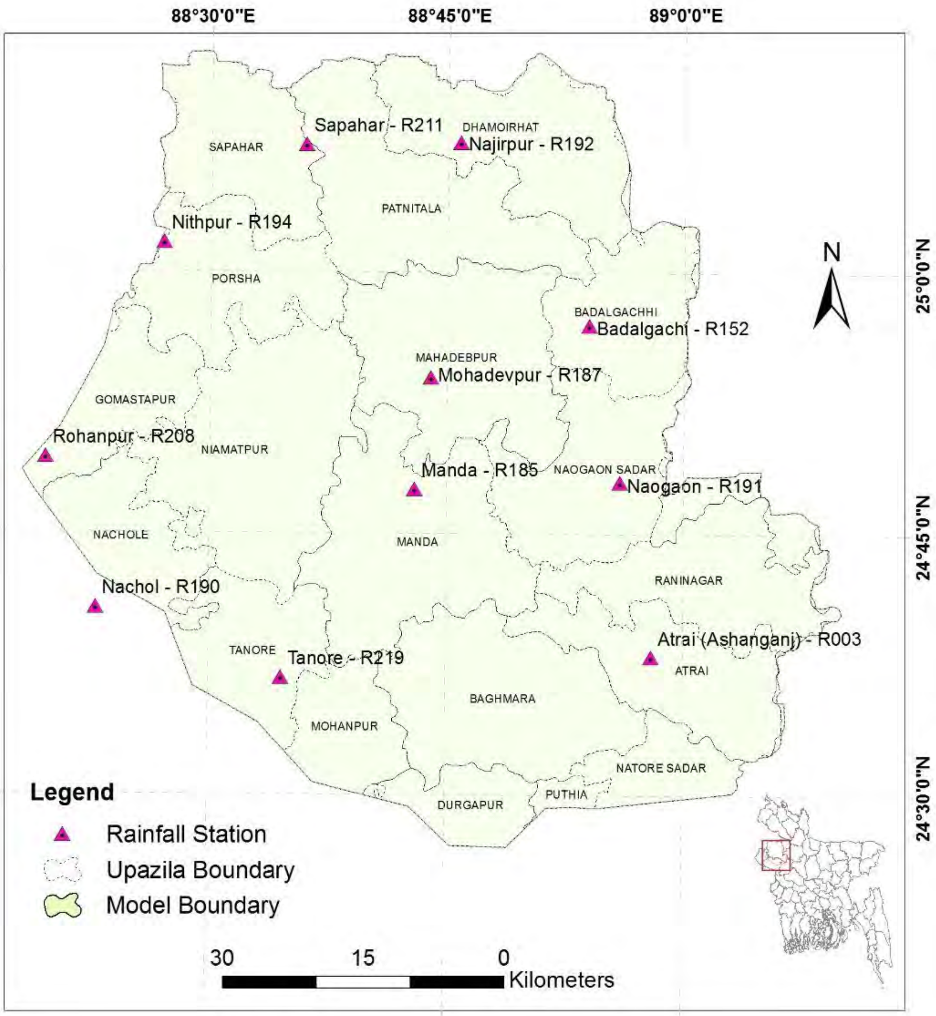


Figure 3.4: Rainfall Stations within/around the Model Area

3.3.2 Evapotranspiration

Evapotranspiration data have collected directly from the referenced IWM study (IWM, 2012). No evaporation station in the study area. For this nearest station, Rajshahi has been used for the study. Table 3.2 show the status of the data. It has been observed that there is relatively little variation of Evapotranspiration between the study area and outside the study area. It is due to the fact that important parameters such as temperature and sunshine hours are largely similar across the area (IWM, 2012). As such, data from one station has been used for the whole study area. The daily evaporation values outside the range of 2.0 - 7.0 mm have been considered as rejected.

Table 3.2: Evaporation Station in Rajshahi District (Source: BWDB)

Sl.	Station ID	Station Name	Data Availability
1	E44	Rajshahi	1990 - 2015

3.4 Hydrogeology of the study area

3.4.1 Groundwater Level

Groundwater observation level data is an important parameter for the groundwater model as it is used for calibration, boundary condition and initial condition of the model. There are 32 groundwater observation wells of BWDB is selected in the study area is shown in Figure 3.11. A sample plot of groundwater level has been shown in Figure 3.12. Among them 17 observation wells are on the study area boundary, which have used as boundary condition.

The frequency of measurement in the observation wells is generally conducted once in a week. The measured groundwater levels are expressed in terms of national datum, mPWD. Data has checked by visual inspection of those time series plots of groundwater levels and missing data is filled up by interpolation of nearby stations. However, topology, groundwater level fluctuation and rainfall pattern of those nearby stations are taken into consideration during filling the missing data.

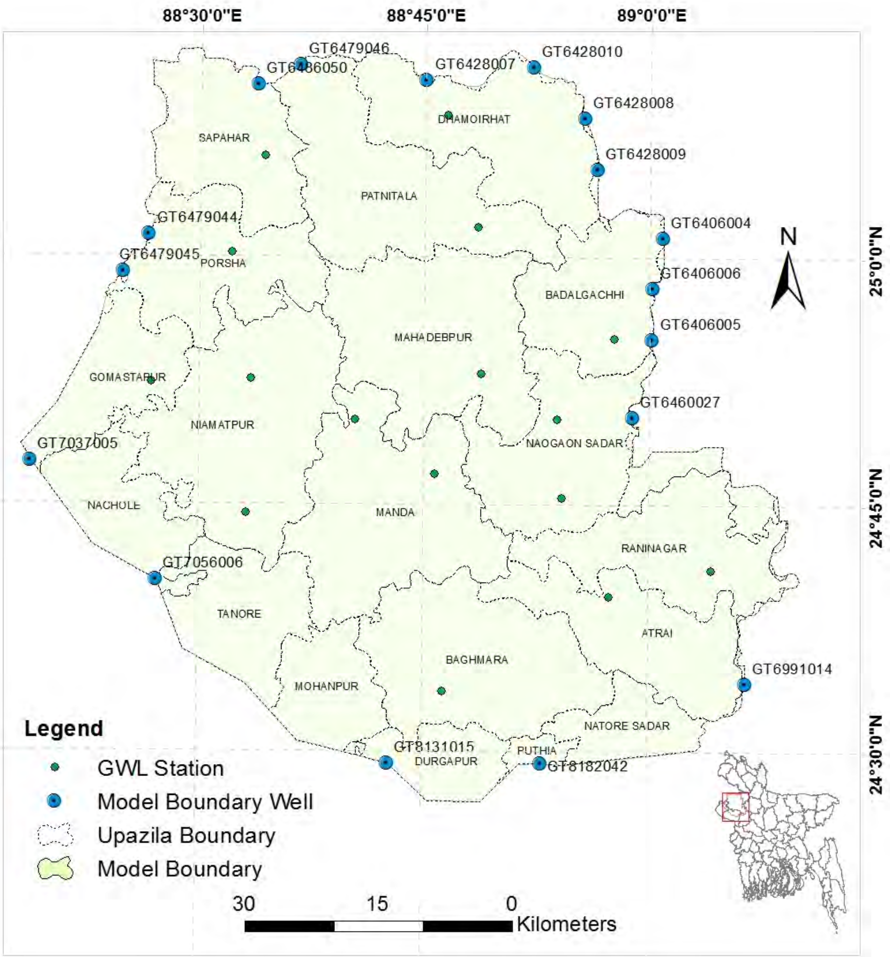


Figure 3.5: Groundwater Observation within the Model Area

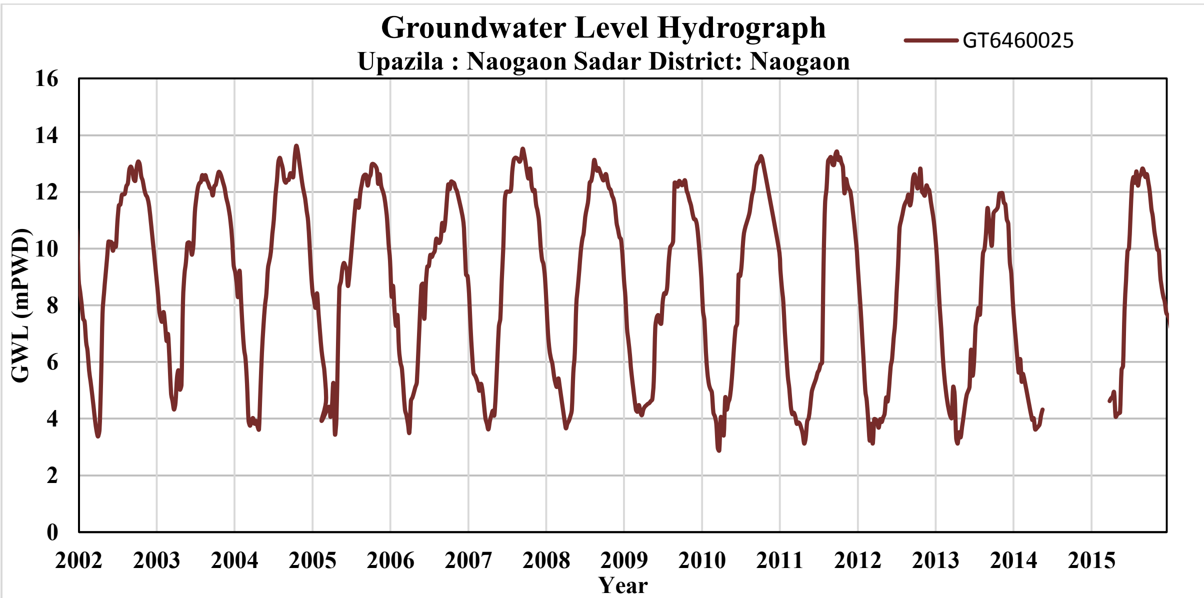


Figure 3.6: Groundwater Level Hydrograph

3.4.2 Borelog Data

Subsurface lithological characterization of the study area and configuration of the hydro-stratigraphic units for groundwater flow model has been prepared by analyzing sedimentary structure, lithology, thickness and depth of different aquifers. Total 2344 number of borelog and well logs distributed over study area have been reviewed which is shown in Figure 3.7. Considering lithological variations and groundwater flow capacity, hydro-stratigraphic units of the study area have been defined as Top Soil, Aquitard, Aquifer (upper & lower), Clay and Bottom. Accordingly, up to the studied depth (~80 m), total 5 hydro-stratigraphic units have been demarcated. Geological layers of having nearly similar properties and small thickness are merged together to define layers. It reveals from the hydro-stratigraphic analysis that within the studied depth upper aquifer and lower aquifer is interconnected. Clay middle is not continuous layer. In fact there is only one aquifer in the study area and the aquifer is unconfined in nature. Some reduce level of the bottom of the geological layers given in Table 3.6. The lithological cross section of geological layer for the model area shown in Figure 3.9, Figure 3.10 and section lines are shown in Figure 3.8.

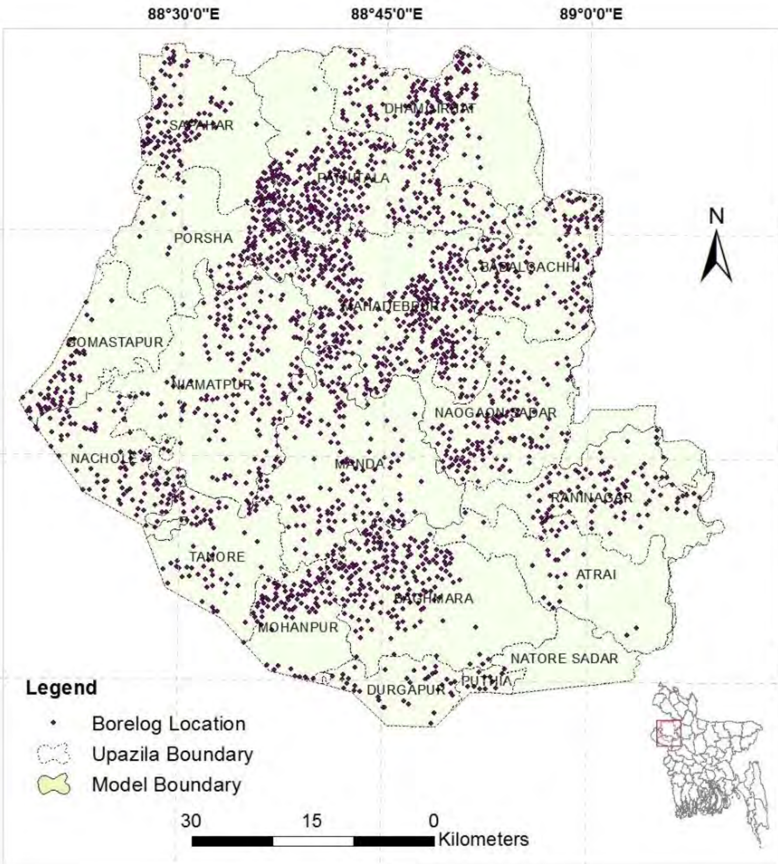


Figure 3.7: Borelog Location Map

Table 3.3: Reduce Level of Bottom of Geological Layers (Source: IWM, 2012)

No	Upazila	Easting (m)	Northing (m)	Topo mPWD	Bottom of Layers (mPWD)				
					Clay 1	Upper Aquifer	Clay 2	Lower Aquifer	Clay Bottom
1	Atrai	394902	724940	11.25	5.15	-0.94	-13.03	-13.13	-39.04
2	Atrai	394425	730271	11.61	5.51	-9.73	-24.87	-24.97	-43.15
3	Atrai	394454	728682	11.85	5.75	-3.39	-6.34	-6.44	-45.96
4	Atrai	396173	729043	11.46	5.36	-3.78	-18.92	-19.02	-40.36
5	Badalgachi	396195	765167	17.25	11.15	2.01	-6.03	-7.13	-43.71
6	Badalgachi	398808	766165	17.94	11.94	11.84	2.80	2.70	-36.92
7	Badalgachi	396519	762919	16.35	13.30	10.25	4.16	-1.94	-41.56
8	Badalgachi	400396	763399	16.33	13.28	7.19	-4.91	-5.01	-41.48
9	Baghmara	367017	723373	12.99	9.94	-11.39	-14.44	-17.49	-53.97
10	Baghmara	370073	720742	12.65	9.60	-14.78	-19.35	-26.97	-48.21
11	Baghmara	370702	720675	12.07	9.02	-12.31	-20.24	-27.25	-37.61
12	Baghmara	370634	721352	13.04	9.99	-11.34	-21.40	-23.54	-45.08
13	Dhamoirhat	381972	784557	21.95	15.85	12.91	12.81	3.66	-32.91
14	Dhamoirhat	380636	781550	21.08	14.98	8.89	-9.30	-9.40	-32.26
15	Dhamoirhat	382813	785593	21.77	15.67	0.43	-2.51	-2.61	-31.47
16	Dhamoirhat	383472	780503	21.13	11.99	-6.30	-12.30	-12.40	-27.64
17	Durgapur	368603	710828	15.35	9.25	-12.08	-33.42	-39.51	-42.56
18	Durgapur	369237	710338	13.89	4.75	-13.54	-25.64	-25.73	-50.12
19	Durgapur	368688	709155	14.22	5.08	-3.97	-4.07	-10.16	-16.26
20	Durgapur	368454	710233	14.57	11.52	-9.81	-22.92	-28.10	-46.29
21	Gomastapur	333699	745106	33.34	15.05	12.00	9.01	5.91	-6.28
22	Gomastapur	335095	745635	28.87	7.53	4.49	-7.71	-22.75	-22.85
23	Gomastapur	333251	746112	23.66	0.90	0.80	-9.77	-9.87	-14.44
24	Gomastapur	331625	744969	22.82	10.63	7.58	-12.23	-31.84	-31.94
25	Mahadevpur	365631	751268	17.09	10.99	8.05	7.95	-1.20	-4.25
26	Mahadevpur	368401	751698	19.71	13.61	7.52	-1.63	-6.81	-16.87
27	Mahadevpur	368659	753576	20.28	17.23	5.04	-8.68	-15.69	-20.87
28	Mahadevpur	366340	753215	19.04	9.90	6.85	-5.24	-5.34	-15.91
29	Manda	364298	744558	14.18	8.18	8.08	-7.06	-7.16	-28.49
30	Manda	364275	741616	13.92	10.87	3.25	-1.32	-18.39	-46.94
31	Manda	363252	745014	14.12	4.98	-1.12	-10.16	-10.26	-16.36
32	Manda	364401	745505	14.38	11.33	-6.96	-16.00	-16.10	-23.72
33	Mohanpur	363569	720619	13.66	10.61	-13.67	-13.77	-19.87	-47.20
34	Mohanpur	361372	721746	13.63	7.53	-7.71	-19.80	-19.90	-47.23
35	Mohanpur	361497	723100	12.67	9.62	-4.09	-16.29	-20.25	-52.76
36	Mohanpur	365492	719276	13.39	10.34	-12.52	-14.04	-21.66	-47.47
37	Nachole	345872	736370	28.05	12.81	3.67	0.72	0.62	-3.85
38	Nachole	348305	736149	23.79	11.70	11.60	5.60	5.50	-6.69

No	Upazila	Easting (m)	Northing (m)	Topo mPWD	Bottom of Layers (mPWD)				
					Clay 1	Upper Aquifer	Clay 2	Lower Aquifer	Clay Bottom
39	Nachole	345487	735580	33.97	21.88	21.78	15.78	15.68	0.44
40	Nachole	345204	734265	27.92	15.83	15.73	9.73	9.63	-2.56
41	Naogaon	391046	748118	12.59	0.40	-5.70	-17.79	-17.89	-42.27
42	Naogaon	388513	750027	14.54	8.44	-3.75	-15.84	-15.94	-37.28
43	Naogaon	387793	752931	14.33	8.23	2.14	-6.91	-7.01	-40.53
44	Naogaon	396256	749913	14.57	-0.67	-3.72	-15.81	-15.91	-46.39
45	Niamatpur	360831	737080	13.76	7.66	1.57	-10.62	-16.72	-47.10
46	Niamatpur	357899	731689	16.36	13.31	-8.02	-20.12	-20.22	-44.60
47	Niamatpur	353901	735083	22.06	15.96	3.87	3.77	-2.32	-14.52
48	Niamatpur	354037	735488	22.06	19.01	6.82	-17.56	-20.61	-45.00
49	Puthia	387096	709908	12.60	3.46	-8.64	-8.74	-11.78	-42.26
50	Puthia	386742	710530	12.80	6.70	-5.49	-11.48	-11.58	-20.12
51	Puthia	385487	709020	12.36	0.17	-12.02	-14.97	-15.07	-37.93
52	Puthia	384846	709360	12.76	6.66	-11.62	-17.62	-17.72	-42.10
53	Porsha	360188	765689	19.05	12.95	3.81	-23.52	-23.62	-35.81
54	Porsha	362162	764067	18.14	15.09	2.90	-0.05	-0.15	-33.68
55	Porsha	357678	764839	22.66	16.66	16.56	1.32	-3.25	-35.25
56	Porsha	361737	765013	18.35	9.31	9.21	3.11	-9.08	-32.55
57	Patnitala	377469	770322	19.88	15.31	10.74	1.69	1.59	-15.07
58	Patnitala	377781	769686	19.49	13.39	10.45	10.35	1.20	-18.31
59	Patnitala	378181	770315	19.84	13.74	10.80	10.70	7.65	-19.17
60	Patnitala	378114	768562	19.22	13.22	13.12	10.18	10.08	-21.93
61	Tanore	352483	725596	20.49	5.25	-0.75	-0.85	-3.89	-19.03
62	Tanore	349258	724130	26.12	23.07	7.83	-7.31	-7.41	-11.88
63	Tanore	351544	722568	19.69	13.59	-4.59	-4.69	-10.79	-33.25
64	Tanore	352458	721857	19.66	13.56	7.47	-1.58	-1.68	-32.06
65	Sapahar	348724	786069	27.45	3.17	3.07	-15.02	-15.12	-15.22
66	Sapahar	349178	786056	25.51	4.17	-8.02	-23.06	-23.16	-23.26
67	Sapahar	348457	784976	27.66	12.42	0.23	-5.77	-5.87	-14.91
68	Sapahar	351096	787236	22.12	-5.21	-5.31	-17.40	-17.50	-28.17
69	Raninagar	406248	730471	12.95	6.85	0.76	-5.24	-5.34	-41.81
70	Raninagar	405683	735384	13.35	7.25	1.26	1.16	-4.94	-41.41
71	Raninagar	407836	732948	13.59	7.49	-7.75	-25.93	-26.03	-35.18
72	Raninagar	402950	732140	12.60	6.50	-11.78	-17.78	-17.88	-36.17

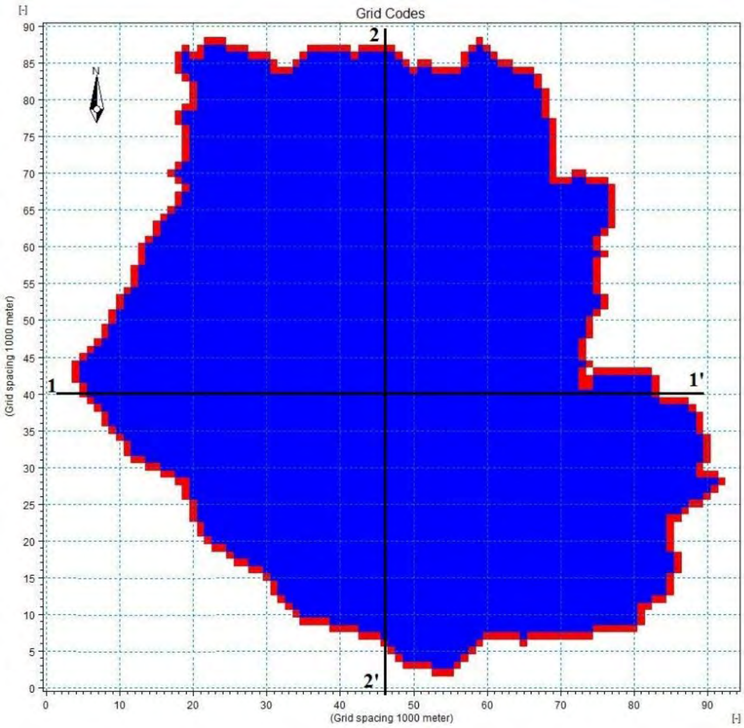


Figure 3.8: Plan of Sections for Lithological Layers

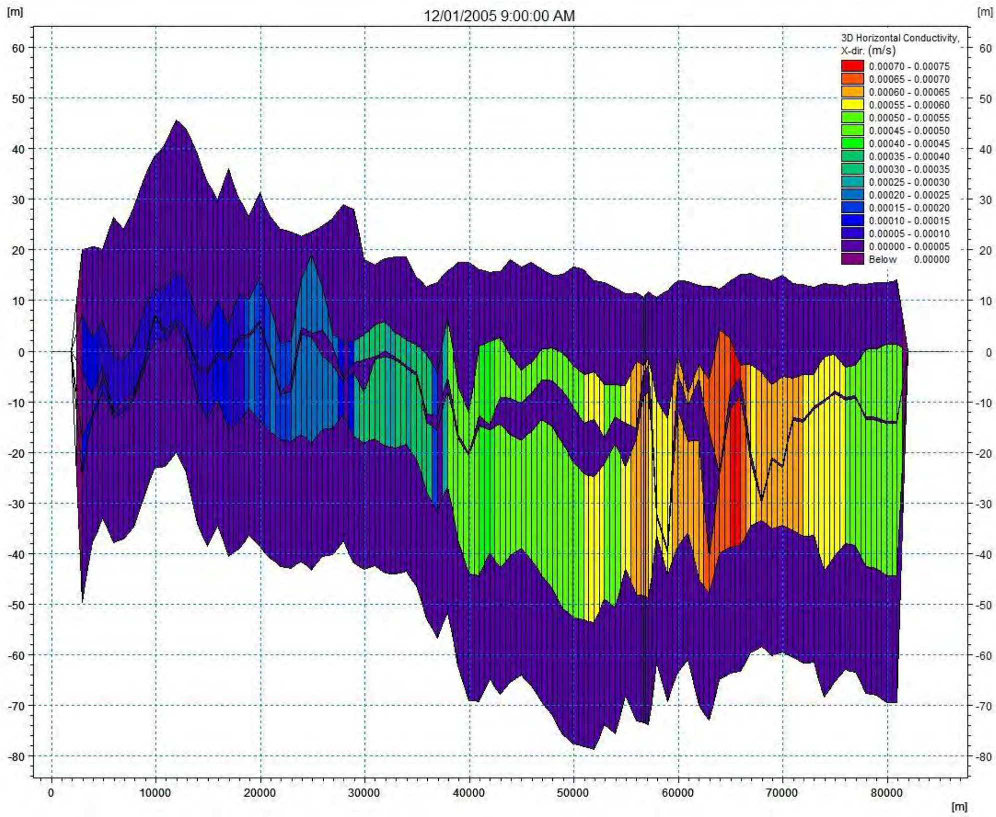


Figure 3.9: Lithological Cross Section 1-1´

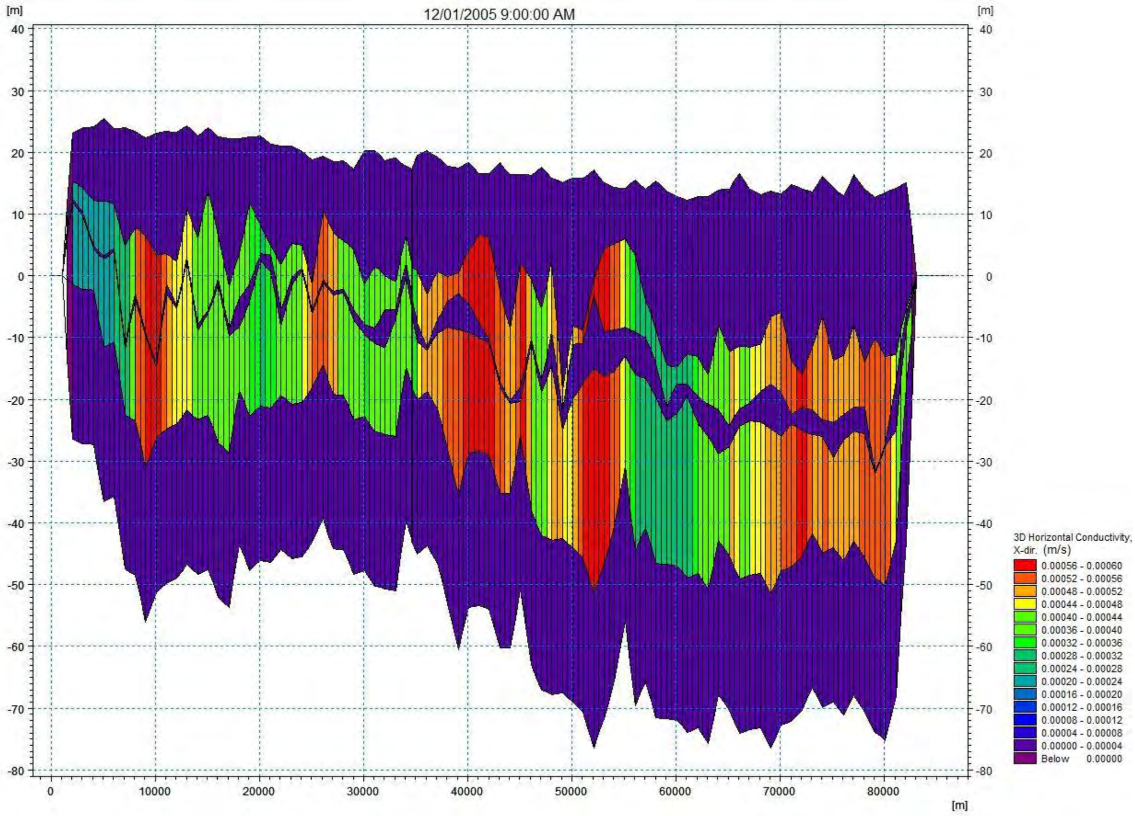


Figure 3.10: Lithological Cross Section 2-2´

3.4.3 Aquifer Properties

The aquifer test data has been collected from IWM, BWDB and BMDA. Aquifer test results have been used to understand the aquifer geometry and aquifer characteristics which include horizontal hydraulic conductivity and specific yield. These properties have been used as main parameters in groundwater model. The values of hydraulic conductivity (K) and specific yield (Sy) are obtained from IWM (IWM 2012) and used in model development. Spatial distribution map of horizontal hydraulic conductivity (K) and specific yield (Sy) have been shown in Figure 3.11 and Figure 3.12. In the study area, horizontal hydraulic conductivity varies from 5 m/day to 75 m/day and specific yield varies from 0.01 to 0.30. The upazila wise maximum and minimum values of horizontal hydraulic conductivity and specific yield given in Table 3.4 and Table 3.5 respectively.

Table 3.4: Upazila Wise Horizontal Hydraulic Conductivity (Source: IWM, 2012)

Sl No	Upazila Name	Minimum (m/day)	Maximum (m/day)
1	Atrai	30	63
2	Badalgachi	29	71
3	Dhamoirhat	8	51
4	Manda	25	59
5	Mahadevpur	14	64
6	Naogaon Sadar	32	64
7	Niamatpur	8	60
8	Patnitala	8	63
9	Porsha	5	62
10	Raninagar	34	75
11	Sapahar	5	51

Table 3.5: Upazila Wise Specific Yield (Source: IWM, 2012)

Sl No	Upazila Name	Minimum	Maximum
1	Atrai	0.08	0.024
2	Badalgachi	0.10	0.15
3	Dhamoirhat	0.09	0.21
4	Manda	0.07	0.17
5	Mahadevpur	0.06	0.14
6	Naogaon Sadar	0.08	0.16
7	Niamatpur	0.05	0.13
8	Patnitala	0.06	0.21
9	Porsha	0.06	0.13
10	Raninagar	0.06	0.25
11	Sapahar	0.08	0.16

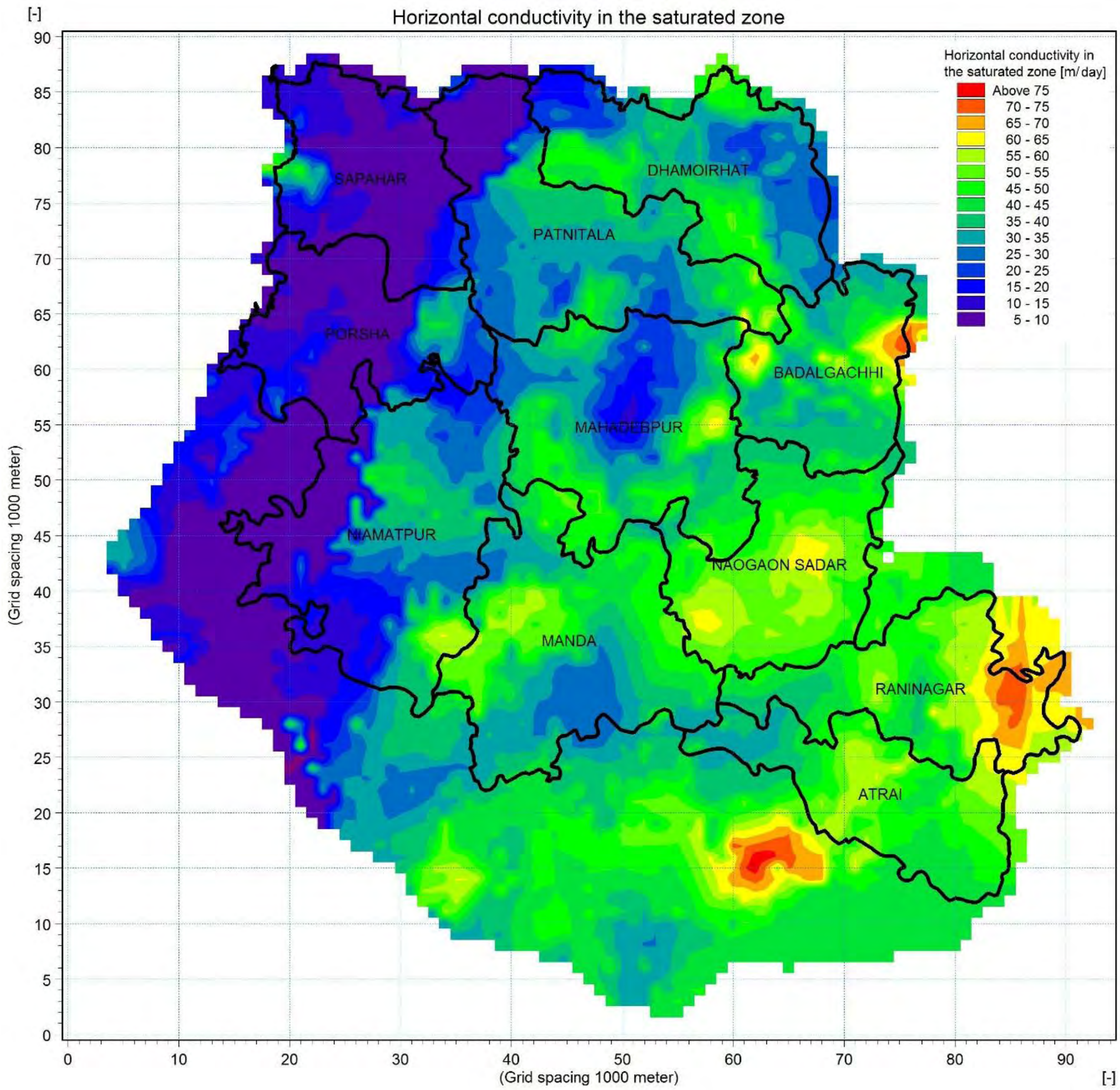


Figure 3.11: Spatial Distribution Map of Hydraulic Conductivity in m/day

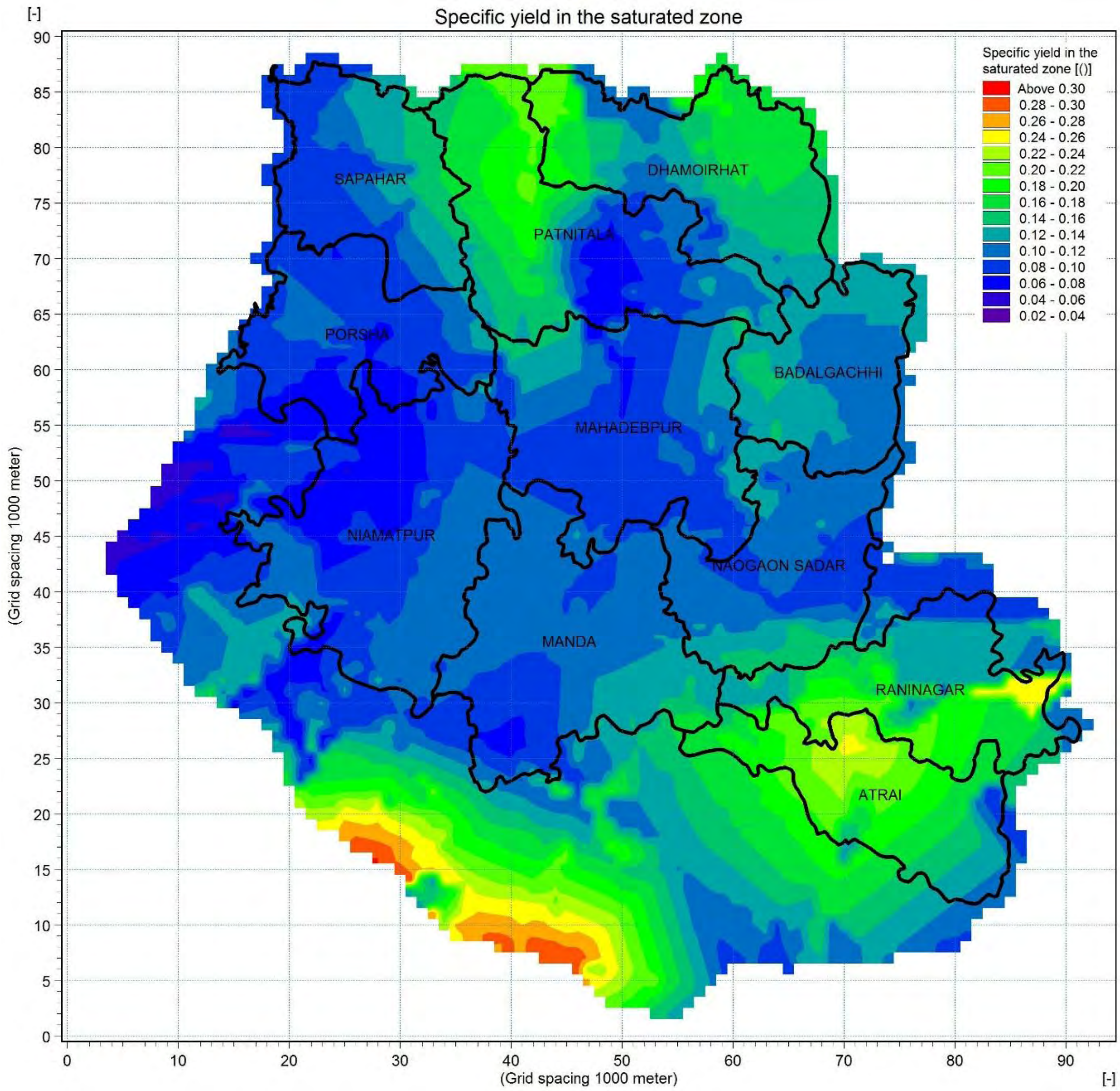


Figure 3.12: Spatial Distribution Map for Specific Yield

3.5 Topography of the Study Area

From updated topography of the study area, level variation throughout the study area is about 38 m; Topography of the area varies from 9.50 m PWD in Naogaon to 47.0 m PWD in Nachol area. Based on topography, the area can be divided into three categories; High Barind, Medium Barind and Low Barind. In high Barind area, topography varies from 20.0 m PWD to 47.0 m PWD, whereas in medium Barind area it varies from 15.0 m PWD to 20.0 m PWD and in low Barind area, it is from 9.50 m PWD to 15.0 m PWD. Most of the area in high and medium Barind is flood free and low Barind is subject to flood and drainage congestion. Topography of the study area is shown in Figure 3.13.

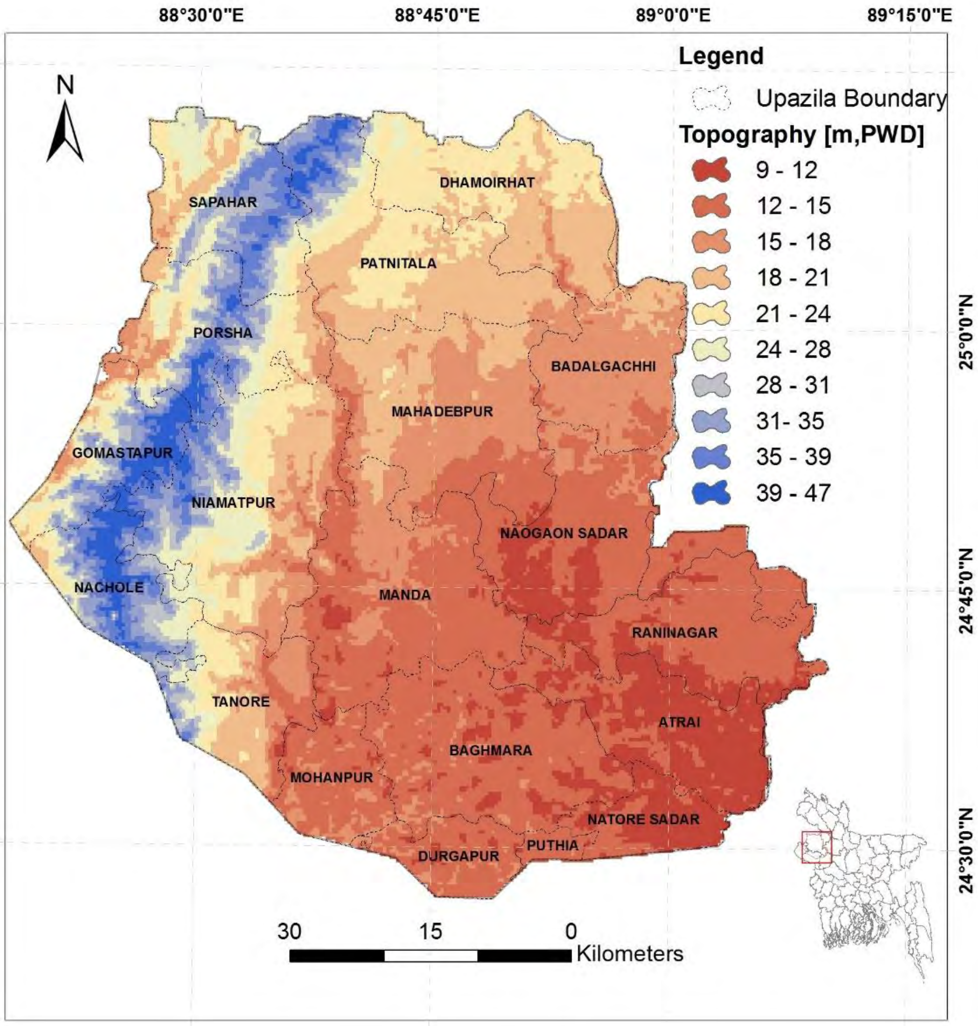


Figure 3.13: Topography within/around the Naogaon District

The available topographic map of the study area was prepared in the sixties. Lot of development activities have taken place since then which have resulted in changes of land level, drainage catchments and settlement areas. Survey conducted by IWM for updating of land level of 20 km^2 under the referenced project (IWM, 2012). Topographic digital elevation map (DEM) has been updated and now, is available in IWM.

3.6 Zoning of the Study Area

From soil characteristics point of view, the model area has been divided into five zones. But Zone-3 has varied rainfall pattern, hence it is further divided into two zones which are situated in different locations, namely Zone-3 and Zone-5. Figure 3.14 shows six zones of the study area (IWM, 2012).

3.7 Abstraction due to Water Use

In the study area abstraction data is not available. To overcome this limitation, water abstraction data for 2011 to 2015 have been estimated. Main assumption behind this estimation that the irrigation water requirement is directly proportional to the rate of abstraction. Information on cropping pattern and crop coverage throughout the study area for different crops are the based data. Total abstraction by the DTWs and STWs for different cropping seasons (Rabi, Kharif-I and Kharif-II) have been estimated based on the seasonal irrigation water requirement.

Spatial and temporal variation of water demand due to irrigation water requirement has been considered for the study. Irrigation water requirement mainly depends on land use map, cropping pattern and intensities through the study area. This irrigation water demand has been estimated using CROPWAT.

3.7.1 Irrigation Water Requirement

Factors Affecting Irrigation

Irrigation Water requirement depends on several factors e.g. land use, cropping pattern, soil type, evapotranspiration, rainfall, percolation and crop water requirement etc.

3.7.2 Land Use and Cropping Pattern

Present Cropping Pattern

The percentages of area under different types of crops are collected from Sub Assistant Agricultural Officer (SAAO) of Department of Agriculture Extension (DAE) based on the field data of 2016. Present cropping pattern is shown in the Table 3.6.

Table 3.6: Crop Coverage of the Project Area (2016)

Sl. No.	Crop Type	Area under crop (ha)	% of irrigable area
1	HYV Aman	190850	55.2%
2	HYV Boro	186510	53.9%
3	HYV Aus	61325	17.7%
4	Wheat	29345	8.5%
5	Potato	24850	7.2%
6	Vegetable	17618	5.1%

3.7.3 Potential Evapotranspiration

Potential Evapotranspiration of Rajshahi is calculated using Penman-Montieth method. Evapotranspiration depends on the mean monthly temperature, relative humidity, wind speed and daily sunshine hours. The potential Evapotranspiration calculated using CROPWAT (FAO, 1992) for Rajshahi is shown in Table.3.7.

Table.3.7: Potential Evapotranspiration

Month	Mean Daily Temperature ^{o}C	Relative humidity	Wind speed (km/day)	Sunshine hours	ETO mm/day	Remarks
January	17.3	76.9	86.2	7.2	2.1	
February	20.3	70.9	93.6	8.2	2.8	
March	25.3	61.2	116.3	8.5	4.1	
April	29.4	63.7	168.0	8.4	5.3	Maximum
May	29.6	75.6	183.6	7.2	5.0	
June	29.7	83.0	183.2	5.4	4.3	
July	29.2	87.3	163.5	4.2	3.7	
August	29.4	86.5	136.4	5.1	3.9	
September	28.9	86.1	118.0	5.2	3.6	
October	27.3	83.0	73.7	7.4	3.5	
November	23.5	78.6	74.6	8.1	2.8	
December	19.2	78.1	82.4	7.7	2.2	

3.7.4 Mean Areal Rainfall

There are eleven rainfall stations in and around Naogaon district. The average monthly rainfall for each zone has been calculated using Thiessen Polygon method. Table 3.8 shows the monthly total rainfall.

Table 3.8: Monthly Areal Mean Rainfall (mm) of Six Zones

Month	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
January	11.7	9.9	7.8	6.3	9.6	9.8
February	18.3	25.8	20.8	31.1	36.2	39.7
March	19.6	20.2	23.8	21.9	24.3	22.5
April	80.4	69.7	67.5	61.2	59.9	39.8
May	144	129.2	125.6	134	140.6	128.1
June	287.1	276.4	305	302.6	250.5	255.4
July	320.2	298.4	291.5	273.6	261.3	278.4
August	279.3	277	275.3	247.9	276.7	259.3
September	351.2	328.9	274.9	322	355.8	350.8
October	128.3	141.7	104.8	125.6	129.4	126.8
November	12.6	13.8	11	13.3	11.9	12.5
December	2.9	3.9	1.9	4.1	5.4	1.9

3.7.5 Crop Water Requirement and Unit Scheme Water Requirement

Crop water requirement is a very important factor to know the total amount of water to be abstracted for irrigation. If actual water requirement of crop is supplied to the crop at right time corresponding to the stage of development the production will be maximum. Crop Water Requirement (CWR) and unit Scheme Water Requirement (SWR) have been computed from CROPWAT (FAO, 1992) version 5.7.

Eight types of crops have been considered to calculate CWR and SWR, namely,

1. HYV Boro during Rabi Season
2. HYV Aus during Kharif -I Season
3. HYV Aman during Kharif-II Season
4. Potato during Rabi Season
5. Wheat during Rabi Season
6. Vegetable during Rabi Season
7. Vegetable during Summer Season
8. Sugarcane Round the Year

Depending on the growing period, crops are divided as Rabi (Winter/dry period) and Kharif season (wet period) crops. Again Kharif period is further divided as Kharif I and Kharif II. Some Rabi crops are Boro rice, wheat, potato, mustard, groundnuts, pulses, spices, millets (kaon), vegetables, tobacco and melons. Some crops, plantation in pre monsoon but harvest in monsoon is Kharif I crop e.g. B. Aus, B. Aman and jute. Crops such as T. Aman, HYV Aman and L. T Aman plantation in monsoon and harvest in post monsoon are Kharif II. Sugarcane and orchards are perennial crops growing in both the Rabi and Kharif seasons.

Water requirement has been computed on the basis of full unit area with single crop. In reality full area with single crop is not practiced but yet the water requirement has been computed to see how much water will require if whole unit area with single crop.

3.7.6 CWR for Full Area with Paddy

Criteria for the Computation of Crop Water Requirement

Water requirement for HYV Boro rice is maximum but compared to other crops water requirement of rice is higher, we have computed on the basis of different types of rice. The following assumptions have been made:

(1) Rice is cultivated in part of cultivable land.

(2) Nursery is done on 5 to 10% land.

(3) Water requirement for **Land preparation** for dry period is 180 mm for a period of 20 days and for supplementary irrigation during rainy season period is 80 mm.

(4) Time staggered plantation of crops. The HYV Boro planting time normally lies between January to February. Crop-wise staggering is discussed in the following sections.

(5) **Potential Evapotranspiration (ETO)** is computed from Penman-Montieth method. Climatic data of Rajshahi has been used for Naogaon districts.

(6) **Effective monthly rainfall** is taken as the 80% of monthly total rainfall. Mean aerial rainfall is computed from long-term monthly mean of eleven stations in and outside the area.

(7) **Crop coefficient** of rice for different stages of crop growth and corresponding length in days are given as follows:

Stage	**Co-efficient**	**Length (days)**
a) Land Preparation	.....	20
b) Nursery	1.20	30
c) Initial Stage (A)	1.10	20
d) Development Stage (B)	1.10	30
e) Mid Season (C)	1.25	40
f) Late season (D)	1.00	30

(8) **Percolation Rate:** Percolation rate has been measured at five locations. The locations are shown in Figure 3.14 and detailed information is presented in Table 3.9.

Table 3.9: Seepage & Percolation Rate

Measurement Site	Soil Type	Upazilas	Percolation Rate (mm/day)
Baghmara	Old Ganges	Baghmara, Durgapur, Mohnapur, Shibganj (upper part), Atrai (lower part).	3.0
Manda	Teesta	Badalgachi, Naogaon, Manda, Raninagar (western part).	2.0
Godagari	Lower Barind	Tanore, Godagari, Raninagar (eastern part), Atrai (upper part).	2.0
Niamatpur	Middle Barind	Porsha, Niamatpur, Nachole, Mahadebpur, Gomostapur.	2.0
Sapahar	Upper Barind	Sapahar, Patnitala, Dhamoirhat.	2.0

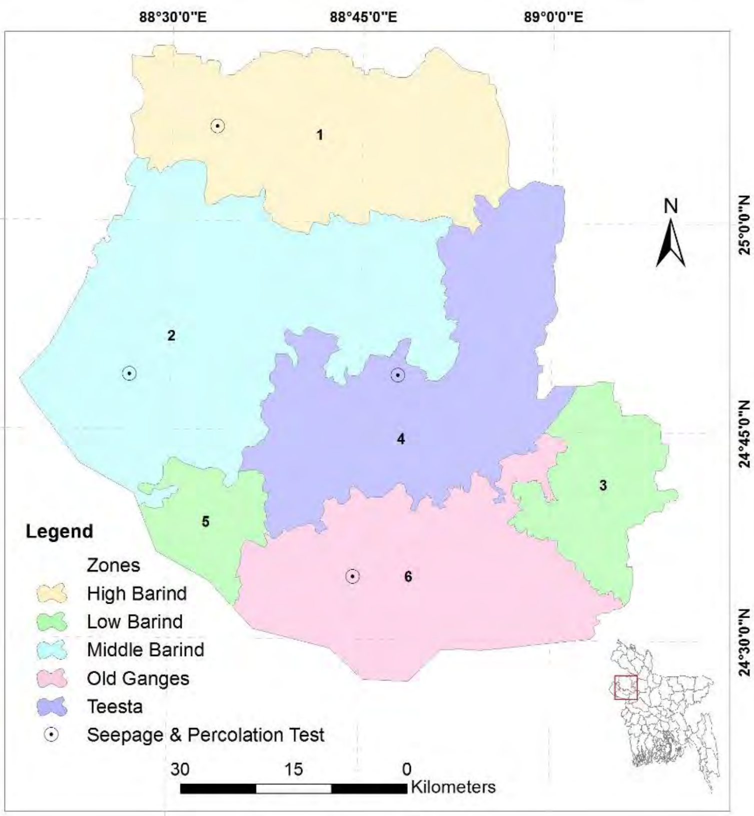


Figure 3.14: Six Zones and Seepage and Percolation Test Location

3.7.7 CWR and SWR for Different Zones

It is already said that under the study CWR and SWR have been calculated for Eight types of crops. The maximum unit scheme water requirement corresponding to critical month for each crop plantation is computed with an overall efficiency of 90% as the scheme is very small.

Water requirement has been calculated for the time staggered plantation. The idea is to find the optimal planting time when water requirement is minimum. Different crops has different planting pattern, so as variable crop water requirements.

HYV Boro: Staggered Plantation with 20% in 1st decade of January, 30% in 2nd Decade of January, 30% in 3rd decade of January and 20% in 1st decade of February have been considered. Table 3.10 shows detail calculation for Boro.

Table 3.10: CWR & SWR for Boro

Month	Crop Water Requirement					
	Zone-1	Zone-2	Zone-3	Zone-4	Zone-5	Zone-6
	mm/day	mm/day	mm/day	mm/day	mm/day	mm/day
Jan	6.80	6.80	6.80	6.80	6.80	7.50
Feb	5.20	5.20	5.20	5.10	5.00	6.10
Mar	6.50	6.50	6.50	6.30	6.30	7.30
Apr	6.10	6.40	6.40	6.10	6.80	7.40
Max. CWR (mm/day)	6.80	6.80	6.80	6.80	6.80	7.50
SWR (mm/day) (10% loss)	7.56	7.56	7.56	7.56	7.56	8.33

HYV Aus: Staggered Plantation with 20% in 3rd decade of April, 30% in 1st decade of May, 25% in 2nd decade of May and 25% in 3rd decade of May have been considered. Table 3.11 shows detail calculation for Aus.

Table 3.11: CWR & SWR for Aus

Month	Crop Water Requirement					
	Zone-1	Zone-2	Zone-3	Zone-4	Zone-5	Zone-6
	mm/day	mm/day	mm/day	mm/day	mm/day	mm/day
Apr	4	4	4	4	4.2	4.3
May	5.7	6.1	6.2	5.7	5.8	6.6
June	0.6	0.7	0.4	0.5	0.8	0.9
Max. CWR (mm/day)	5.70	6.10	6.20	5.70	5.80	6.60
SWR (mm/day) (10% loss)	6.33	6.78	6.89	6.33	6.44	7.33

HYV Aman: Staggered Plantation with 10% in 2nd decade of July, 40% in 3rd decade of July and 50% in 1st decade of August has been considered. Table 3.12 shows detail calculation for Aman.

Table 3.12: CWR & SWR for Aman

Month	Crop Water Requirement					
	Zone-1	**Zone-2**	**Zone-3**	**Zone-4**	**Zone-5**	**Zone-6**
	mm/day	**mm/day**	**mm/day**	**mm/day**	**mm/day**	**mm/day**
July	1.6	1.8	1.9	1.8	1.9	2.1
Aug	0.8	0.7	0.8	0.5	0.9	1.3
Sep	0	0.1	0.1	0	0	0
Oct	1.9	1.8	2.2	1.8	1.8	2.7
Max. CWR (mm/day)	1.90	1.80	2.20	1.80	1.90	2.70
SWR (mm/day) (10% loss)	2.11	2.00	2.44	2.00	2.11	3.00

Potato: Staggered Plantation with 1st decade of November 20%, 2nd decade of November 30%, 3rd decade of November 30% and 1st decade of December 20% have been considered. Maximum CWR occurs at February. Table 3.13 shows detail calculation for Potato.

Table 3.13: CWR & SWR for Potato

Month	Crop Water Requirement					
	Zone-1	**Zone-2**	**Zone-3**	**Zone-4**	**Zone-5**	**Zone-6**
	mm/day	**mm/day**	**mm/day**	**mm/day**	**mm/day**	**mm/day**
Dec	1.3	1.3	1.4	1.3	1.3	1.3
Jan	1.8	1.8	1.9	1.8	1.8	1.9
Feb	2.9	2.7	2.8	2.7	2.6	2.7
Max. CWR (mm/day)	2.90	2.70	2.80	2.70	2.60	2.70
SWR (mm/day) (10% loss)	3.22	3.00	3.11	3.00	2.89	3.00

Wheat: Staggered Plantation with 1st decade of November 20%, 2nd decade of November 30%, 3rd decade of November 30% and 1st decade of December 20% have been considered. Maximum CWR occurs at February. Table 3.14 shows detail calculation for Wheat.

Table 3.14: CWR & SWR for Wheat

Month	Crop Water Requirement					
	Zone-1	Zone-2	Zone-3	Zone-4	Zone-5	Zone-6
	mm/day	mm/day	mm/day	mm/day	mm/day	mm/day
Dec	1.3	1.2	1.2	1.2	1.1	1.2
Jan	1.8	1.8	1.9	1.8	1.8	1.9
Feb	2.9	3	3	3	2.9	2.9
Max. CWR (mm/day)	2.90	3.00	3.00	3.00	2.90	2.90
SWR (mm/day) (10% loss)	3.22	3.33	3.33	3.33	3.22	3.22

Rabi Vegetable: Plantation with 100% in 2nd decade of November has been considered. Maximum CWR occurs at January. Table 3.15 shows detail calculation for Rabi Vegetable.

Table 3.15: CWR & SWR for Rabi Vegetable

Month	Crop Water Requirement					
	Zone-1	Zone-2	Zone-3	Zone-4	Zone-5	Zone-6
	mm/day	mm/day	mm/day	mm/day	mm/day	mm/day
Dec	2	2	2	2	2	2
Jan	2	2.1	2	2.1	2	2
Feb	1.6	1.6	1.6	1.6	1.5	1.5
Max. CWR (mm/day)	2.00	2.10	2.00	2.10	2.00	2.00
SWR (mm/day) (10% loss)	2.22	2.33	2.22	2.33	2.22	2.22

Summer Vegetable: Plantation with 100% in 2nd decade of March has been considered. Zone-wise CWR varies from 2.8 mm/day to 4.1 mm/day with maximum value occurs for zone-6. Maximum CWR occurs at the month of April. Table 3.16 shows detail calculation for Summer Vegetable.

Table 3.16: CWR & SWR for Summer Vegetable

Month	Crop Water Requirement					
	Zone-1	Zone-2	Zone-3	Zone-4	Zone-5	Zone-6
	mm/day	mm/day	mm/day	mm/day	mm/day	mm/day
Mar	1.8	1.8	1.5	1.6	1.6	1.5
Apr	2.8	3.4	3.6	3.2	3.6	3.8
May	2.8	2.6	3	2.9	2.5	2.3
Max. CWR (mm/day)	2.80	3.40	3.60	3.20	3.60	3.80
SWR (mm/day) (10% loss)	3.11	3.78	4.00	3.56	4.00	4.22

Sugarcane: Plantation with 100% in 1st decade of February has been considered. Maximum CWR occurs at the month of April. Table 3.17 shows detail calculation for Sugarcane.

Table 3.17: CWR & SWR for Sugarcane

Month	Crop Water Requirement					
	Zone-1	Zone-2	Zone-3	Zone-4	Zone-5	Zone-6
	mm/day	mm/day	mm/day	mm/day	mm/day	mm/day
Feb	2.5	2.4	2.4	2.4	2.3	2.3
Mar	3.8	3.6	3.8	3.6	3.5	3.7
Apr	4	4.1	3.9	4.2	4.1	3.8
May	1.4	1.3	1.2	1.1	1.8	1.3
Max. CWR (mm/day)	4.00	4.10	3.90	4.20	4.10	3.80
SWR (mm/day) (10% loss)	4.44	4.56	4.33	4.67	4.56	4.22

CHAPTER 4

DATA PROCESSING AND MODEL SETUP

4.1 General

The objective of this study is to identify the stress of groundwater and to minimize the stress on groundwater level by changing crop pattern. Thus, a mathematical model describing the conditions in the unsaturated and saturated zone of the subsurface together with rainfall, overland flow, evapotranspiration and the flow in the river is required.

The MIKE 11 hydrodynamic module uses an implicit, finite difference scheme for the computation of unsteady flows in rivers and estuaries. The module can describe sub-critical as well as supercritical flow conditions through a numerical scheme and simulate main hydraulic processes i.e. flow, velocity and water level in the river (MIKE 11- DHI, 2011). MIKE SHE is a comprehensive mathematical modelling system that covers the entire land-based hydrological cycle. It is a finite difference model, which solves systems of equations describing the major flow and related processes in the hydrological system and simulates surface flow, infiltration, flow through the unsaturated zone, evapotranspiration and groundwater flow (MIKE SHE-DHI, 2011).

The MIKE 11 and MIKE SHE models are interactively linked and capable of producing water balance and change of storages in the form of groundwater recharge/discharge and fluctuations in water tables. On the other hand, the groundwater model has been used to assess the impact on groundwater. Integrated MIKE 11-MIKE SHE modelling system has been adopted in this study.

4.2 Surface Water Model

The river flow model developed under the study is intended for assessment of river flow. The 1-D river flow model is developed using MIKE 11 mathematical modelling software of DHI. The river flow model used in this study has been customized from the existing validated NW regional model available at IWM. The NW regional model has 57 Catchments Area (CA) and covers the NW region of Bangladesh. The model was updated in 2015 to suit to the study requirements. The 1-D river flow model comprises of a Rainfall-runoff model and a hydro-dynamic model.

4.3 Groundwater Model

The groundwater model has been developed to investigate the groundwater levels for the study area. Groundwater model setup involves a geometrical description and specification of physical characteristics of the hydrological system of the study area. The major components of the model setup include evapo-transpiration, unsaturated zone, saturated zone, overland flow and river systems. Brief descriptions of the groundwater model setup are given below:

4.3.1 Simulation Specification

The default time step control and computational control parameters for overland flow (OL), unsaturated zone (UZ) and Saturated Zone (SZ) have been used for entire simulation period. However, simulation periods of the calibration, validation and prediction models were different and user specified.

4.3.2 Model Domain and Grid Size

The study area has been discretized into 1000m square grids as shown in the horizontal plan of the Figure 4.1. The model has 5074 grid cells shown in Table 4.1, where 285 grids are the boundary cells and the rest are computational cells. The grid cells are the basic units to provide all the spatial and temporal data as input and to obtain corresponding data as output. A geographical limit of the study area is shown in Table 4.2.

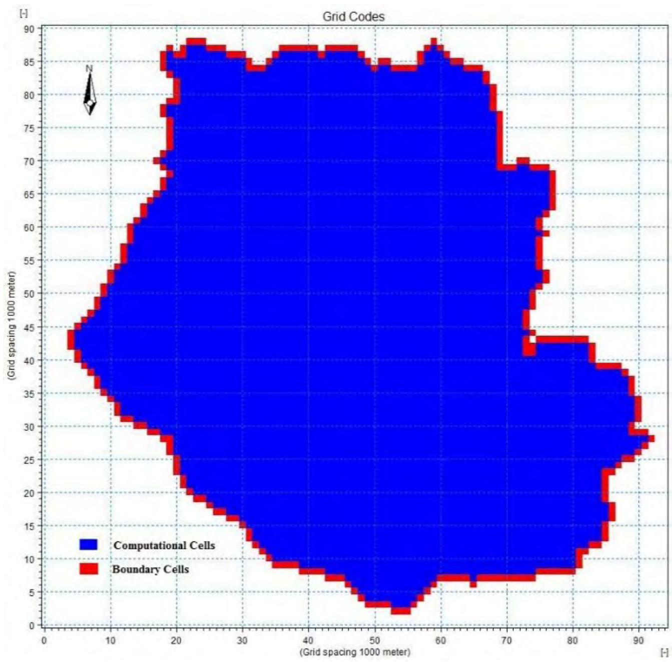


Figure 4.1: Groundwater Model Domain in 1000m Grid Cells

Table 4.1: Grid Cells Used for Model Setup

Upazilas of the Naogaon District	Numbers of Grid Cells (area: 1 km^2)		
	Upazila wise	Study area	Model area
Atrai	283	3435	5074
Badalgachi	211		
Dhamoirhat	301		
Manda	414		
Mahadebpur	396		
Naogaon Sadar	274		
Niamatpur	450		
Patnitala	379		
Porsha	234		
Raninagar	248		
Sapahar	245		

Table 4.2: Geographical Limits of the Study Area

Model Range	Maximum	Minimum
Easting	419000	324000
Northing	792000	701000

4.3.3 Topography

A well-prepared DEM is essential for visualizing the topography and for accurate modeling. A DEM of 300 m resolution has been developed to define the topography of the study area and used in the model which is given in Figure 4.2. The topography of the model area varies from 9.5 mPWD to 47 mPWD. Details have been discussed in Chapter-3 of this project.

4.3.4 Precipitation

Rainfall data is needed as input to the model. 11 rainfall stations are available in and around the model area. To account for the spatial variation in rainfall, the time series data for each station has been associated with an area. This area has been estimated by Thiessen Polygon Method. Thiessen polygons for each rainfall stations have been shown in Figure 4.3.

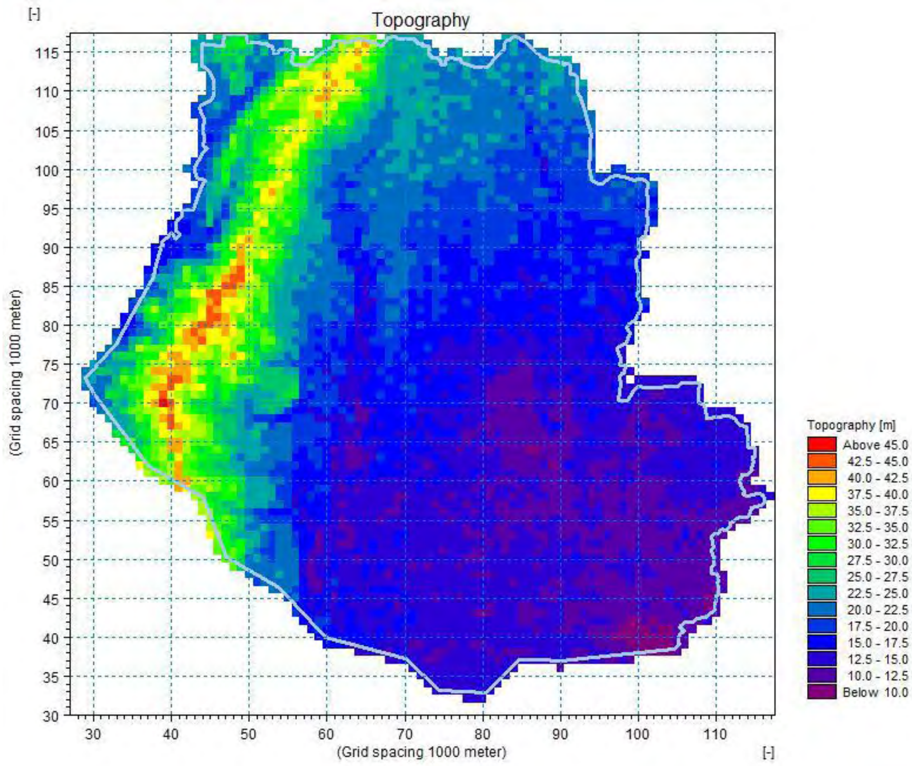


Figure 4.2: Topography Map

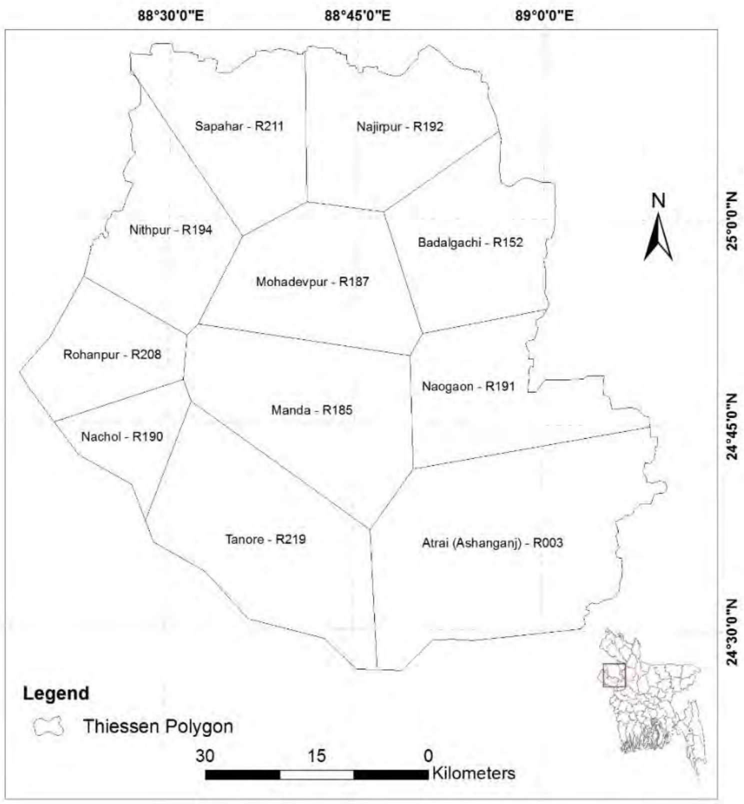


Figure 4.3: Thiessen Polygon for Rainfall Stations in the Model Area

4.3.5 Evapotranspiration

The actual evapotranspirations are estimated in the model on the basis of potential evapotranspiration rates, the root depths and leaf area indices of different crops over the seasons. Time series of the potential evapotranspiration are given as input to the model. Evaporation data for Rajshahi station has been used in this model as mentioned in section 3.6.4.

4.3.6 Land Use

Land use and vegetation are used in the model to calculate actual evapo-transpiration depending on the actual crops grown in the project area. The major part of the study area is agricultural land. It has homestead and water body also. Under the study, spatial distribution of crops has been collected from SRDI map, IWM and DAE (Figure 4.4). For the model input, these cropping types and cropping pattern have further been simplified considering the major crops that require irrigation water. A crop database (Source IWM) for each crop, which defines leaf area index, root depth and other properties of each crop used in the model.

4.3.7 River Systems

The river system included in the model using MIKE 11 as mentioned in section 4.2. The river model has been coupled with the groundwater model.

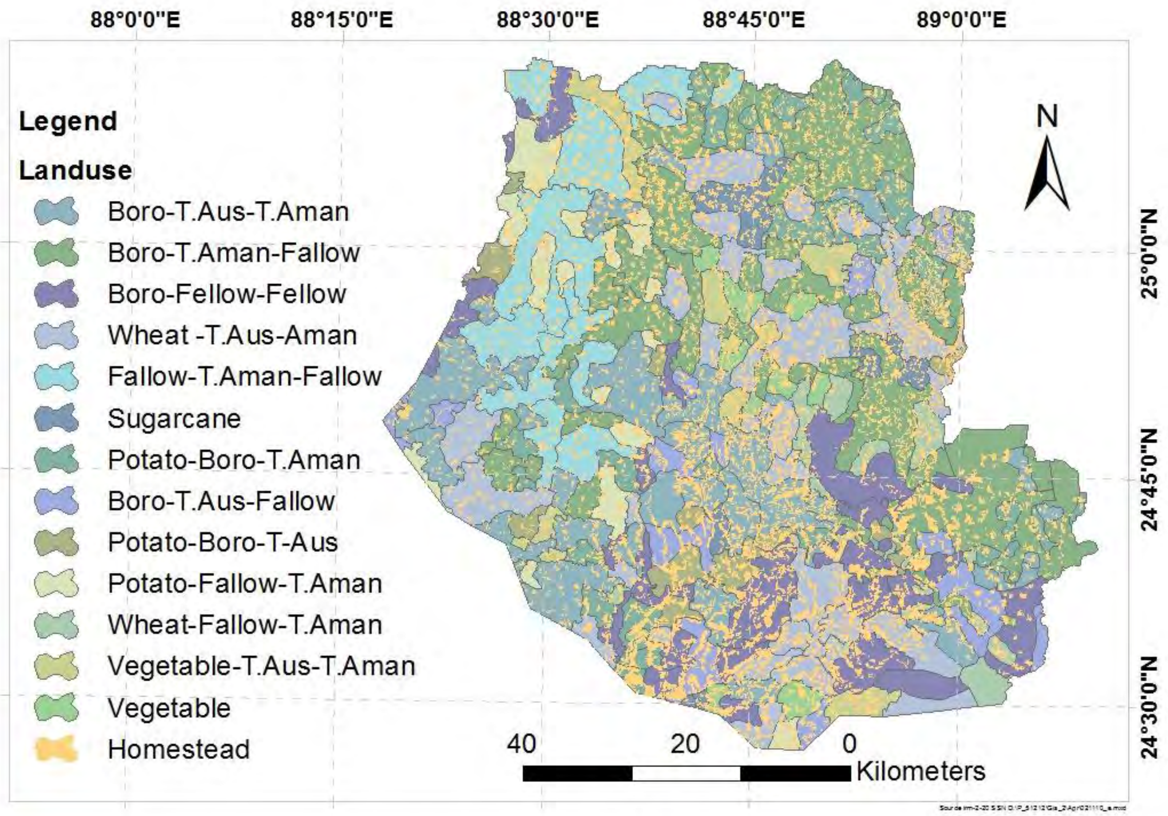


Figure 4.4: Land Use of the Model Area

4.3.8 Overland Flow

When the net rainfall rate exceeds the infiltration capacity of the soil, water gets ponded over the ground surface. This water is then called as surface runoff, to be routed down-gradient towards the river system. The study area is dominated by agricultural land and the main crops are different varieties of paddy. Thus, detention storage is taken 10-50 mm for the initiation of the runoff flows. Since the area is dominantly agricultural, a constant value can be considered for the entire area. However, it has been finally selected through the process of calibration of the model. The value of Manning number (M) that has been considered in the present study is 10.

4.3.9 Unsaturated Zone

The unsaturated zone (UZ) extends from the ground surface to the groundwater table. There are two unsaturated soil functions required for all soil types characterizing the individual soil profiles of the study area. The functions are the relationships on soil potentials (suction) versus soil moistures and the hydraulic conductivities. The vertical distribution of soil in the project area is highly heterogeneous. Due to high heterogeneity, soil parameters of different textures in different locations have been adjusted during calibration.

Table 4.3: Vertical Discretization of Unsaturated Zone

No	From	To	Cell Height	No of Cells
1	0	0.5	0.05	10
2	0.5	2	0.1	15
3	2	50	0.5	96

4.3.10 Saturated Zone

Setting up the saturated zone component includes defining the computational layers from geological layers, hydrogeological characteristics, initial and boundary conditions, drainage and pumping wells, etc.

4.3.11 Geology and Hydrogeology

The Geological layers for the model have been developed based on the collected borelog data from various agencies like BMDA, BWDB, IWM etc. The hydraulic properties obtained from aquifer tests carried out by IWM and BWDB are used in the model study. A plot of horizontal hydraulic conductivity for aquifer used in the model is described in section 3.4.3.

4.3.12 Computational Layers

Computational layers have been defined using geological layers of the study area. As discussed in section 3.4.2. the geological layer has been divided in five different sub-layer. Therefore in the computational layer, five layer have been used.

4.3.13 Initial Condition of Groundwater Level

Initial conditions in terms of potential heads of groundwater have been specified in the model. Potential heads of the monitoring wells are used to generate initial condition contour map and it is considered applicable for all the computational layers as like which is shown in Figure 4.5.

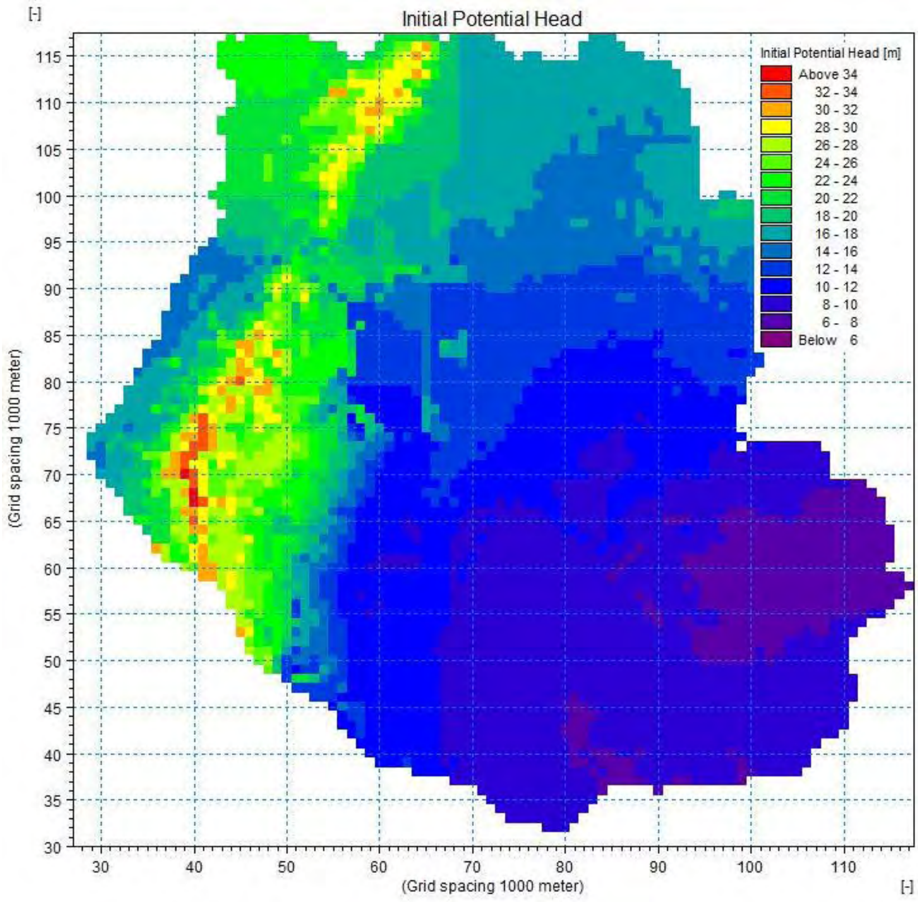


Figure 4.5: Initial Potential Head in the Model Area

4.3.14 Boundary Condition

A total of 17 monitoring wells are available along the boundary line of the model area. Using the observed groundwater, a time series head boundary file has been prepared for each boundary cell. The time series data have been interpolated along the boundary of the model to generate boundary groundwater level for the model domain. The 5 computational layers are leaky in nature and thus interconnected. Therefore, the same boundary condition is applied in all the 5 computational layers. The location of the boundary wells is given in Figure 4.6.

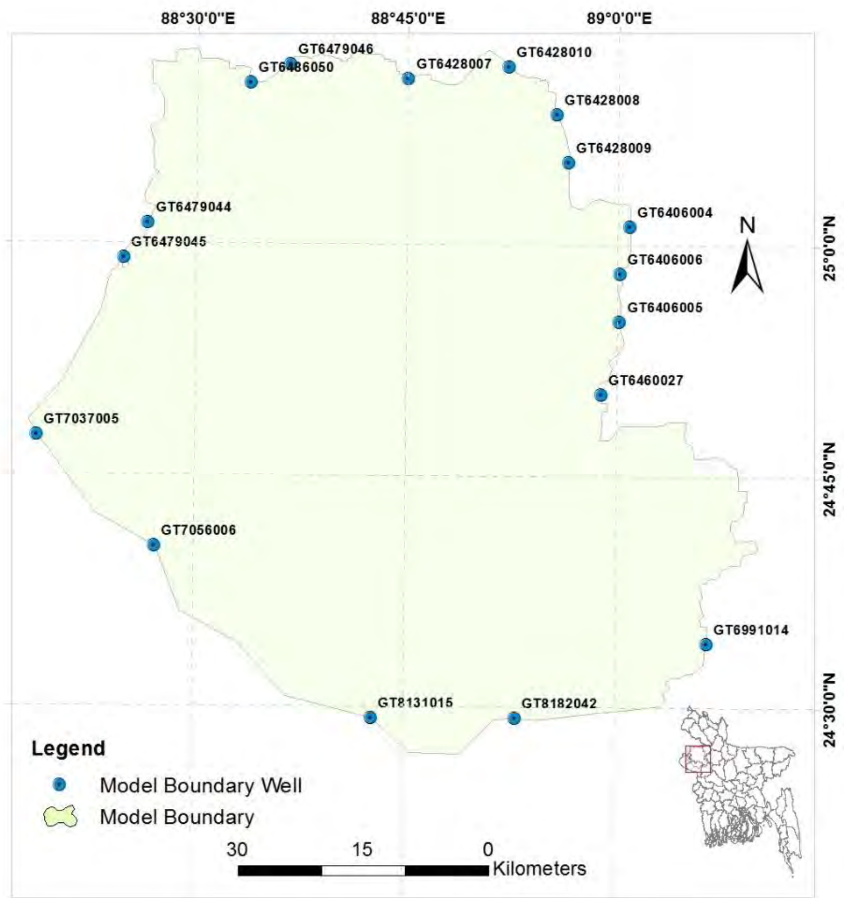


Figure 4.6: Boundary Wells Location in the Model

4.3.15 Calibration and Validation

The purpose of model calibration is to achieve an acceptable agreement with measured data by adjusting the input parameters within acceptable range. As a coupled surface water-groundwater model contains huge number of input data, the parameters to adjust during the calibration could be numerous. The model has been calibrated for the period 2011 to 2014 and validated for 2015. In the present groundwater model, calibration and validation has been done against groundwater levels. In the Barind area, the groundwater flow to a large extent is controlled by the relatively impermeable clay layer and the limited aquifer extent. Hence the geological model is one of the major components in the calibration of the model. During calibration overland leakage coefficient, vertical hydraulic conductivity, storage coefficient and river leakage coefficient have been adjusted. The calibration parameters have been given in Table 4.4.

Table 4.4: Calibration Parameter

Geological Layer	Horizontal Hydraulic Conductivity (m/day)			Vertical Hydraulic Conductivity (m/day)			Specific Yield		
	Max	Min	Avg.	Max	Min	Avg.	Max	Min	Avg.
1. Clay (Top)	0.777	0.086	0.259	0.432	0.005	0.086	0.29	0.077	0.05
2. Aquifer	75.18	5.64	34.56	15.23	1.03	4.83	0.30	0.05	0.12
3. Clay (Bottom)	0.008			0.004			0.08		

During the calibration of the model, 2 observation wells have been used in the calibration and validation purposes. The locations of the monitoring wells for observed data used in calibration process are shown in Figure 4.7. The calibration plots are given in Figure 4.8 and Figure 4.9.

In general, the overall calibration of the model is acceptable, but there are scopes of improvements for further study.

Figure 4.7: Distribution of Calibration Wells in the Model Area

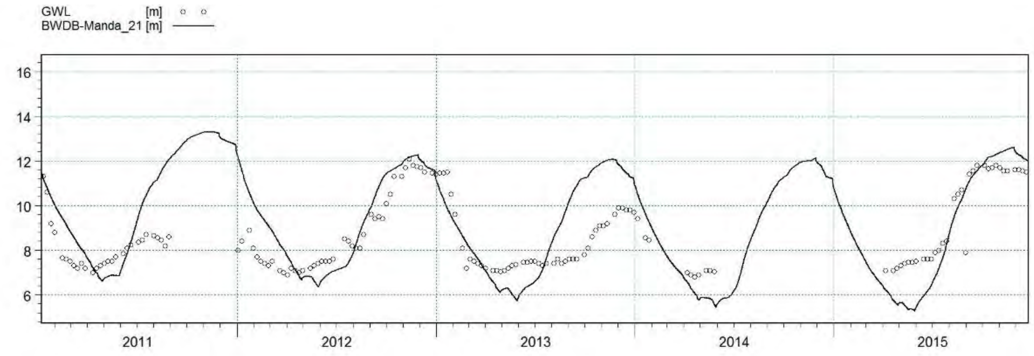


Figure 4.8: Groundwater Calibration (Year 2011-2014) and Validation (Year 2015)for Well GT6447021

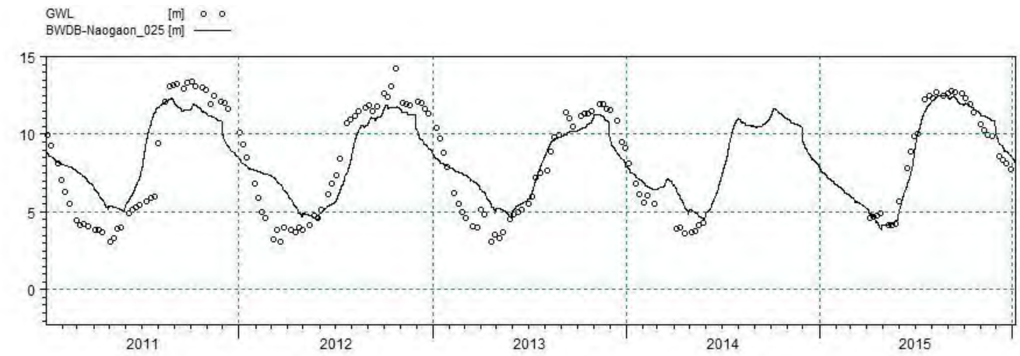


Figure 4.9: Groundwater Calibration (Year 2011-2014) and Validation (Year 2015) for Well GT6460025

4.4 Option Formulation

The main objective of the study is to investigate the effect of different cropping pattern on groundwater for Naogaon district. In view of this, three different options, including a base condition (Option-0) was formulated, simulated and evaluated to assess the impacts of the options on groundwater level. Assessment of groundwater level began with the assessment of the present condition (Option-0) where it was attempted to assess the groundwater level under present crop pattern. Wheat and vegetable consume very less water compared to boro rice. From the crop water requirement for boro rice highest water requirement 8.33 mm/day, whereas wheat and vegetable highest water requirement 3.33 mm/day and 2.33 mm/day respectively. (50% boro & 50% wheat) in the whole crop area [Option-1], only wheat (a sample of less water demand crop) in the whole crop area [Option-2], (50% boro & 50% vegetable) in the whole crop area [Option-3] and compared with the present crop pattern.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 Assessment of Spatial and Temporal Variation of Groundwater Level

Bangladesh is an agricultural country. The irrigation is a vital factor for crop cultivation during dry season. The high yield varieties of paddy (boro) requires a lot of water for its growth. It is the common practice that, the demand for water for this purpose mainly meet up with groundwater sources. This is leading to groundwater level lowering across the country.

The study area is Naogaon district. Naogaon district consist of 11 upazilas namely Atrai, Badalgach, Dhamoirhat, Manda, Mahadebpur, Naogaon Sadar, Niamatpur, Patnitala, Porsha, Raninagar, Sapahar. The phreatic surface indicates the level of the water table; portion below this level is considered as saturated. Depth of phreatic surface is the vertical distance of water table from the surface.

Hydrographs for simulated phreatic surface at pre-selected location (Naogaon Sadar upazila: Figure 5.1) show that the maximum depth of groundwater table occurs within the period of April to May (end of the dry period) and minimum depth of groundwater table occurs within the period of October to November (end of the wet period) (Hydrograph: Figure 5.2). Hydrographs of observed groundwater table also support the above findings (IWM, 2012). Suction mode tubewells such as hand tubewell and shallow tubewell will not operate where, groundwater table remains below 7.0 m. For Naogaon district the areas where groundwater table below 7m have been considered as stress condition.

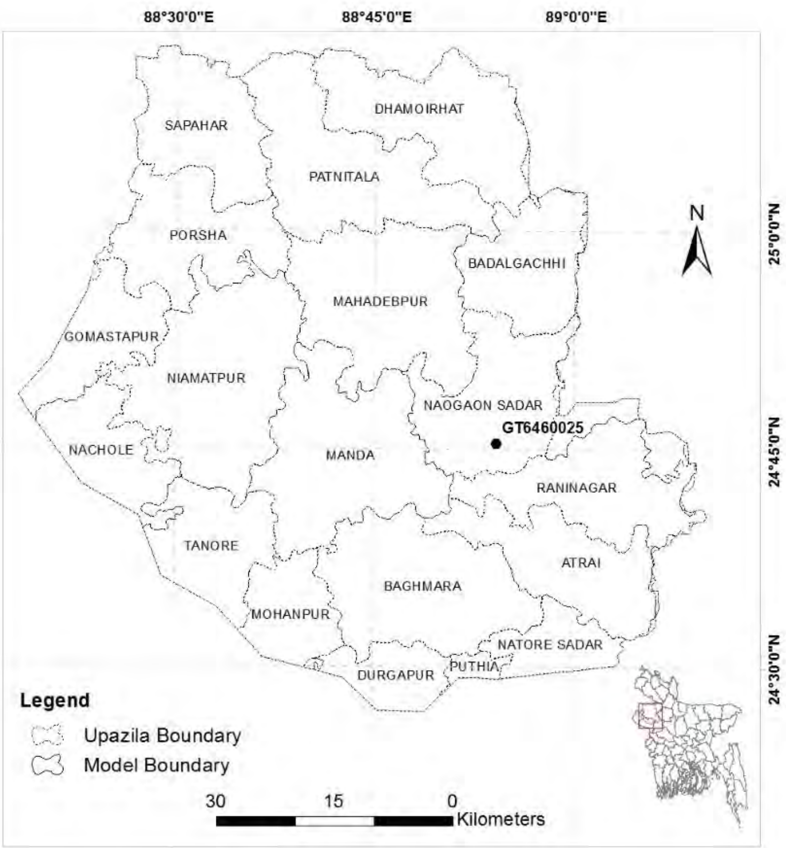


Figure 5.1: Groundwater Level Station at Naogaon Sadar Upazila

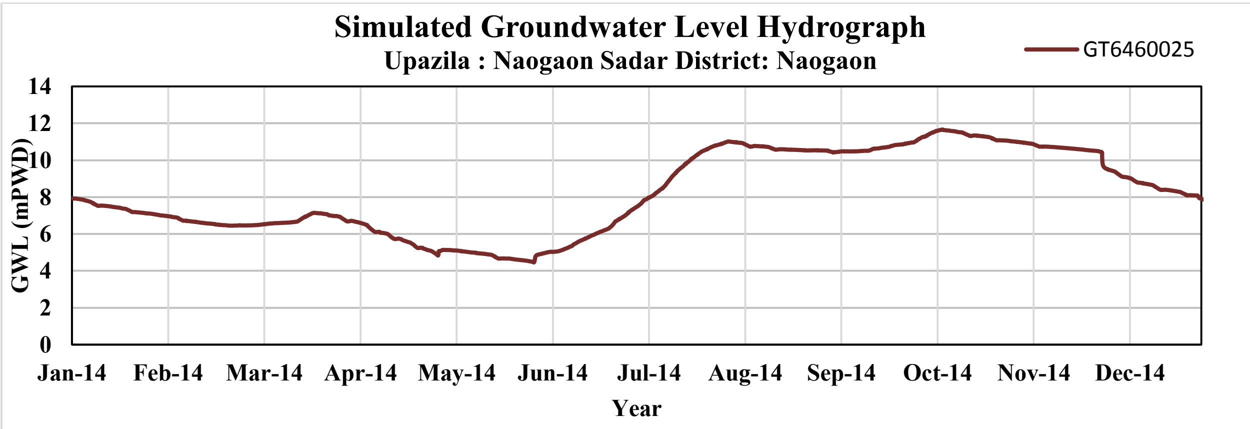


Figure 5.2: Simulated Groundwater Level Hydrograph

To analyze the stress condition phreatic surface on 1st May for dry (maximum depth of phreatic surface) and 1st October for wet period (minimum depth of phreatic surface) of each consecutive year has been considered.

Year 2002

The spatial variation for dry and wet periods of year 2002 in Naogaon district has been shown in Figure 5.3. It can be seen from the Figure 5.3 that maximum depth to phreatic surface range between (-) 0.0 m to (-) 25.2 m for dry period and (-) 0.0 m to (-) 24.8 m for wet period. From the cell calculation 1598 grid cells between (0 to -7m), 1389 grid cells between (-7 to -14 m), 394 grid cells between (-14 to -21 m), 53 grid cells between (-20 to -25.2 m) for dry period. And for wet period 2907 grid cells between (0 to -7m), 377 grid cells between (-7 to -14 m), 131 grid cells between (-14 to -21 m), 18 grid cells between (-21 to -24.8 m). In the dry period of year 2002, 47% area was within 7 m and remaining 53% area was in stress condition. For in wet period 85% area was with in 7m and remaining 15% area in stress condition.

Year 2005

The spatial variation for dry and wet periods of year 2005 in Naogaon district has been shown in Figure 5.4. It can be seen from the Figure 5.4 that maximum depth to phreatic surface range between (-) 0.0 m to (-) 25.5 m for dry period and (-) 0.0 m to (-) 24.4 m for wet period. From the cell calculation 1731 grid cells between (0 to -7m), 1405 grid cells between (-7 to -14 m), 235 grid cells between (-14 to -21m), 62 grid cells between (-21 to -25.2 m) for dry period. And for wet period 2762 grid cells between (0 to -7m), 502 grid cells between (-7 to -14 m), 140 grid cells between (-14 to -21 m), 30 grid cells between (-21 to -24.8 m). In the dry period of year 2005, 50% area was within 7 m and remaining 50% area was in stress condition. For in wet period 80% area was with in 7m and remaining 20% area in stress condition.

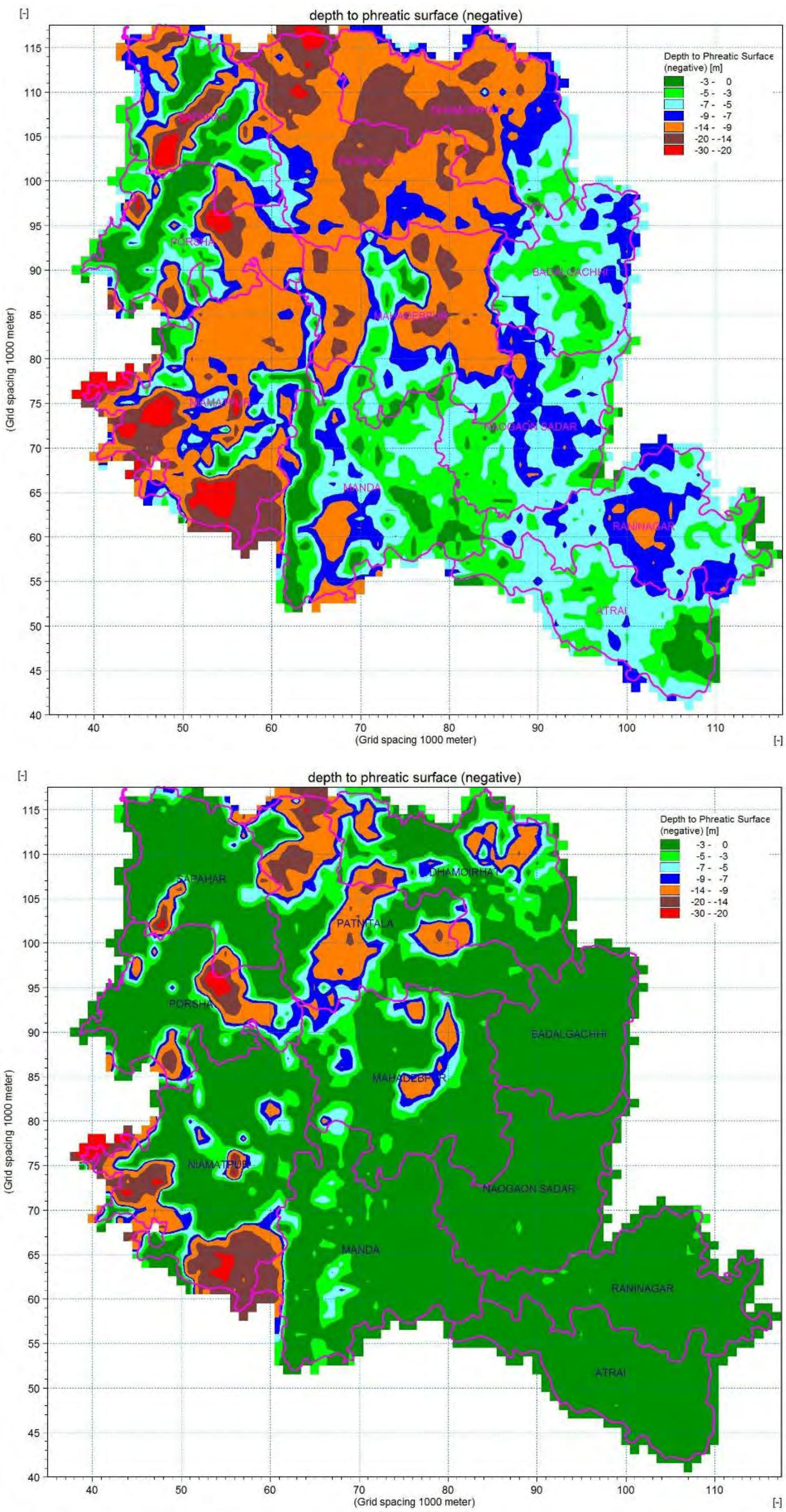


Figure 5.3: Maximum Depth to Phreatic Surface on May 01(top) and Minimum Depth to Phreatic Surface on October 01(bottom), 2002

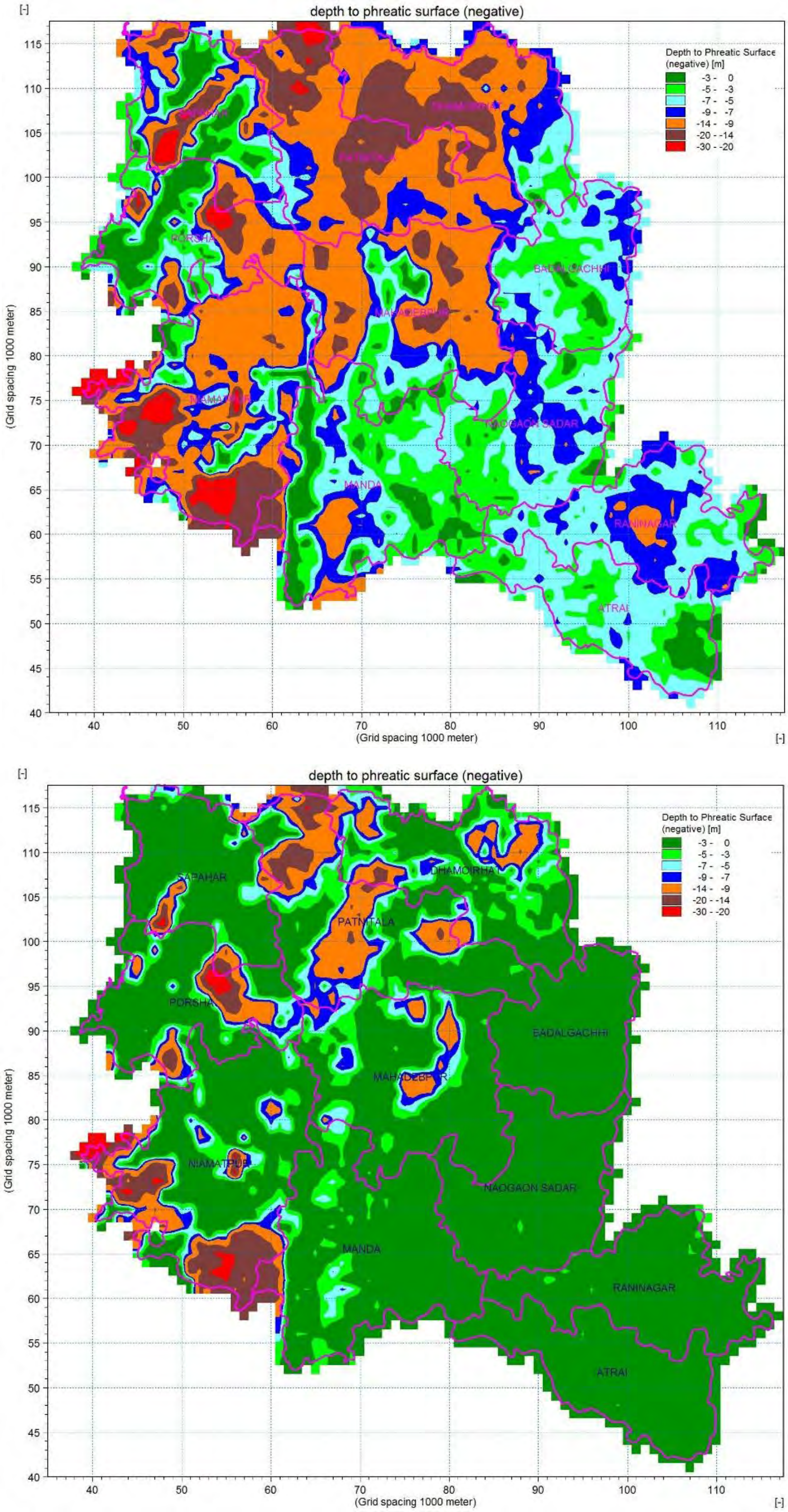


Figure 5.4: Maximum Depth to Phreatic Surface on May 01(top) and Minimum Depth to Phreatic Surface on October 01(bottom), 2005

Year 2008

The spatial variation for dry and wet periods of year 2008 in Naogaon district has been shown in Figure 5.5. It can be seen from the Figure 5.5 that maximum depth to phreatic surface range between (-) 0.0 m to (-) 25.3 m for dry period and (-) 0.0 m to (-) 25.0 m for wet period. From the cell calculation 1514 grid cells between (0 to -7m), 1476 grid cells between (-7 to -14 m), 396 grid cells between (-14 to -21 m), 48 grid cells between (-21 to -25.3 m) for dry period. And for wet period 2578 grid cells between (0 to -7m), 635 grid cells between (-7 to -14 m), 194 grid cells between (-14 to -21 m), 27 grid cells between (-21 to -25.3 m). In the dry period of year 2008, 44% area was within 7 m and remaining 56% area was in stress condition. For in wet period 75% area was with in 7m and remaining 25% area in stress condition.

Year 2011

The spatial variation for dry and wet periods of year 2011 in Naogaon district has been shown in Figure 5.6. It can be seen from the Figure 5.6 that maximum depth to phreatic surface range between (-) 0.0 m to (-) 27.8 m for dry period and (-) 0.0 m to (-) 26.7 m for wet period. From the cell calculation 1235 grid cells between (0 to -7m), 1371 grid cells between (-7 to -14 m), 604 grid cells between (-14 to -21 m), 224 grid cells between (-21 to -25.3 m) for dry period. And for wet period 2495 grid cells between (0 to -7m), 536 grid cells between (-7 to -14 m), 298 grid cells between (-14 to -21 m), 105 grid cells between (-21 to -25.3 m). In the dry period of year 2011, 36% area was within 7 m and remaining 64% area was in stress condition. For in wet period 72% area was with in 7m and remaining 28% area in stress condition.

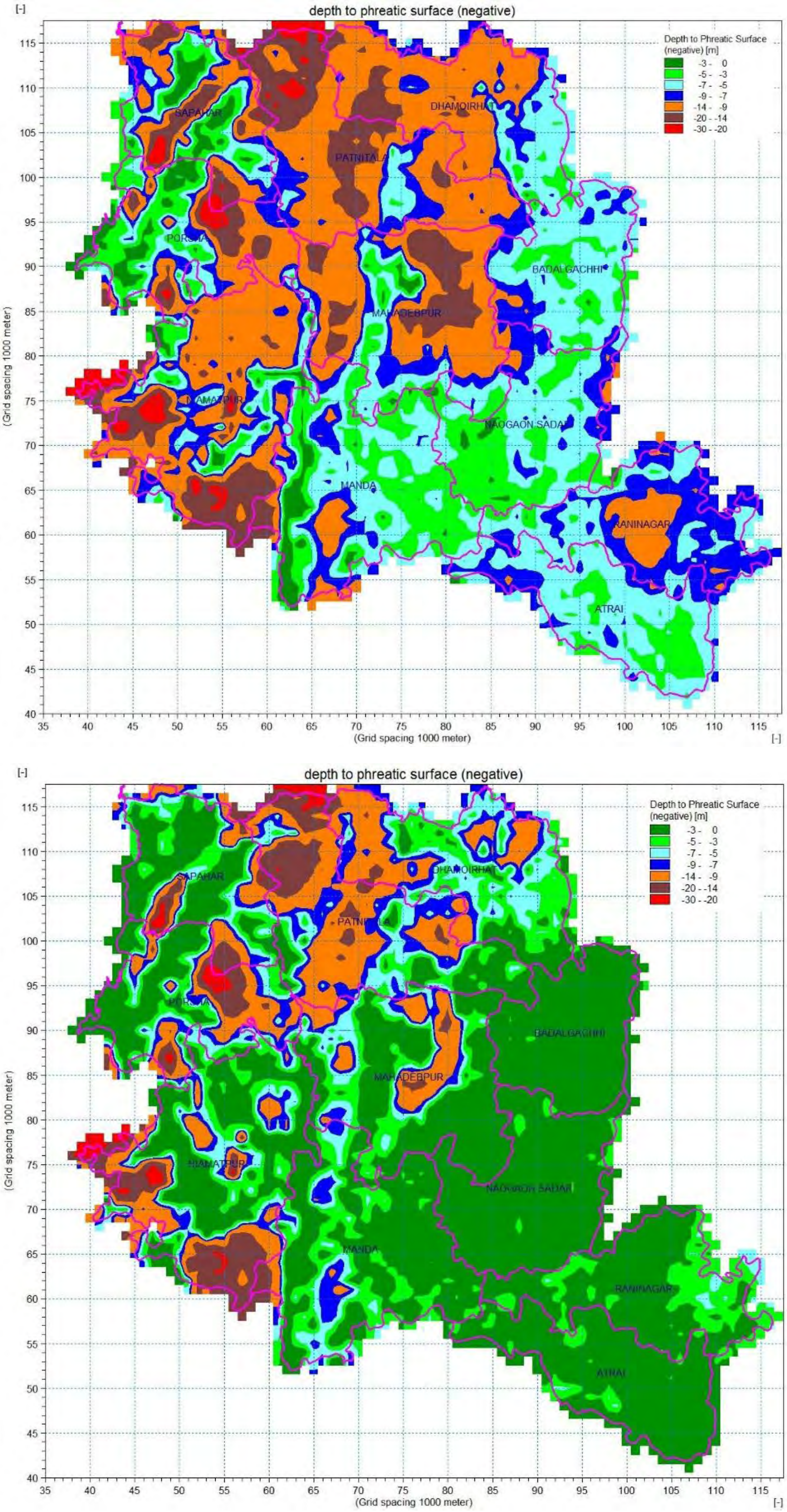


Figure 5.5: Maximum Depth to Phreatic Surface on May 01(top) and Minimum Depth to Phreatic Surface on October 01(bottom), 2008

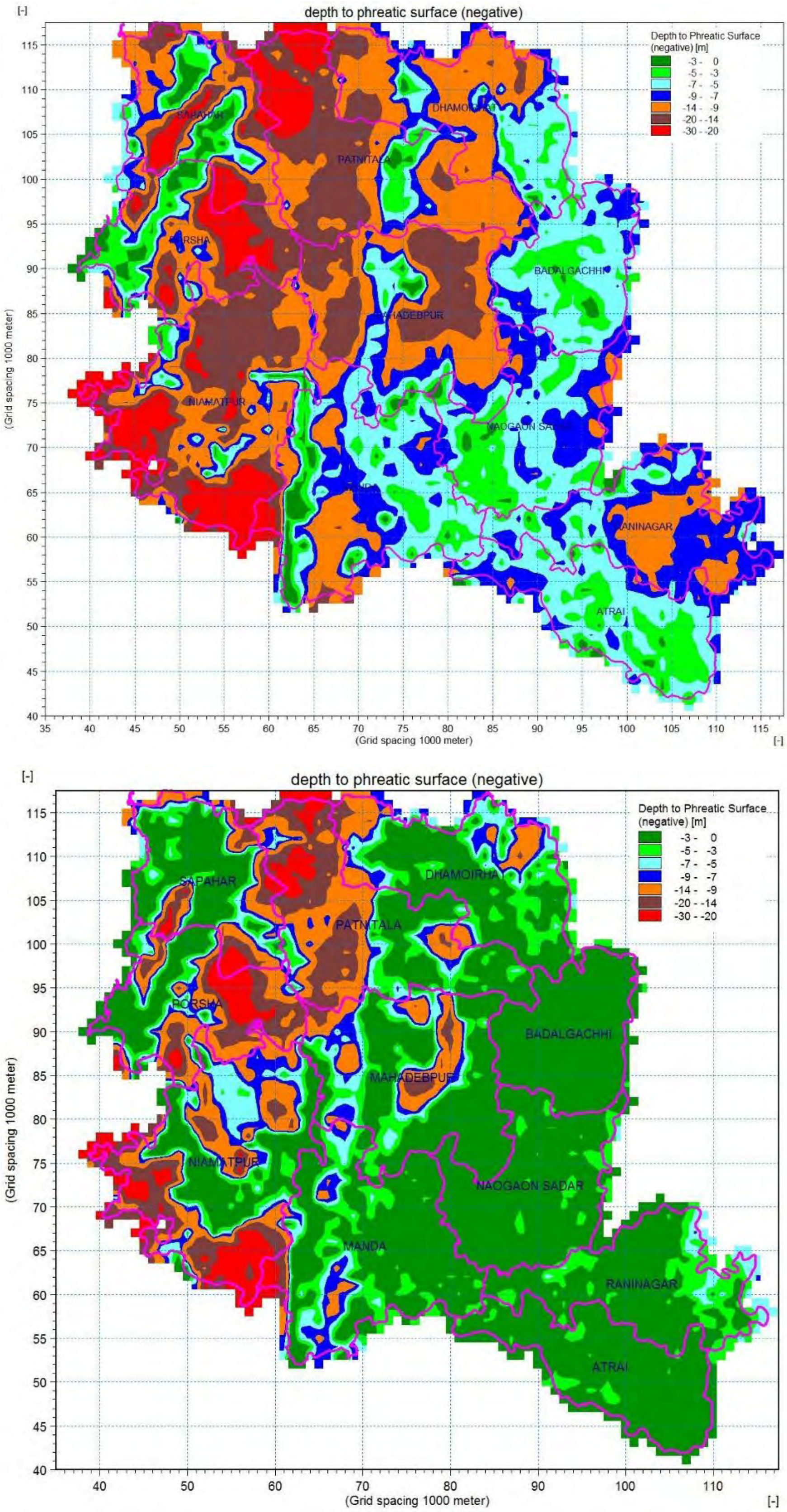


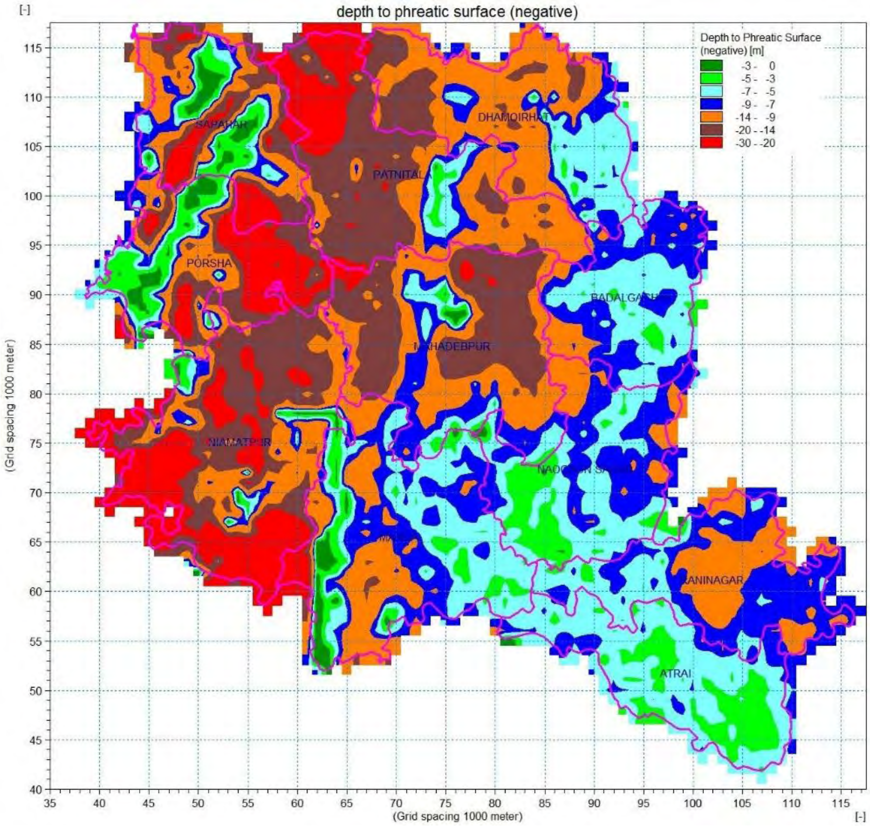
Figure 5.6: Maximum Depth to Phreatic Surface on May 01(top) and Minimum Depth to Phreatic Surface on October 01(bottom), 2011

Year 2013

The spatial variation for dry and wet periods of year 2013 in Naogaon district has been shown in Figure 5.7. It can be seen from the Figure 5.7 that maximum depth to phreatic surface range between (-) 0.0 m to (-) 27.8 m for dry period and (-) 0.0 m to (-) 26.7 m for wet period. From the cell calculation 1025 grid cells between (0 to -7m), 1398 grid cells between (-7 to -14 m), 696 grid cells between (-14 to -21 m), 315 grid cells between (-21 to -25.3 m) for dry period. And for wet period 1949 grid cells between (0 to -7m), 805 grid cells between (-7 to -14 m), 500 grid cells between (-14 to -21 m), 180 grid cells between (-21 to -25.3 m). In the dry period of year 2013, 30% area was within 7 m and remaining 70% area was in stress condition. For in wet period 57% area was with in 7m and remaining 43% area in stress condition.

Year 2015

The spatial variation for dry and wet periods of year 2015 in Naogaon district has been shown in Figure 5.8. It can be seen from the Figure 5.8 that maximum depth to phreatic surface range between (-) 0.0 m to (-) 27.8 m for dry period and (-) 0.0 m to (-) 26.7 m for wet period. From the cell calculation 893 grid cells between (0 to -7m), 1514 grid cells between (-7 to -14 m), 679 grid cells between (-14 to -21 m), 349 grid cells between (-21 to -25.3 m) for dry period. And for wet period 2339 grid cells between (0 to -7m), 494 grid cells between (-7 to -14 m), 405 grid cells between (-14 to -21 m), 196 grid cells between (-21 to -25.3 m). In the dry period of year 2015, 26% area was within 7 m and remaining 74% area was in stress condition. For in wet period 68% area was with in 7m and remaining 32% area in stress condition.



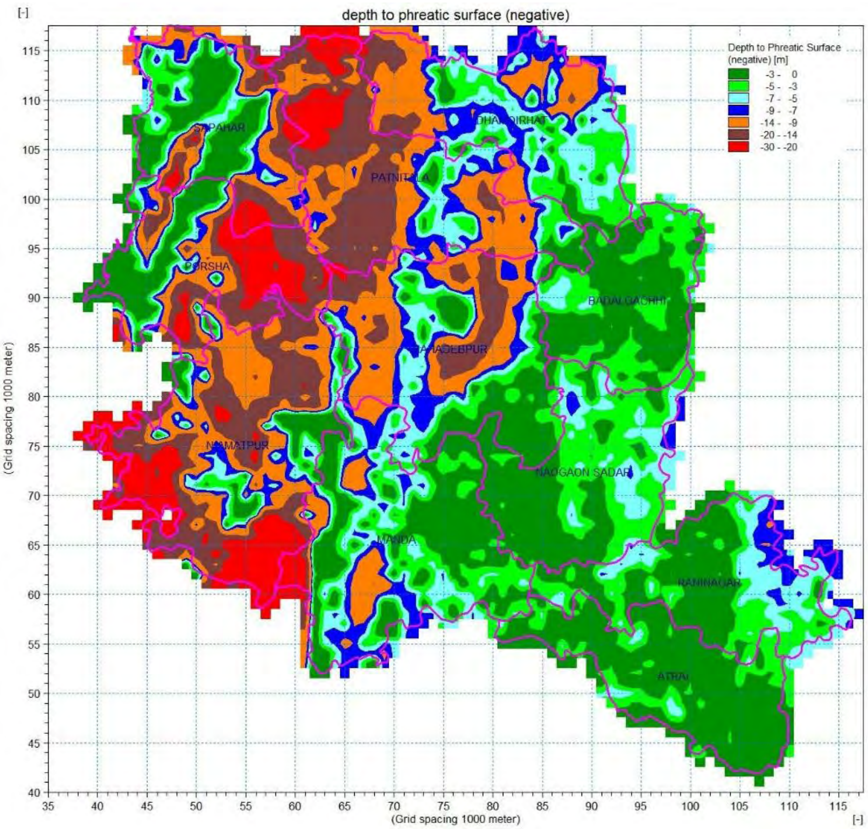
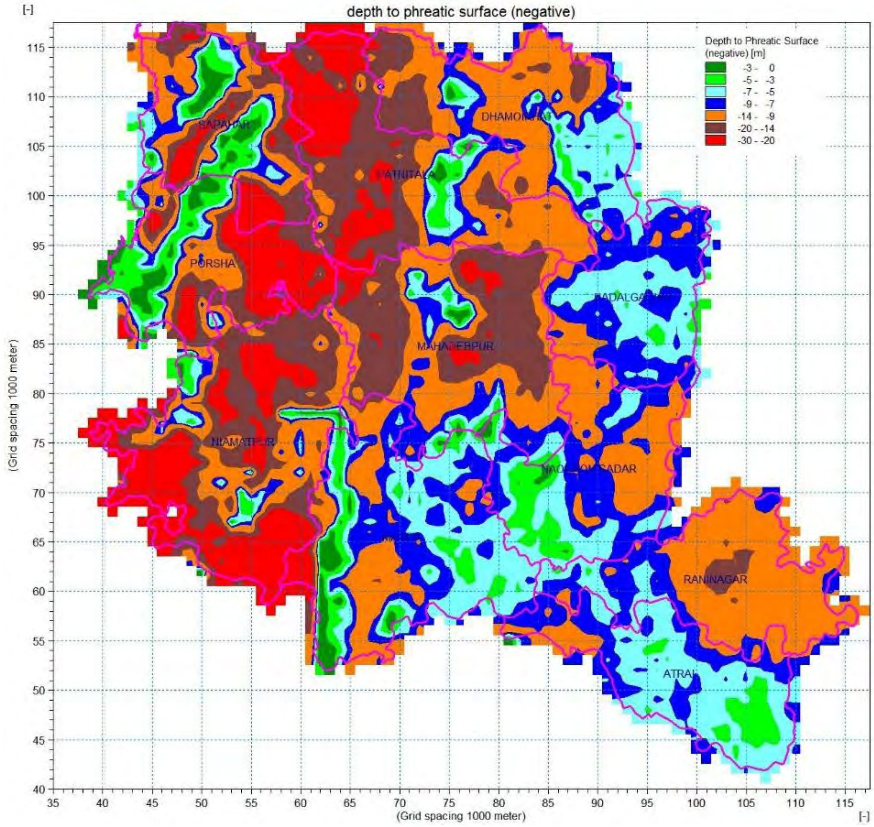


Figure 5.7: Maximum Depth to Phreatic Surface on May 01(top) and Minimum Depth to Phreatic Surface on October 01(bottom), 2013



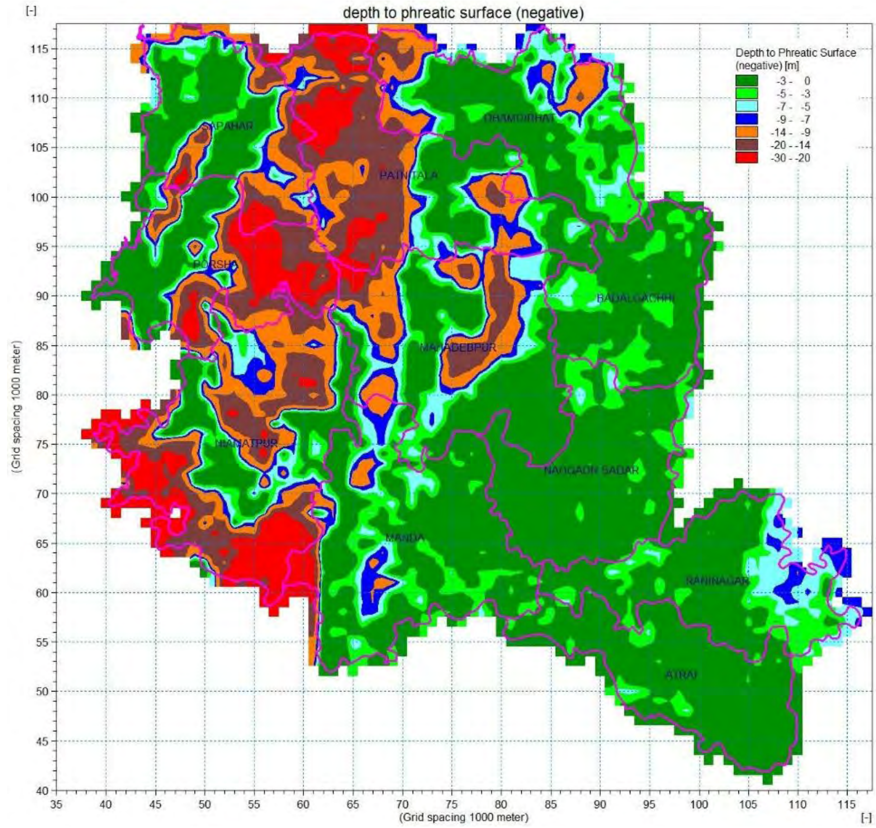


Figure 5.8: Maximum Depth to Phreatic Surface on May 01(top) and Minimum Depth to Phreatic Surface on October 01(bottom), 2015

5.1.1 Summary of Temporal Variation of Groundwater Level

The summery of the temporal variation for different year of Naogaon district shown in Table 5.1. In Figure 5.9 shows, the yearly temporal variation for dry period and in Figure 5.10 shows the yearly temporal variation for wet period.

Table 5.1: Yearly Comparison of Dry and Wet Period (area in sq km and % of total area)

Year	Dry Period				Wet Period			
	0 to -7 m	-7 to -14 m	-14 to -21 m	-21 to -30 m	0 to -7 m	-7 to -14 m	-14 to -21 m	-21 to -30 m
2002	1598 (47%)	1389 (16%)	394 (35%)	53 (2%)	2907 (85%)	377 (4%)	131 (10%)	18 (1%)
2005	1731 (50%)	1405 (15%)	235 (32%)	62 (3%)	2762 (80%)	502 (5%)	140 (13%)	30 (2%)
2008	1514 (44%)	1476 (16%)	396 (38%)	48 (2%)	2578 (75%)	635 (6%)	194 (17%)	27 (2%)
2011	1235 (36%)	1371 (16%)	604 (40%)	224 (8%)	2495 (72%)	536 (5%)	298 (19%)	105 (4%)
2013	1025 (30%)	1398 (17%)	696 (42%)	315 (11%)	1949 (57%)	805 (9%)	500 (27%)	180 (7%)
2015	893 (26%)	1514 (17%)	679 (45%)	349 (12%)	2339 (68%)	494 (5%)	405 (20%)	196 (7%)

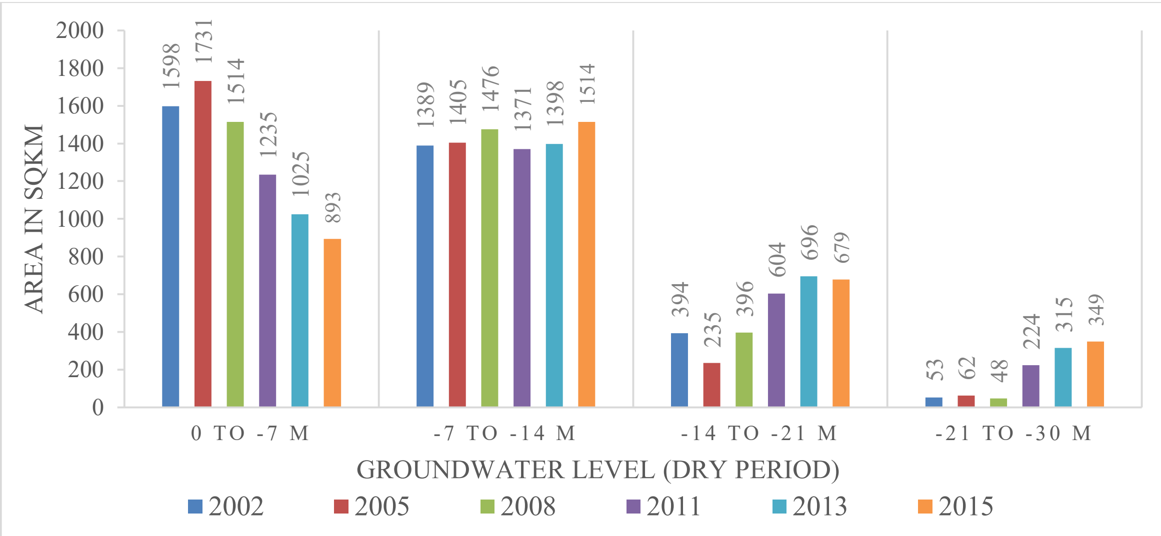


Figure 5.9: Yearly Comparison of Dry Period

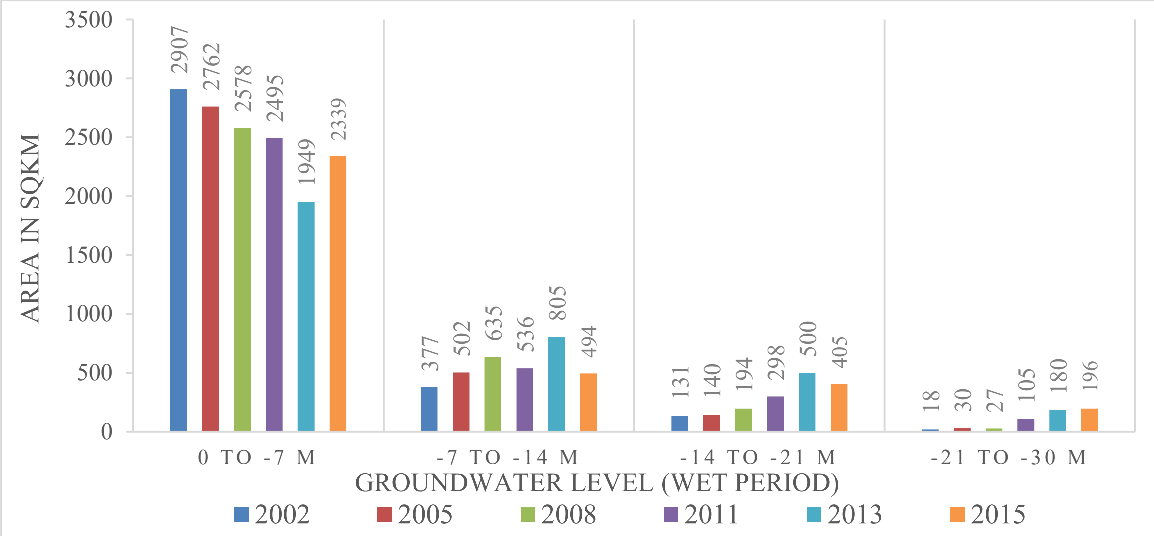


Figure 5.10: Yearly Comparison of Wet Period

5.1.2 Summary of Spatial Variation of Groundwater Level

In dry period of year 2002, over ninety percent area of Dhamoirhat, Patnitola, Niamatpur upazila, fifty percent area of Porsha, Sapahar, Mohadevpur upazila and less than twenty percent area of Naogaon Sadar, Raninagar, Manda upazila are in stress condition. On the other hand in dry period of year 2015, more than ninety percent area of Mohadevpur, Patnitola, Niamatpur upazila, over sixty percent area of Naogaon Sadar, Porsha, Sapahar, Dhamoirhat, Raninagar upazila and less than thirty percent area of, Manda, Atrai upazila are in stress condition. In year 2015 stress condition areas of groundwater level between -20 to -30m in Patnitola, Niamatpur, Porsha, Sapahar and other stress areas between -7 to -20 m. But in year 2002, most of the stress areas groundwater level is range between -7 to -14m in year 2002.

5.2 Effect of Different Cropping Pattern on Groundwater

The crop cultivation of Naogaon district during dry season (December - May) depends on irrigation. In Rabi season most of the cultivable area under Boro rice. Boro rice is the highest water consuming crop. So the stress condition for groundwater has been increasing which is shown in section 5.1. To reduce stress condition Boro cultivation should be change by other less water demand crops.

Wheat and vegetable consume less water compared to Boro rice. Three (3) types of crop pattern in dry season have considered as (i) present crop pattern [Option-0], (ii) (50% boro & 50% wheat) in the whole crop area [Option-1], and (iii) only wheat (a sample of less water demand crop) in the whole crop area [Option-2], (iv) (50% boro & 50% vegetable) in the whole crop area [Option-3] and compared with the present crop pattern.

The main conclusions drawn from this study are given below:

Option-1

Comparing the two figures (Figure 5.11) for present crop pattern in year 2015 maximum depth to phreatic surface range between (-) 0.0 m to (-) 27.8 for dry period. Then change in cropping pattern (50% boro & 50% wheat) maximum depth to phreatic surface range between (-) 0.0 m to (-) 26.5 for dry period. From the cell calculation 893 grid cells between (0 to -7m), 1514 grid cells between (-7 to -14 m), 679 grid cells between (-14 to -21 m), 349 grid cells between (-21 to -26.5 m) for dry period. And after change in crop pattern 1022 grid cells between (0 to -7m), 1546 grid cells between (-7 to -14 m), 630 grid cells between (-14 to -21 m), 235 grid cells between (-21 to -26.5 m) for dry period. In the dry period of year 2015, 26% area was within 7 m and remaining 74% area was in stress condition and after changing crop pattern dry period 31% area was with in 7m and remaining 69% area in stress condition.

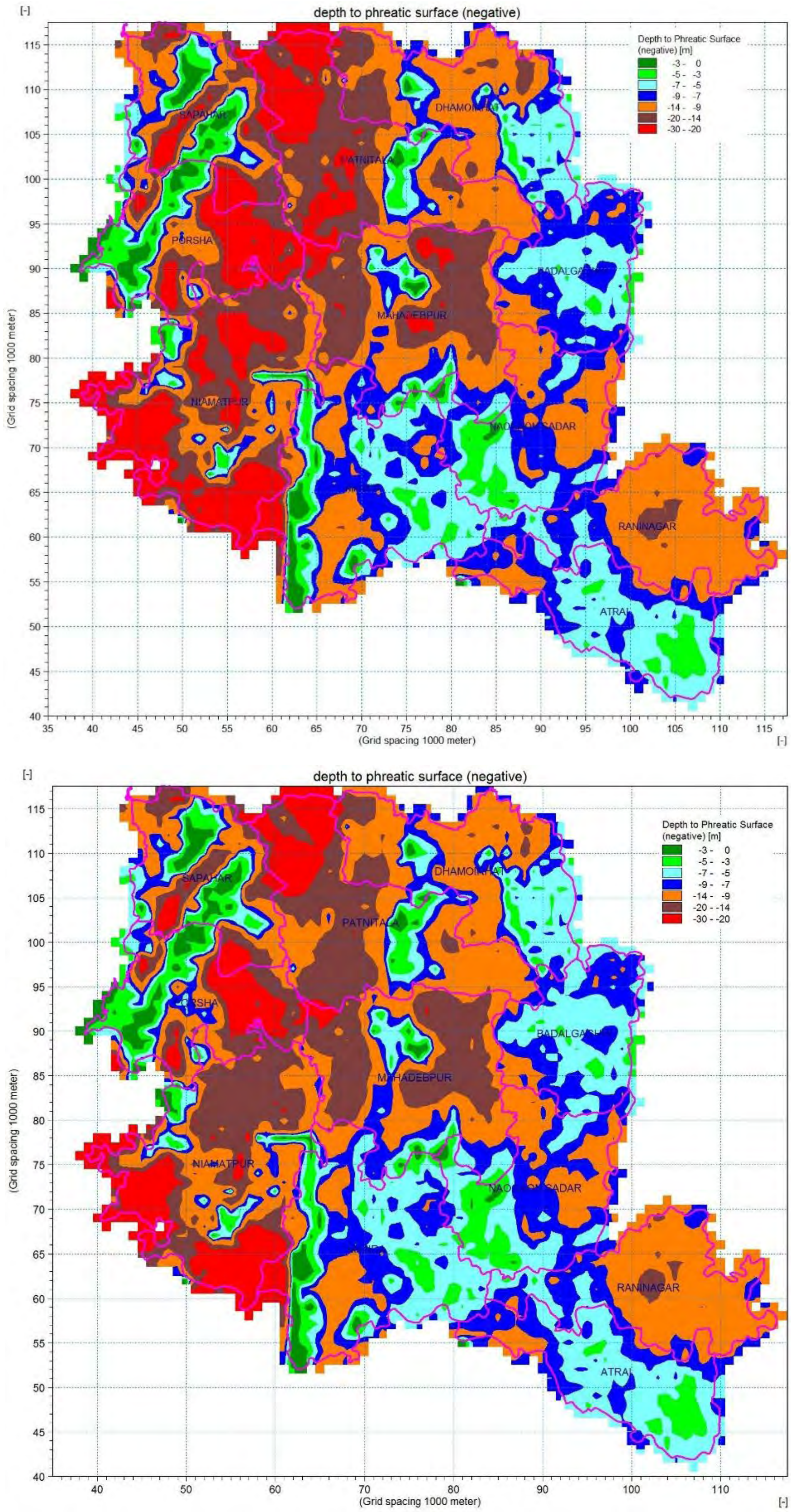


Figure 5.11: Maximum Depth to Phreatic Surface on May 01(top) and Maximum Depth to Phreatic Surface on May 01 (bottom) (50% boro & 50% wheat), 2015

Option-2

Comparing the two figures (Figure 5.12) for present crop pattern in year 2015 maximum depth to phreatic surface range between (-) 0.0 m to (-) 27.8 for dry period. Then change in cropping pattern (100% wheat) maximum depth to phreatic surface range between (-) 0.0 m to (-) 25.3 for dry period. From the cell calculation 893 grid cells between (0 to -7m), 1514 grid cells between (-7 to -14 m), 679 grid cells between (-14 to -21 m), 349 grid cells between (-21 to -25.3 m) for dry period. And after change in crop pattern 1834 grid cells between (0 to -7m), 1367 grid cells between (-7 to -14 m), 178 grid cells between (-14 to -21 m), 54 grid cells between (-21 to -25.3 m) for dry period. In the dry period of year 2015, 26% area was within 7 m and remaining 74% area was in stress condition and after changing crop pattern dry period 54% area was with in 7m and remaining 46% area in stress condition.

Option-3

Comparing the two figures (Figure 5.13) for present crop pattern in year 2015 maximum depth to phreatic surface range between (-) 0.0 m to (-) 27.8 for dry period. Then change in cropping pattern (50% boro & 50% vegetable) maximum depth to phreatic surface range between (-) 0.0 m to (-) 26.5 for dry period. From the cell calculation 893 grid cells between (0 to -7m), 1514 grid cells between (-7 to -14 m), 679 grid cells between (-14 to -21 m), 349 grid cells between (-21 to -26.5 m) for dry period. And after change in crop pattern 956 grid cells between (0 to -7m), 1525 grid cells between (-7 to -14 m), 663 grid cells between (-14 to -21 m), 289 grid cells between (-21 to -26.5 m) for dry period. In the dry period of year 2015, 26% area was within 7 m and remaining 74% area was in stress condition and after changing crop pattern dry period 28% area was with in 7m and remaining 72% area in stress condition.

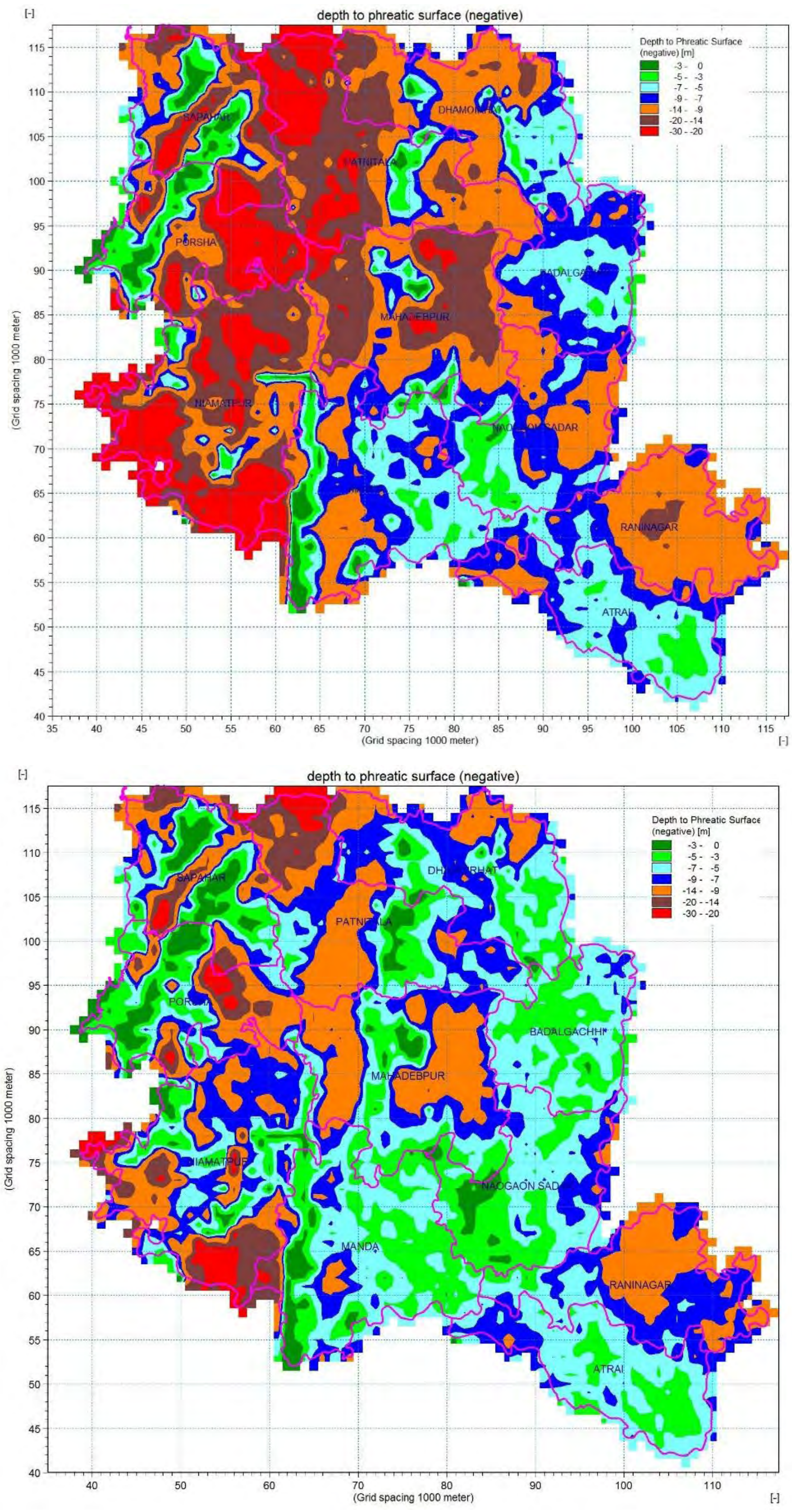
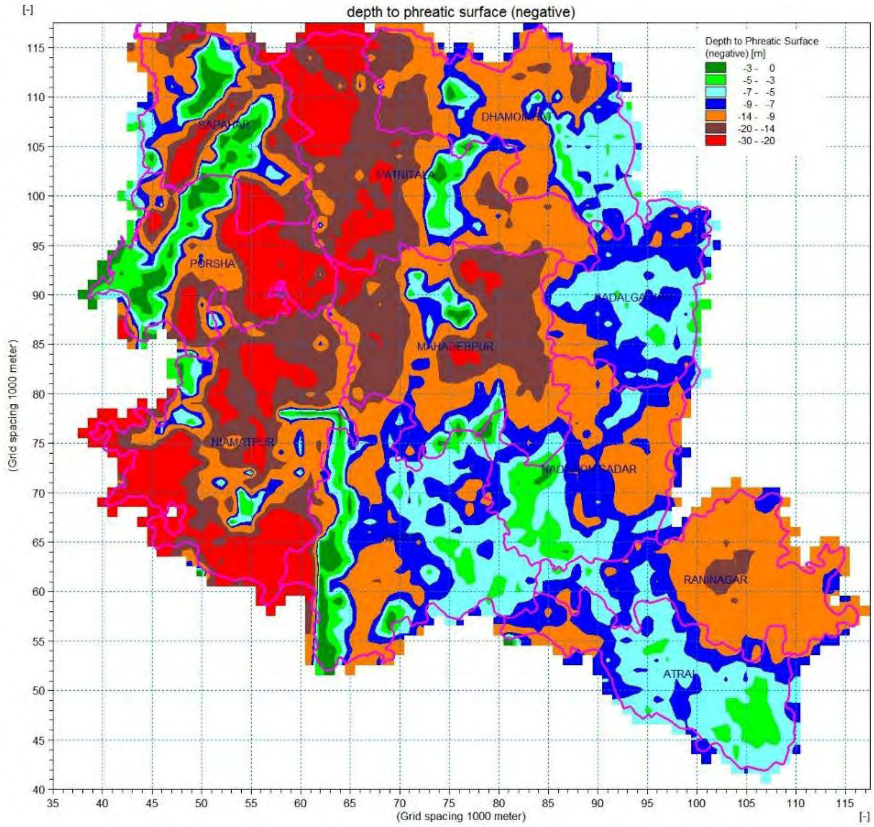


Figure 5.12: Maximum Depth to Phreatic Surface on May 01(top) and Maximum Depth to Phreatic Surface on May 01 (bottom) (100% wheat), 2015



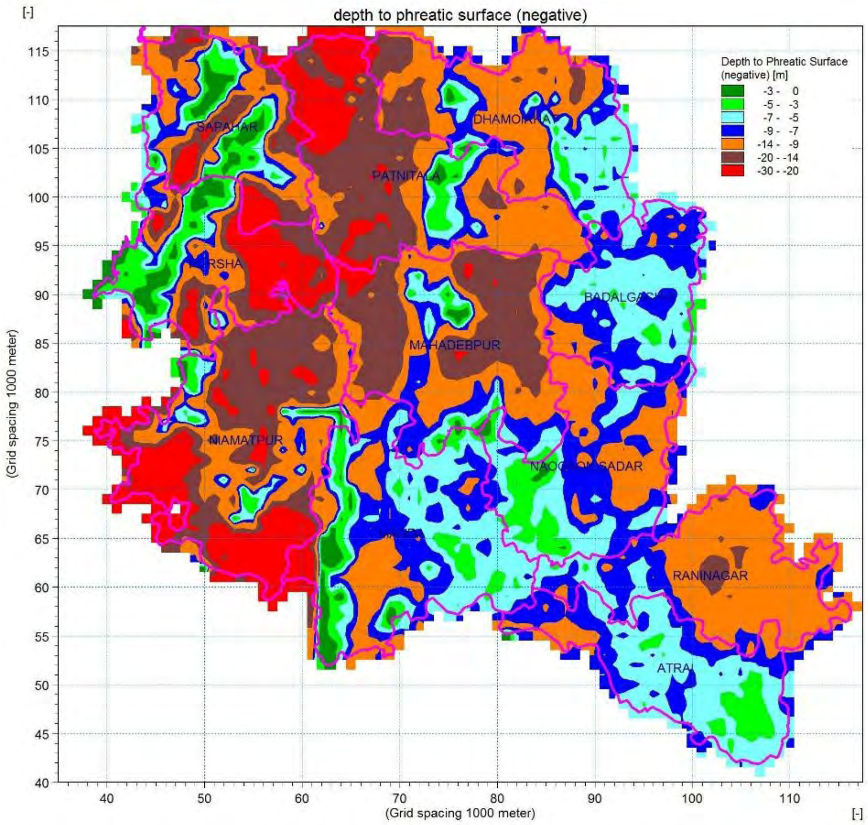


Figure 5.13: Maximum Depth to Phreatic Surface on May 01(top) and Maximum Depth to Phreatic Surface on May 01 (bottom) (50% boro & 50% vegetable), 2015

From this analysis, the overall condition for this three option of Naogaon district has been presented in Table 5.2 and Figure 5.14. It is seen from the table that in year 2015, 26% area groundwater table above -7.0 m and 74% area below -7.0m in Naogaon district. In option-1, 30% area groundwater table above -7.0 m and 70% area below -7.0m, Option-2, 54% area groundwater table above -7.0 m and 46% area below -7.0m and in Option-3, 28% area groundwater table above -7.0 m and 72% area below -7.0m in Naogaon district.

Table 5.2: Comparison between the Options (area in sq km and % of total area)

Option	Groundwater Level		0 to -7 m	-7 to -14 m	-14 to -21 m	-21 to -30 m
Option-0	Present condition	Year 2011	1235 (36%)	1371 (16%)	604 (40%)	224 (8%)
		Year 2015	893 (26%)	1514 (17%)	679 (45%)	349 (12%)
Option-1	50% Boro & 50% Wheat	Year 2015	1022 (31%)	1546 (15%)	630 (46%)	235 (8%)
Option-2	100% Wheat	Year 2015	1834 (54%)	1367 (20%)	178 (24%)	54 (2%)
Option-3	50% Boro & 50% Vegetable	Year 2015	956 (28%)	1525 (17%)	663 (45%)	289 (10%)

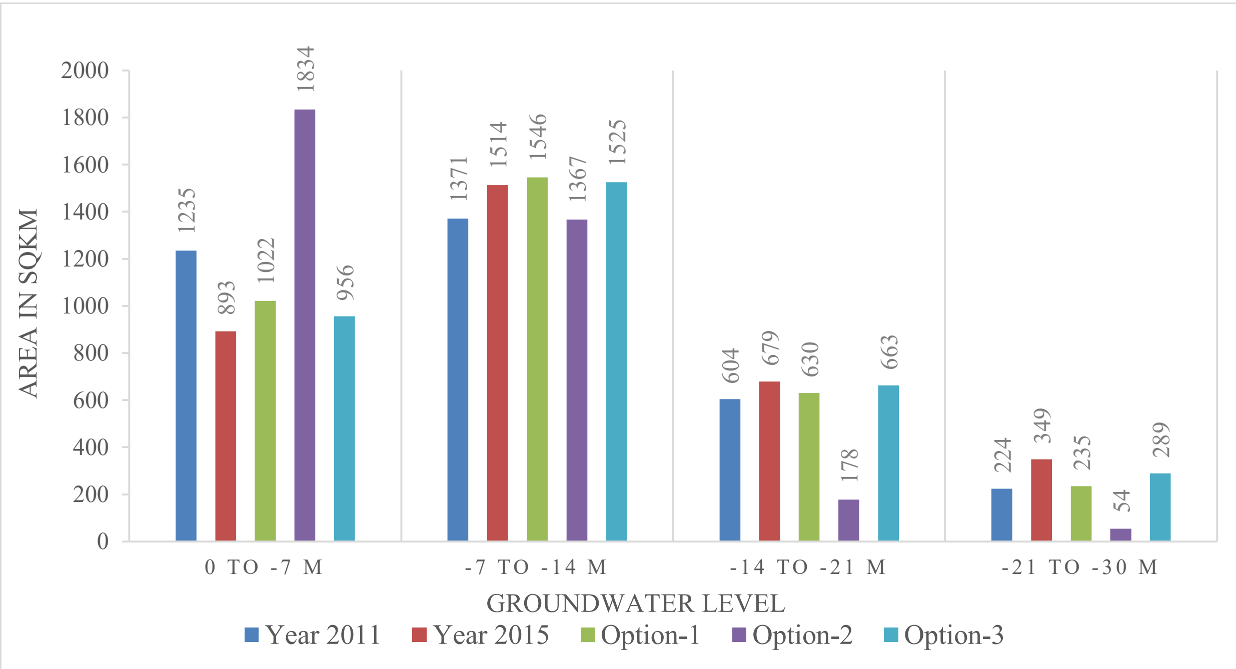


Figure 5.14: Comparison between the Options

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 General

The objective of the study is to identify the groundwater level variation for dry and wet period and the effect of different cropping pattern on ground water level of the underlying aquifer system of the Naogaon district using MIKE SHE hydrologic model. The recorded groundwater level and other relevant data are used to predict the phreatic surface up to year 2015. The other factors consider in the model are change in crop pattern and reduction of crop water demand. The outcome of the study is listed below as conclusions and the constraints of the study listed as limitations.

6.2 Conclusions

- MIKE SHE model has been simulated for Naogaon district. Calibration has been done against groundwater level.
- Spatial and temporal variation of groundwater level has been analysed for Naogaon district using MIKE SHE model for year 2002, 2005, 2008, 2011, 2013 and 2015.
- For dry period irrigation in the year 2002, the extent of groundwater level from 0 to -7m was 1598 km^2 (47%) which reduced to 893 km^2 (26%) in year 2015 and in 2002 groundwater level of area from -7 to -30m increased from 1836 km^2 (53%) to 2542 km^2 (74%) in year 2015.
- For wet period irrigation in the year 2002, the extent of groundwater level from 0 to -7m was 2907 km^2 (85%) which reduced to 2339 km^2 (68%) in year 2015 and in 2002 groundwater level of area from -7 to -30m increased from 526 km^2 (15%) to 1095 km^2 (32%) in year 2015. This scenario is due to low irrigation demand, increased rainfall and groundwater recharge.
- In dry period of year 2002, over ninety percent area of Dhamoirhat, Patnitola, Niamatpur upazila, fifty percent area of Porsha, Sapahar, Mohadevpur upazila and less than twenty percent area of Naogaon Sadar, Raninagar, Manda upazila are in stress condition. On the other hand in dry period of year 2015, more than ninety percent area of Mohadevpur, Patnitola, Niamatpur upazila, over sixty percent area of Naogaon Sadar, Porsha, Sapahar, Dhamoirhat, Raninagar upazila and less than thirty percent area of, Manda, Atrai upazila are in stress condition. In year 2015 stress condition areas of groundwater level between -

20 to -30m in Patnitola, Niamatpur, Porsha, Sapahar and other stress areas between -7 to -20 m. But in year 2002, most of the stress areas groundwater level is range between -7 to -14m in year 2002.

- Out of the three options, such as (50% boro & 50% wheat) in the whole crop area [Option-1], only wheat (a sample of less water demand crop) in the whole crop area [Option-2] and (50% boro & 50% vegetable) in the whole crop area [Option-3], the option-2 (100% wheat coverage) found to be the best. In this option the extent of area could be increase from 893km^2 (26%) to 1834 km^2 (54%) in dry period for the safe groundwater level of 0 to -7m in year 2015. Which is close to the year 2005 dry period area.

6.3 Recommendations

- The borelog data used in this model found upto 80m below ground surface. So, the depth of the model is limited to 80m. As a result, the impact on deeper aquifer could not be addressed. The present study results based on the upper aquifer only.
- The rainfall data outside the border of Bangladesh not available. If the actual ground station data was available, the flow in the river could be estimated more accurately
- The resolution of DEM is 300 sq. m but the model grid size is 1000 sq. m which may cause the simulated groundwater level to deviate from the observed groundwater levels. Effect of the refine grid size should be investigated.
- The effect of change in landuse pattern on groundwater should be investigated.
- The effect of change in the amount and rainfall pattern on groundwater should be investigated.

REFERENCES

FAO [Food and Agriculture Organization] (2012). Coping with water scarcity. An action framework for agriculture and food security. Retrieved from http://www.fao.org/docrep/016/i3015e/i3015e.pdf

Altaner, S. (2012). Physical Resources: Water, Pollution, and Minerals - Chapter Introduction. Connexions module: m41523. Revision 3.

Subramanya, K. (1994). Engineering Hydrology. Second Edition. Tata McGraw Hill Publishing Company Limited. ISBN 0-07-462449-8.

Chow, V.T., Maidment, D.R. and Mays, L.W. (1988). Applied Hydrology. McGraw-Hill Series in Water Resources and Environmental Engineering. McGraw-Hill Book Company. New York. ISBN 0-07-100174-3.

Siebert, S. and D¨oll, P. (2010). Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation, J. Hydrol., 384(3–4), 198–217, doi:10.1016/j.jhydrol.2009.07.031, 2010.

Shaw R., Nguyen H., Habiba U. and Takeuchi Y. (2011): Overview and characters of Asian monsoon drought, in Drought in Asian Monsoon Region, page 35, Emerald Publisher, UK.

Shahid, S. and Behrawan, H. (2008). Drought risk assessment in the western part of Bangladesh, Journal of Natural disaster. 46 (3): 391-413.

Amin, M.N. (2009). Ground Water Utilization for Agricultural Development: Some Policy Suggestions. Thoughts on Economics, Vol. 19, No. 01. ISSN: 02568586.

Jahan, C.S., Mazumder, Q.H., Islam, A.T.M.M. and Adham, M.I. (2010). Impact of irrigation in barind area, NW Bangladesh-an evaluation based on the meteorological parameters and fluctuation trend in groundwater table. Journal Geological Society of India.

Luby, S. (2013). Water management for a healthy Bangladesh: The need for multi-sector collaboration. Paper presented at National Public Health Conference, Dhaka, Bangladesh. 15 January.

Harvey, C.F., Ashfaque, K.N., Yu, W., Badruzzaman, A.B.M., Ali, M.A., Oates, P.M., Michael, H.A, Neumann, R.B., Beckie, R., Islam, S. and Ahmed, M.F. (2006). Groundwater Dynamics and Arsenic Contamination in Bangladesh, Chemical Geology, 228, 112-136.

Dey, N.C., Bala, S.K., Islam, A.K.M.S. Rashid, M.A. and Hossain M. (2013). Sustainability of Groundwater Use for Irrigation in Northwest Bangladesh, brac, Bangladesh.

NWMP [National Water Management Plan] (2001). Main Report, Volume 2, Ministry of Water Resources. Government of Bangladesh.

BBS [Bangladesh Bureau of Statistics] (2005). Statistical pocket book of Bangladesh. Government of the People's Republic of Bangladesh. Ministry of Planning. P.194.

BARI [Bangladesh Agricultural Research Institute] (1990). Means of profitable wheat cultivation. Wheat Research Center, Bangladesh Agril. Res. Inst. Nashipur, Dinajpur. Page 1-11.

IWM [Institute of Water Modelling] (2012). Groundwater Resources Study and Decision Support System Development of Rajshahi, Naogaon, Chapai Nawabganj, Pabna and Natore Districts and Also Remaining Districts (Except Thakurgaon, Panchagarh, Dinajpur & Joypurhat Districts) of Rajshahi Division through Mathematical Model Study for Barind Integrated Area Development Project, Phase-III. Final Report submitted to Barind Multipurpose Development Authority (BMDA) under Ministry of Agriculture Government of Bangladesh.

Essink, G.O. (2000). Groundwater Modelling. Utrecht University, Interfaculty Centre of Hydrology Utrecht, Institute of Earth Sciences, Department of Geophysics, L4018/GWMI (2000).

DHI (Danish Hydraulic Institute), (2016). MIKE SHE- Reference Manual. Danish Hydraulic Institute.

Bedient, P.B. and Huber, W.C. (2002). Hydrology and Floodplain Analysis, 3rd Edition, Prentice Hall, NJ.

DHI [Danish Hydraulic Institute] (2011), MIKE SHE User Manual Volume 2: Reference Guide, edited.

BADC [Bangladesh Agricultural Development Corporation] (2005). Minor Irrigation Report 2004-05. Government of the People's Republic of Bangladesh. Ministry of Agriculture.

BADC [Bangladesh Agricultural Development Corporation] (2008). Minor Irrigation Report 2007-08. Government of the People's Republic of Bangladesh. Ministry of Agriculture.

BADC [Bangladesh Agricultural Development Corporation] (2011). Minor Irrigation Report 2010-11. Government of the People's Republic of Bangladesh. Ministry of Agriculture.

BADC [Bangladesh Agricultural Development Corporation] (2015). Minor Irrigation Report 2004-05. Government of the People's Republic of Bangladesh. Ministry of Agriculture.

BBS [Bangladesh Bureau of Statistics] (2008). Bangladesh Agriculture Census. Government of the People's Republic of Bangladesh. Ministry of Planning.

Islam, M.T. (2009). A Study on Barind Aquifer-Ganges River Interaction. Master of Engineering in Water Resources. Department of Water Resources Engineering. Bangladesh University of Engineering and Technology.

IWM (2007). Mathematical Modelling and Topographic Survey for Integrated Water Resources Management of Chalan Beel Area Including Beel Halti Development Project. Final Report submitted to Barind Multipurpose Development Authority (BMDA) under Ministry of Agriculture, Government of Bangladesh

IWM (2012). Strengthening BMDA's Capacity on Water Resources Management. Final Report submitted to Barind Multipurpose Development Authority (BMDA) under Ministry of Agriculture, Government of Bangladesh.

IWM [Institute of Water Modelling] (2006). Groundwater Model Study for Deep Tube Well Installation Project in Barind Area. Final Report submitted to Barind Multipurpose Development Authority (BMDA) under Ministry of Agriculture, Government of Bangladesh

IWM [Institute of Water Modelling] (2013). Groundwater Resources Study and IIS Development of Pabna, Sirajgonj, Bogra, Gaibandha, Rangpur, Kurigram, Nilphamari and Lalmonirhat Districts through Mathematical Model Study. Interim Report submitted to Barind Multipurpose Development Authority (BMDA) under Ministry of Agriculture, Government of Bangladesh

Razzaque, M.A., Suffium, M.A. and Badruddin, M. (1992). Wheat in national economy of Bangladesh. Crop Sci. Proc. First Biennial Conf. CSSB, 18-20 January, 1992: 13-26.

Karim, M.A., (1984): Upazila-wise groundwater recharge conditions of Bangladesh. Groundwater Investigation Circle, Bangladesh Water Development Board, Dhaka.

Karim, M. A. (1972). Ground Water Potential in Northern Areas of Dinajpur and Rangpur Districts, Bangladesh Water Development Board.

Graham, D.N. and Butts, M. B. (2005) Flexible, integrated watershed modelling with MIKE SHE. In Watershed Models, Eds. V.P. Singh & D.K. Frevert Pages 245-272, CRC Press. ISBN: 0849336090.