STUDY ON SUSTAINABILITY OF GROUNDWATER RESOURCES IN RAJSHAHI DISTRICT OF BANGLADESH

M. Sc. Engineering Thesis

by

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OCTOBER, 2020

STUDY ON SUSTAINABILITY OF GROUNDWATER RESOURCES IN RAJSHAHI DISTRICT OF BANGLADESH

A Thesis Submitted

by

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In partial Fulfillment of the requirements for the Degree of
MASTER OF SCIENCE IN WATER RESOURCES ENGINEERING

DEPARTMENT OF WATER RESOURCES ENGINEERING
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OCTOBER, 2020

CERTIFICATION OF APPROVAL

The Thesis titled **“Study on Sustainability of Groundwater Resources in Rajshahi District of Bangladesh”**, submitted by Md. Ashraful Islam, Roll no. 1015162042 P, Session October 2015, to the Department of Water Resources Engineering, Bangladesh University of Engineering and Technology, has been accepted as satisfactory in partial fulfillment of the requirements for the degree of Master of Science in Water Resources Engineering on 18th October, 2020.

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This is to certify that this M.Sc. thesis entitled **"Study on Sustainability of Groundwater Resources in Rajshahi District of Bangladesh"** has been done by me under the supervision of Dr. Umme Kulsum Navera, Professor, Department of Water Resources Engineering, Bangladesh University of Engineering and Technology, Dhaka. I do hereby declare that this project or any part of it has not been accepted elsewhere for the award of any degree or diploma from any other institution.

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ACKNOWLEDGEMENT

At first, the author acknowledges the blessing of almighty Allah for enabling him to complete the study successfully.

The author is obliged to his thesis supervisor Dr. Umme Kulsum Navera, Professor, Department of Water Resources Engineering, BUET, for her continuous guidance, and caring and affectionate encouragement at every stage of this work.

The author also expresses profound gratitude to his thesis committee member Dr. Anika Yunus, Professor and Head, DWRE, BUET, Dr. Md. Sabbir Mostafa Khan, Professor, DWRE, BUET and external member of thesis committee Dr. A.F.H. Afzal Hossain, Ex-DED (P&D), IWM for their nice and careful guidance and constructive suggestions during final thesis defense which have been immensely contributed to the improvement of this thesis.

The author wishes his sincere gratitude to Mr. Mohammad Salah Uddin, Senior Specialist, Irrigation Management Division, IWM, Ms. Anin Dita Dey, Assistant Engineer, BWDB, Mr. S.M. Sahabuddin, Junior Specialist, IWM and Ms. Swarna Chowdhury, Junior Engineer, IWM for their continuous support and consultations regarding this research work.

The author is grateful to IWM authority for giving supports by providing valuable guidance, necessary data, and permission to use software during this research work.

The author is thankful to all the officials of WRE department and the authority for allowing him to use the WRE library.

The author finally expresses his profound thanks to his parents for supporting and inspiring to conduct the M.Sc. in Water Resources Engineering at BUET.

ABSTRACT

Bangladesh is predominantly an agricultural country where agriculture sector plays a significant role in accelerating the economic growth of the country. It is therefore important to have a sustainable, environment-friendly and profitable agricultural system in order to ensure long-term food security. Agriculture in Bangladesh is largely dependent on groundwater resources. But this scarce groundwater resources have been decreasing alarmingly in Rajshahi district which is one of the most drought prone districts and driest place of Bangladesh. This situation has threatened the sustainability of agriculture in this area at present as well as in the near future. Over abstraction of groundwater, lack of surface water bodies, low rainfall, high elevation, thick clay layer are the major hindrances in the study area to sustain groundwater resources. As a result, groundwater level in this district is successively falling in each year. In this study it has been strived to sustain this valuable groundwater sources for the sustainable agriculture of this region.

An integrated Surface Water- Groundwater base model from 2012 to 2016 has been developed, calibrated and validated. It has helped to understand current situation of the study area. In order to sustain groundwater resources up to year 2030, it is needed to foresee future condition of groundwater resources from 2017 to 2030. For this reason, there are ten (10) scenarios have been chosen to understand future groundwater condition in the study area by considering different driving forces such as Rainfall, Evaporation, Groundwater Level, Surface Water Level, and Water Demand. These scenarios have been analyzed to identify the most extreme future scenario that is needed to be countered by applying suitable interventions.

Model output has been analyzed on eight Upazilas (Upazila wise) to understand the condition of groundwater precisely instead of taking study area as a whole. In spite of having different climatic conditions, soil type, cropping pattern, water demand and water availability most of these Upazilas have shown similar result. Scenario number 10 (S-10) has been found the most extreme scenario in most of the Upazilas (six out of eight). There are three interventions have been considered out of which intervention 1 (I-1) has shown significant result towards sustainable groundwater resources. In intervention 1, crop diversification technique has been applied by substituting high water consumed Boro rice by low water consumed Wheat and the outcome is remarkable. Groundwater resources of 96.55% of the study area has improved and additional 3620 million cubic meter saturated zone is increased in the study area in the most extreme event (April, 2028) of most extreme scenario. Moreover, all analysis has been done to counter the driest event (April, 2028) of worst scenario so that reaming events could be could be countered. Based on analysis it can be said that this intervention will be a suitable solution to sustain groundwater resources for future in this area. The results that have been found from this study will be very much helpful to carry out further studies in future.

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LIST OF ABBREVIATIONS

BWDB	Bangladesh Water Development Board
BUET	Bangladesh University of Engineering and Technology
DWRE	Department of Water Resources Engineering
FAP	Flood Action Plan
NWMP	National Water Management Plan
IWM	Institute of Water Modelling
BMDA	Barind Multipurpose Development Authority
SW	Surface Water
GW	Groundwater
GWD	Groundwater Depletion
FAO	Food and Agriculture Organization
WARPO	Water Resources Planning Organisation
UNDP	United Nations Development Programme
DTW	Deep Tube Well
SWT	Shallow Tube Well
MPO	Master Plan Organization
GWT	Groundwater Table
NW	North West
SDG	Sustainable Development Goals
K	Hydraulic Conductivity
Sy	Specific Yield
T	Transmissivity

CHAPTER 1
INTRODUCTION

1.1 Background of the Study

Groundwater in Bangladesh transpires at a very shallow depth where the recent river-borne sediments form prolific aquifers in the floodplains. In the hilly areas, the Pliocene Tipam sands serve as aquifers. In the higher terraces, the Barind and Madhupur tracts, the Pleistocene DupiTila sands act as aquifers (Rahman et al., 2012). The groundwater level is at or very close to the surface during the monsoon whereas it is at maximum depth during the months of April and May. This trend is common over most of Bangladesh except Dhaka City and the Barind Tract (Ahmed, 2014).

Barind Tract, the largest Pleistocene physiographic unit of the Bengal basin, covering an area of about 7,770 sq km (Rahman et al., 2012 and Ahmed, 2014) can be divided into high, medium and low based on their elevation (IWM, 2012). Elevation of the area varies from 9 m to 47 m PWD (Public Works Datum) (BMDA, 2006). Because of the elevation of high Barind, Rajshahi is one of the most drought prone districts of Bangladesh (Chowdhury et al., 2018). The impact of drought can be much higher and can cause greater loss than flood, cyclone and storm surge (Alam et al., 2012; Paul, 1998; Shahid, 2008). Drought is related to groundwater recharge.

Groundwater recharging in Bangladesh mainly occurs by monsoon rainfall and flooding. Due to elevation of high Barind (topography varies from 20.0 m PWD to 47.0 m PWD) (IWM, 2012) it is located in flood free zone. So, main source of groundwater recharging in this area is rainfall (Islam et al., 2014). With the exception of the relatively dry western region of Rajshahi, where the annual rainfall is about 1600 mm, most parts of the country receive at least 2000 mm of rainfall per year (Weatheronline, 2018). Moreover, thick sticky clay surface of Barind Tract acts as aquitard which impedes groundwater recharging and increases surface run-off (Rahman et al., 2012). As a result, groundwater level in this part is successively falling by years with increasing withdrawal of water for irrigation (Rahman et al., 2012).Over abstraction of groundwater, lack of surface water bodies, low rainfall, high elevation, thick clay layer etc. are the major hindrances in the study area to sustain groundwater resources.

A recent study shows that groundwater level in some areas falls between 5-10 m in dry season and most of the tube wells fail to lift sufficient water (Dey et al., 2010). The Groundwater dependent irrigation system in the area has reached a critical phase as the GW level has dropped below the depth of the shallow tube wells in many places (Adhikary et al., 2013). Rice dominate the cropping pattern of Barind soil, which suffer from drought in dry season. Only one crop (Aman paddy) in wet season was cultivated in Barind (IBRD, 1970). With the rapid expansion of groundwater irrigation after 1980s, High Yielding Variety (HYV) paddies are introduced in this area. Now Barind Tract produces three crops in one agricultural season with the blessing of groundwater irrigation (Rahman et al., 2012).

Researchers and policymakers are advocating sustainable development as the best approach to today's and future water problems (Loucks, 2000; Cai et al., 2001). But sustainability of groundwater resources is at risk in terms of quantity in the northwest region (Simonovic, 1997).

1.2 Scope of the Study

Rajshahi is the most water stressed district in Bangladesh. Groundwater level in this area is successively falling by years due to over extraction of groundwater, climatological unfavorable condition, geo-morphological condition and reduction of surface water flow of major transboundary rivers etc. Increasing demand of ground water against decreasing trend of groundwater resources has created an alarming situation for sustainable development of this area. For sustainable development of any area, sustainable water resources are a prerequisite.

There are many studies available in the context of groundwater sustainability in Bangladesh. Most of these studies are based on statistical analysis and in a broad area basis specially for whole Barind area. Assessment of state of water resources for 64 districts has been carried out by WARPO (WARPO, 2016) for updating NWMP. In this study (WARPO, 2016), statistical analysis has been carried out to assess state of the water resources based on secondary data up to 2012.

Study of Upazila wise analysis of groundwater sustainability focusing the most water stressed area of Bangladesh by using state of the art mathematical modeling technology is very limited. There is a scope to take a study in Rajshahi district and develop possible future scenarios considering climate change impacts, future water demands etc. to find a way towards sustainability of this scarce groundwater resources with the help of historical climate, hydrological data and advanced integrated SW-GW modeling tools. The scope of this study is not limited to the finding of the extreme scenario up to 2030 in this area, there are scope to explore possible ways to sustain groundwater resources in this study area.

1.3 Objectives of the Study

The objective of the study is to assess the sustainability of groundwater resources of the underlying aquifer system of the Rajshahi district and also prediction of future scenarios under different conditions from 2017 to 2030 using MIKE 11(HD)-MIKE SHE coupled model. However, the specific aims of the study are as follows:

1. To assess the current situation of groundwater resources in Rajshahi district.
2. To develop an integrated surface water-groundwater (MIKE 11-MIKE SHE) model of the study area.
3. To predict the future groundwater scenarios under different conditions to assess sustainability of groundwater resources by applying suitable interventions.

Expected outcome of the research based on the above-mentioned objectives may be listed as follows:

- Hydro-stratigraphic map of the study area.
- Calibrated and validated integrated surface water-groundwater model.
- Spatial and temporal distribution of existing groundwater level.
- Spatial and temporal distribution of future groundwater level for different scenarios which will be considered in the study.

1.4 Organization of the Thesis

This research work has been carried out step by step through six chapters as given below.

Chapter 1 deals with the background, scope and objectives of the study.

Chapter 2 mainly focuses on the reviews of literature related to the objectives and outcomes of this study. Findings of the previous research works related to this study have also been summarized in this chapter.

Chapter 3 deals with the theoretical background of groundwater, development of groundwater theories, basic theory and equations behind the model study and detail methodology of this study.

Chapter 4 deals with the description of the study area including geographical location, climate, topography, geomorphology and hydrogeological setting, river system, soil condition and agricultural system and practices. Model set up for this study has been discussed in this chapter.

Chapter 5 illustrates the data analysis, results and discussions related to the study. Calibration and validation of surface water model and groundwater model, selection of design year for future scenario development, development of future scenarios, finding extreme scenario, development of interventions to counter extreme scenario, water balance analysis, assessment of suitable intervention for sustainable groundwater resources have been discussed in this chapter.

Chapter 6 discusses the major findings of the study. In this chapter the recommendations for further study have also been discussed.

CHAPTER 2

LITERATURE REVIEW

2.1 General

Groundwater is the water in the saturated zone of earth materials under pressure greater than atmospheric. Water enters to the groundwater through infiltration or percolation. Again, seepage from surface water bodies also causes groundwater recharge. Discharge to rivers or lakes causes depletion of groundwater storage in addition to pumping of groundwater for irrigation. The withdrawal and replenishment of groundwater is slow, complex phenomena and necessitates carefully investigation. Availability of groundwater for irrigation has contributed to manifold increase in crop productivity in Bangladesh (Dey et al. 2013). About 90 percent of irrigation water in Bangladesh is provided from groundwater (Zahid et al. 2006). This chapter will discuss about some selected previous studies around the world and in Bangladesh.

2.2 Previous Studies and Researches on Groundwater

A significant number of studies on groundwater resources, water demand, land use for crop pattern, groundwater sustainability, extension of crop intensity and their effects on groundwater level were carried out around the world and in Bangladesh. The available study reports, project documents, published scientific articles have collected and reviewed to get information on the study area and corresponding groundwater resources related to this study. Some of the important studies are briefly described below.

2.2.1 Groundwater Related Studies around the World

Döll (2014) showed that groundwater depletion (GWD) compromises crop production in major global agricultural areas and has negative ecological consequences. To derive GWD at the grid cell, country, and global levels, they applied a new version of the global hydrological model WaterGAP that simulates not only net groundwater abstractions and groundwater recharge from soils but also groundwater recharge from surface water bodies in dry regions. From their study the rate of global GWD has likely more than doubled since the period 1960–2000 and estimated GWD of 113 km^3/yr during 2000–2009.

Villholth (2018) identified governance and management are critical components of sustainability. The term governance is evolving, especially with regard to surface water and groundwater resources. No other components cannot bring expected result if there is no good governance. There should be good coordination between organizations and stakeholders regarding this sector.

FAO (2016) demonstrated that groundwater governance contains four key elements and these are (i) effective institutions that integrate stakeholders; (ii) policies and capital that support local, regional, and global resource goals; (iii) legal systems with the capacity to create and implement laws effectively; and (iv) local knowledge, customary or cultural context, and scientific understanding of groundwater systems.

Megdal (2018) summarized the results of efforts to bring attention to the importance of understanding and improving groundwater governance and management. Discussion of survey work in the United States and global case studies highlights the importance of focusing attention on this invisible water resource before pollution or depletion of it causes severe economic, environmental, and social dislocations. Better governance and management of groundwater are required to move toward sustainable groundwater use.

Gleeson (2019) showed some important groundwater management tools in his study and there are (i) Long-term, adaptive and conjunctive groundwater management plans, (ii) Monitoring, metering, and reporting and (iii) Green to grey infrastructure.

Achiransu (2017) described storage of rainwater through rainwater harvesting and aquifer recharge through watershed management are the main options for sustainable groundwater management. Some of the other suggested option are unbundling of irrigation services much on the lines of unbundling of electricity utilities, use of piped delivery from tertiary and below tertiary level, better measurement at all levels, construction of farm level storage ponds to increase flexibility and re-orientation of canal bureaucracy towards better service delivery.

2.2.2 Groundwater Related Studies in Bangladesh

Abdullah (2019) analysed the trend and extent of the groundwater table in Bogura district up to the year 2030 because of the expanding status and possible variability of the water demand. MIKE SHE, an integrated hydrological model has been used to simulate the fluctuating water table to assess the groundwater resources and future scenario analyses. Normal rainfall for the period of years 1985 to 2011 has been found 1672 mm. The same normal rainfall has been considered for the projection years 2012 to 2030. The temporal rainfall fluctuations were taken directly from a different study. Projections of the relevant hydrological components were anticipated in relation to the suitable projection models. The simulated result from the year 2006 to 2030 shows the depletion rate of the study area varies from 0.00 to 2.92 cm/year for mean depth of phreatic surface. In case of maximum depth of phreatic surface, the depletion rate varies from 1.20 cm/year to 14.45 cm/year. After a drought of rainfall events, a lower phreatic surface has been observed; this is however regained in subsequent heavy rainfall events.

WARPO (2016) conducted a comprehensive assessment of state of water resources throughout the whole Bangladesh (64 districts). This analysis was based on secondary data and statistical spreadsheet-based calculation. Analysis period is 1965 to 2012. Upazila wise rainfall, climate and evapotranspiration, flooding, droughts, water demand, water resources and state of water resources were assessed in this study.

IWM (2006) carried out a study on Deep Tubewell Installation Project in Barind Area. The main objective of this project was upazilla-wise groundwater resources assessment. Under this study the exchange rate of groundwater and the rivers Punarbhaba, Mahananda and Ganges were also investigated using mathematical modeling for the year 2001 (average year condition). In this study it was found that for the reach of Godagari to Charghat, annual groundwater loss per kilometer was about 0.33 MCM. The study recommended further investigation on the interaction between the Ganges river and Barind aquifer.

IWM (2013) carried out a study on Deep Tubewell Installation Project Phase II, of Barind Multi-Purpose Development Authority (BMDA) covers 65 Upazilas of Pabna, Sirajganj, Bogra, Gaibandha, Rangpur, Kurigram, Nilphamari and Lalmonirhat districts having gross area of 17, 455 km2 and cultivable area of 12, 765 km2. The objectives of this project was to assess Upazilawise 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. Upazilawise 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.

IWM (2012) carried out a groundwater resources study and DSS development for Barind covering 25 Upazilas of Rajshahi, Chapai Nawabganj and Naogaon districts with an area of 7500 km^2. A comprehensive model study was carried out for groundwater resources assessment for the study area. The study findings were limited up to 80m depth. For sustainable use of groundwater, one of the recommendations of this study was to explore the groundwater potential below 80m to bring more area under irrigation in resources constraint and high Barind areas.

HYSAWA (2012) carried out a study covers 31 Upazilas of Rajshahi, Chapai Nawabganj, Noagaon and Natore districts with an area of 9852 km^2. The project area has limited scope of surface water development and potential for groundwater development. Considering total requirement, groundwater deficit found in 7 Upazilas, which are Dhamoirhat, Patnitala, Niamatpur, Godagari, Tanore, Singra and Gurudaspur. Among these, Dhamoirhat and Tanore are constraint both for potential and available resource; 5 Upazilas are constraint for available resource which are Patnitala, Niamatpur, Godagari, Singra and Gurudaspur Upazila. Available resource can be increased by allowing depletion of groundwater table below 7m which is beyond suction limit of STW and HTW. In that case STW and HTW would be needed to be replaced by DTW or tara pump for dry season and it would not be a problem for environment because groundwater table regain to its original position due to recharge from rainfall in monsoon. In that case only 2 Upazilas would be considered as resource constraint area however for safe side the less water required crops should be practiced for these resources’ constraint Upazilas.

Hossain and Shamsuddin (1976) carried out a study which dealt with the groundwater in the Rajshahi district for the year 1968 to 1975. The purpose of this study was to find out usable volume of groundwater and to study the irrigation potential of the groundwater. According to this study, the Barind area was divided into five different zones (Zone 2A, 2B, 4, 8A, 8B) among which high prospect of groundwater potential for STW and DTW in the zone 2 and only DTW in the zone 4 and remaining parts of Barind were not studied. From their analysis the recommended shallow tube wells for zone 2A, 2B and 8A.

Sondipon (2017) carried out in the Mohananda River at Chapai Nawabganj District. The main purpose of the study is to investigate the present scenario of groundwater level in the study area and the impact of replacing groundwater irrigation with surface water irrigation in 2020 and 2030. Three options such as Option-0 (base condition), Option-1 (without Rubber Dam) and Option-2 (with Rubber Dam) have been formulated, simulated and evaluated to attain the study objectives. Due to surface water irrigation, the groundwater level increased adjacent to the Mohananda River especially in the surface water irrigation area. The groundwater level decreasing rate is 96 mm/year for option-1 where the rate reduces to 50 mm/year in option-2 in Surface Water Irrigation Zone. In addition, it has been observed that, the influence area due to surface water irrigation for year 2020 is 234 sq.km where it has been found 242 sq. km for year 2029.

Zahid (2015) described in his study that matching long term withdrawals of groundwater to recharge is the principal objective of sustainable groundwater resource planning. Maintaining the water balance of withdrawals and recharge is vital for managing human impact on water and ecological resources. Regional modeling of the groundwater systems has to be developed for effective water resource management to plan agricultural, rural and urban water supplies and to forecast the groundwater situation in advance for dry seasons.

UNDP (1982) study identified potential groundwater development areas through countrywide survey of groundwater. The identification of potential groundwater development areas was based on (i) annual volume of recharge, (ii) capacity of the system to act as a long-term storage reservoir, (iii) energy source for the pumping lift and (iv) water quality. According to this report the current study area has limited thick sandy aquifer especially in the high Barind area and transmissivity- value ranging from 500 to 1500 m^2/day. Annual recharge varied from a minimum of 80 to a maximum of 190 mm. This study was based on limited data for generalized appraisal of hydrogeological condition of the country and therefore, was in need of a detailed study of available groundwater resources for formulation of the project.

MacDonald (1983) study described the geology, infiltration rate, permeability range, storage range, water level fluctuations and finally development potential of its study area. It was based on existing data analysis and a water balance study. The study area consists mainly of three aquifers namely Sibganj (1200 km^2), High Barind Area (3634 km^2) and Little Jamuna (980 km^2). Sibganj aquifer has been classified as semi-confined. The 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. The specific yield of upper layer is 6%. Drilling of DTW is not constrained except in deeply flooded areas. The high Barind aquifer has been classified as semi confined and multi-layered. The infiltration rate is 1.5 mm/day in wetland and 7.5 mm/day in dry land. Permeability ranges from 25 to 40 m/day with an average of 30 m/day. Specific yield of the upper layer is approximately 4%. Drilling of DTW is not promising because of the large depth to poor aquifer and fine materials, which require special design. Recharge could also be a limiting factor and trial borings were recommended. The Little Jamuna aquifer has been classified as unconfined to semi-confined. Infiltration rate is 1.5 mm/day in wetland and 5 mm/day in dry land. Permeability ranges from 50 to 80 m/day with an average of 65 m/day. Specific yield averages 5%. There is a good potential for drilling of DTW in this area and the recharge is unlikely to hinder development.

Asaduzzaman (1983) showed thana-wise recommended number of DTW for 45% development level (as per Northwest Bangladesh Groundwater Modelling Report), well fixtures, discharge and thanawise fluctuation of groundwater level (average), and rainfall, bore log as well as construction procedure of DTW. His detailed study findings and observations are helpful in this study and other studies in groundwater.

Karim (1984) stated that the potential recharge in the Barind area is in the range of 400 to 700 mm/year, hydraulic conductivity (K) is in the range of 25 to 50 m/day and the specific yield (Sy) value is in the range of 0.05 to 0.12. Majority of the area is within the value of K=40 m/day and Sy=0.10.

MPO (1986) studied 8 representative areas spreading all over Bangladesh. A country-wide contour map of transmissivity was prepared using data based on aquifer tests and development tests of tube wells. In the current study-area the transmissivity values have been estimated in the range of 1000 to 2000 m^2/day; for thin aquifers it may vary from 200-700 m^2/day. A contour map of specific yield was also prepared using bore logs and aquifer test data assuming that the specific yield increases linearly with the increase of depth from ground surface for increase of sand in the aquifers. Specific yield values have been assigned for each layer occurring within 25 m depth from ground surface and later to estimate its average value. The average value of specific yield for the study area is in the range of 2% to 5%. This value depends on the accuracy of identification of aquifer materials in the bore-log. The groundwater recharge model was developed from the study of catchment recharge in the eight representative areas. The catchments were taken as multi-layer single cell models in which only the vertical components of flow were considered. Outputs were the annual rates of potential recharge for each catchment area summarized from simulated ten-day rainfall and soil infiltration using 25 years of climatic data. A relation between rainfall and annual potential recharge was developed, indicating that the higher the rainfall, the higher the annual potential recharge for an area. Potential and available recharge for the study area was estimated to be in the range of respectively 200 to 500 mm, and 100 to 400 mm.

BWDB (1990) studied the groundwater for 17 Upazilas in Rajshahi, Noagaon and Nowabganj districts. The report was prepared based on existing literature and primary data of test-drillings, groundwater monitoring wells and aquifer tests. Geologic cross-sections were prepared to show the thickness and areal extension of sub-surface formations in the study area. Contour maps of groundwater depth and of average maximum fluctuation of groundwater level were prepared. Contour maps of specific yield were also prepared using data from aquifer tests. Field surveys were conducted to determine Upazila-wise irrigation equipment and their uses. The Upazila-wise actual and available groundwater recharges were assessed, which varied from 322 to 567 mm and from 243 to 411 mm, respectively. The balance of available recharge following existing uses was determined assuming all DTWs were of 2 cfs (0.057 m^3/s) capacity and ran 13 hrs/day for 120 irrigation days, and all STWs were of 0.40 cfs (0.011 m^3/s) capacity of the same duration of running and period of irrigation. It was assessed that there is a prospect of drilling additional 850 DTWs with 50% safety factor.

NWMP (2001) was established 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.

BMDA (2012) carried out a model study with IWM (integrated both surface water and groundwater) in the Barind area, which covers 25 Upazilas of Rajshahi, Nawabganj and Noagaon districts with an area of 7500 km^2. Integrated MIKE11-MIKE SHE modeling system with grids size of 1000m×1000m squares has been applied in the study. Based on the data available up to 2005 the study confirms that groundwater resources are inadequate in 11 Upazilas to meet the present water demand for Boro crops while in 5 Upazilas the present withdrawals of groundwater are more compare to potential recharges and available groundwater resources.

Islam (2009) investigated Barind Aquifer – Ganges River interaction over 55 km reach of the Ganges River from Godagari to Charghat, having an area of 916 km^2. 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 (2013) conducted a study 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.

Ahmed (2008) exploited thickness of the aquifer ranges from less than 10 m in parts of Bogra district to over 60 m in the northwest. Aquifer conditions are found to be good in most parts of the Teesta, Brahmaputra-Jamuna and Ganges river floodplains and on the Old Himalayan Piedmont plain. Potential aquifers are not found in high Barind area. Based on pumping tests, the transmissibility of the main aquifer ranges from 300 to 4,000 sq. m/day. Highest transmissibility's are common adjacent to the area of Brahmaputra-Jamuna river and lowest transmissibility's are common in high Barind area. Highly transmissible aquifer material indicates excellent opportunity for groundwater development. In most areas, the lower two aquifers are probably hydraulically interconnected. The main aquifer, in most of the area, is either semi-confined and leaky or consists of stratified, interconnected, unconfined water bearing zones which are subject to delayed drainage. Recharge to the aquifer is predominantly derived from deep percolation of rain and flood water. Lateral contribution from rivers comprise only a small percentage (0.04%) of total potential recharge. Hydrographs of observed groundwater tables show that the maximum and minimum depth to groundwater table occurs at the end of April and end of October respectively.

2.2.3 Groundwater Related Studies in the North-West Region of Bangladesh

Rahman (2017) demonstrated that unplanned irrigation for the dry season rice production is the significant responsible factor for groundwater depletion. Moreover, climate-related factors, like decreasing trend in rainfall, distribution of rainfall (SI and PCI), frequent drought, are also related to the groundwater depletion. The study also demonstrates that water resources management also related to the transboundary river relationship. To achieve sustainability in groundwater resource at first, it is time to take decision about the land use patterns as rice, which cultivates in about 81% cultivable area during the dry season, is the highest water consuming crop in the area. Though it is the staple food in the country, it is necessary to reduce this crop cultivation to protect rapid depletion of groundwater resource. Moreover, water-saving irrigation techniques such alternate drying and wetting, raised bed techniques need to promote for farming. Surface water irrigation where and when it is available need to facilitate to minimize the stress on groundwater. The present study also indicates that groundwater recharge in some Upazilas increases due to create favorable recharge structures like re-excavation of rivers and Kharis(small channel). However, the effort is not quite enough for protecting groundwater depletion. As annual surplus water is higher than the net groundwater recharge, groundwater recharge favorable structures for rainwater harvesting need to develop. An experimental study on MAR shows the potentiality of the technique for ensuring drinking water supply especially in the rural areas. An IWRMP considering the driving forces of groundwater depletion, potentiality of surface water, and MAR and land use pattern of the area need to prepare and execute the plan accordingly for achieving the sustainability in water resources management.

Ali (2011) revealed that the depth of water (WT) of almost all the wells is declining slowly. In many cases, the depth will approximately double by the year 2040, and almost all will double by 2060, if the present trend continues. If the decline of water-table is allowed to continue in the long run, the result could be a serious threat to the ecology and to the sustainability of food production, which is vital for nation's food security. Therefore, necessary measures should be taken to sustain water resources and thereby agricultural production. Demand-side management of water and the development of alternative surface water sources seem to be viable strategies for the area. These strategies could be employed to reduce pressure on groundwater and thus maintain the sustainability of the resource.

Mojid (2019) showed that most of the NW parts of the study area encounter face water scarcity during dry months. In 15% of the monitoring wells, located in Bogura, Rajshahi, Naogaon, Joypurhat, and Chapai Nowabgonj districts, GWTs remained below 6 m throughout the year. These districts, comprising the Barind track, face severe water scarcity, especially for domestic supply, due to failure of STWs and HTWs. Therefore, it is inevitable that the currently practiced groundwater development and use policy in those areas need to be revised to make groundwater use more sustainable. Strategies such as artificial recharge to the aquifers and rain water harvesting along with water-saving technologies and integrated water resources management need to be adopted. Special attention needs to be given in areas where GWTs drop below the critical suction limit of suction-mode pumps. Alternate technology for pumping groundwater needs to be made available to provide household water.

Dey (2017) showed that depletion of groundwater table was most evident in Rajshahi, followed by Dinajpur, Bogra, Pabna and Rangpur, but when other factors interlinked with the groundwater resources (i.e. river water level, boro rice area, dry season rainfall, wetland area) was considered, the scenario changed to some extent. Bangladesh has abundant rain during the monsoon season, and technological solutions need to be explored to artificially replenish aquifers with rainfall. Efforts should continue to negotiate an increased share of water from the river system originating in the Himalayas during the dry season. Therefore, the Government of Bangladesh and other countries associated with this water-sharing issue and situated upstream should maintain mutually beneficial cooperation. Changes in cropping patterns should be promoted by the Department of Agriculture Extension according to his study.

2.3 Groundwater and the Sustainable Development Goals (SDGs)

The concept of sustainability or sustainable development is generally 'meeting the needs of the present without compromising the ability of future generations to meet their own needs' (World Commission on the Environment and Development, 1987), which is a foundation of the widely – adopted UN Sustainable Development Goals. Groundwater is an important resource for achievement of the UN Sustainable Development Agenda for 2030 yet it is poorly recognized and weakly conceptualized in the SDGs (Guppy et al., 2018). Groundwater is an important resource for achievement of the UN Sustainable Development Goals SDGs. Groundwater could be important to ensuring access to water and sanitation for all (Goal 6) as well as contributing to a number of other goals: poverty eradication (Goal 1), food security (Goal 2), and combating climate change (Goal 13). Yet even in the targets of Goal 6, groundwater is only explicitly referenced once and a detailed analysis by Guppy et al was necessary to highlight the potential relationship between groundwater and many other targets. More than half of these relationships are reinforcing meaning that achievement of the target would have a positive impact on groundwater. Yet the few conflicting relationships where achievement of the target would 5 have a negative impact on groundwater are important since conflicting relationships are the most critical and difficult ones to manage. The most important potentially conflicting relationship may be between groundwater and some of the targets for food security (Goal 2) including ending hunger and doubling agricultural productivity (Guppy et al., 2018).

2.4 Summary

The review of findings of previous study is very much needed before undertaking any research work. Therefore, the literature review of the previous studies around the world as well as in Bangladesh has been done in this chapter. It is necessary to gain a clear concept about the research work and also to identify the scope of the work. Based on these literature review works, findings of the results are as follows:

Previous studies of groundwater sustainability mainly focused on statistical based calculation of historical data instead of using groundwater models. Driving forces related to groundwater sustainability varies largely from region to region, so it is difficult to replicate sustainable solution of other countries to Bangladesh especially in Rajshahi district. Sustainability of groundwater resource is dependent on climate change and transboundary issues, so there are many uncertainties to achieve sustainability in the longer period. In developed countries, understanding and improving groundwater governance and management have been given importance towards sustainability of groundwater resources, Groundwater related studies in North-West region covers a large area while it was not possible to focus the most drought prone Rajshahi district. Generation of future scenarios up to 2030 considering climate change and other driving forces to understand future groundwater condition in this water stressed area to achieve sustainability of groundwater resources has not been found in the literature review.

Focusing only Rajshahi district, very limited studies have been found that finds some ways towards sustainable groundwater resources in this area specially by application of state-of-the-art mathematical modelling tools. Several studies have been done considering the whole Barind Tract which have been mentioned in Article 2.2.2 and 2.2.3. Based on the above literatures, there exist scopes to focus in the Rajshahi district and to find ways towards sustainable groundwater resources, this research has been chosen. Under this research, a SW-GW interactive model has been developed for this area for better understanding of the existing situation of groundwater. Future scenarios have been developed considering climate change issues and other relevant driving factors which will eventually help to find suitable measures to make the groundwater resources sustainable up to 2030 to achieve SDG goals.

CHAPTER 3
THEORY AND METHODOLOGY

3.1 General

The world's total water resources are estimated at 1.37x 108 million ha-m. Of these global water resources about 97.2% is salt water, mainly in oceans and remaining 2.8% is available as fresh water at any time on the planet earth. Out of this 2.8%, about 2.2 % is available as surface water and 0.6% as groundwater (Raghunath, 1987). Groundwater is the principle Source of freshwater for rural, industrial and irrigation demands (Buttler et al., 2003). It provides nearly 70% of world's drinking water and is the major source of water for most industry and agricultural irrigation. For instance, Florida relies on groundwater for 95% of its total water supply (Jackson et aI.,1989). Groundwater is commonly understood to mean water occupying all the voids within a geologic stratum. It constitutes one portion of the earth's water circulatory system known as the hydrologic cycle. Utilization of groundwater dates from ancient time, although an understanding of occurrence and movement of subsurface water as part of hydrologic cycle has come relatively recent. The science of the occurrence, distribution and movement of water below the surface of the earth is called groundwater hydrology. The literature is now composed of interdisciplinary contributions from geologists, hydrologists, engineers, chemists, mathematicians, petroleum and agricultural scientists.

Water bearing formations of the earth's crust is acting as conduits for transmission and as reservoirs for storage of water. Water enters these formations from the ground surface or from bodies of surface water is called recharge after which it travels slowly underneath varying distances until it returns to the surface by action of natural flow or artificial abstraction. The storage capacity of the groundwater aquifers with slow rates of flow combination provides large and extensive sources for water supply. The major reservoirs of groundwater are called aquifers, which are recharged by rain, snowmelt, or interchange with surface waters. Groundwater is not stationary, but moves vertically or horizontally in response to gravity and hydraulic pressure. Groundwater flow rate is frequently only several meter per year, although in permeable sand and gravel aquifers groundwater can move one or two meter per day (Rahman, 2005).

3.2 Occurrence of Groundwater

The rainfall that percolates below the ground surface passes through the voids of the rocks and joins the water table. These voids are generally interconnected, permitting the movement of the groundwater. But some rocks, they may be isolated, and thus, preventing the movement of water between the interstices. Hence it is evident that the mode of occurrence of groundwater depends upon the type of formation, and hence upon the geology of the area. The possibility of occurrence of groundwater mainly depends upon two geological factors; i.e., (i) the porosity and (ii) the permeability of the water bearing formation. As we move down below the surface of earth towards its center, water found exists in different forms in different regions. With regards to the existence of water at different depths, the earth crust can be divided into various zones, namely, (i) zone of rock fracture, and (ii) zone of rock flowage. The depth of zone of rock flowage is not accurately known but is generally estimated as many miles. Interstices are probably absent in this zone, because the stress are beyond the elastic limits and the rock remains in a state of plastic flow. Water present in this zone is known as internal water, and hydraulic engineer has nothing to do with this water. Above the zone of rock flowage, there lies the zone of rock fracture. In this zone, the stresses are within the elastic limit, and the interstices do exist. Water is stored in the voids, the amount of which depends upon porosity. The maximum depth of this zone below the ground surface varies in the range of about 100 m or less to 1,000 m or more (Garg, 1989). The zone of rock fracture can be further sub-divided into two zones. One is the zone of saturation, i.e. below the water table, and the other is the zone of aeration, i.e., above the water table. In the zone of saturation, water exists within the interstices, and is known as groundwater. This is the most important zone for a groundwater hydraulics. Water in this zone is under hydrostatic pressure.

3.3 Development of Groundwater Theories

Some European scientists, in the later part of the 17th century first proved the source of groundwater from rainfall-runoff measurements that yearly precipitation volume is high enough with respect to river flow, which can contribute to groundwater body and other surface water bodies. Before that it was widely believed that earth is practically impermeable to infiltrate rainwater.

After the development of equations for viscous flow in capillary tubes by Poiseuille (1840), Darcy (1856) published his famous empirical equation for flow of water through sand column. Darcy's law, in a generalized form, remains today the fundamental flow equation in the analysis of groundwater motion.

Meinzer (1923) evaluated the occurrence and distribution of groundwater. One of the most important milestones in the development of groundwater resource evaluation was Theis's (1935) introduction of an equation for the non-steady flow to a well. It was Buckingham (1907) and then Green and Ampt (1911) dealt the problem of unsaturated flow, and then finally Richards (1931) was succeeded to develop the Buckingham's (1907) concept of unsaturated soil water potentials further.

At present, most of the studies of soil water movement are based on Richards (1931) equation. Childs (1945) and Youngs (1957) described that both the soil water pressure head and the soil moisture content, approach constant values during a prolonged vertical infiltration in long columns, in which therefore the hydraulic conductivity equals to the vertical downward flux. The effect has been used for the measurement of hydraulic conductivity of unsaturated porous materials (Childs and Collis-George, 1950). For upward movement caused by evaporation at the soil surface or by root water uptake, it was found that the water movement can be limited by the soil conditions, being dependent on the depth of the water table as well as the soil hydraulic properties (Gardner, 1958; Gardner and Fireman, 1958). Gray and Hassanizadeh (1991) gave unsaturated flow theory including interfacial phenomena and advance the theory of multiphase flow in general.

In recent decades, much attention has been paid to hill-slope hydrology, as attested by books edited by Kirkby (1978). In this communication Philip (1991) developed extensions to infiltration theory for horizontal land surfaces needed to embrace hill-slope conditions. Two-and three-dimensional soil-water flow problems that arise, present a more difficult problem for analysis than the one-dimensional flow. In these cases analytical solutions to Richards' equation have been possible only for particular mathematical forms of the relationships between soil-water properties and are as good as those relationships which describe the properties of the given soil (e.g. Wooding, 1968; Philip, 1969). Philip (1986) recognized that an analogy exists between the quasi-steady absorption of water from cavities and the scattering of the plane acoustic waves around soft obstacles. Large series of analytical solutions has resulted from this recognition for absorption and infiltration from cavities of different shapes, as well as for water exclusion from empty subterranean holes (e.g., Philip, 1986; Philip, 1989; Philip et al., 1989).

3.4 Basic Theory of Modelling

Before working with mathematical modelling tools, it is very necessary to review and understand basic theory of modelling and basic equations behind the Graphical User Interface (GUI) of these tools. From this point of view, basic theory of modelling, basic equations of MIKE SHE, MIKE 11 (HD) and MIKE 11 (NAM) have been reviewed in this chapter which are used in this study.

“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 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, MIKE 11 are mathematical models that have been used in the current study.

3.5 Basic Theory and Equation of 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 3.1. 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).

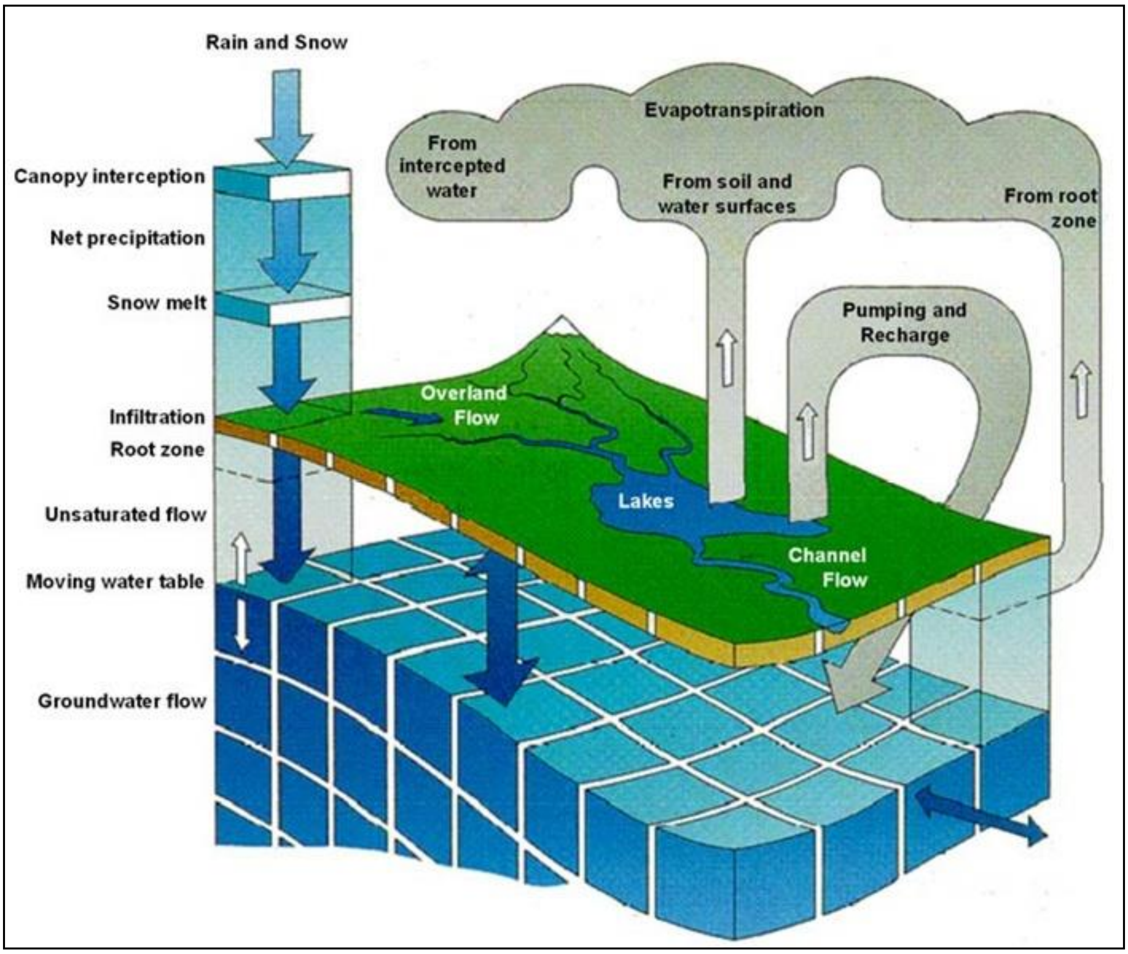


Figure 3.1: Hydrologic processes simulation by MIKE SHE hydrologic model (Source: DHI)

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, the Darcy equation (Chow, Maidment and Mays, 1988) for saturated flow in porous media and Richards equation for unsaturated flow 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 3.2). MIKE SHE hydrologic model consider the variables as precipitation and evapotranspiration, unsaturated flow, overland flow and saturated groundwater flow.

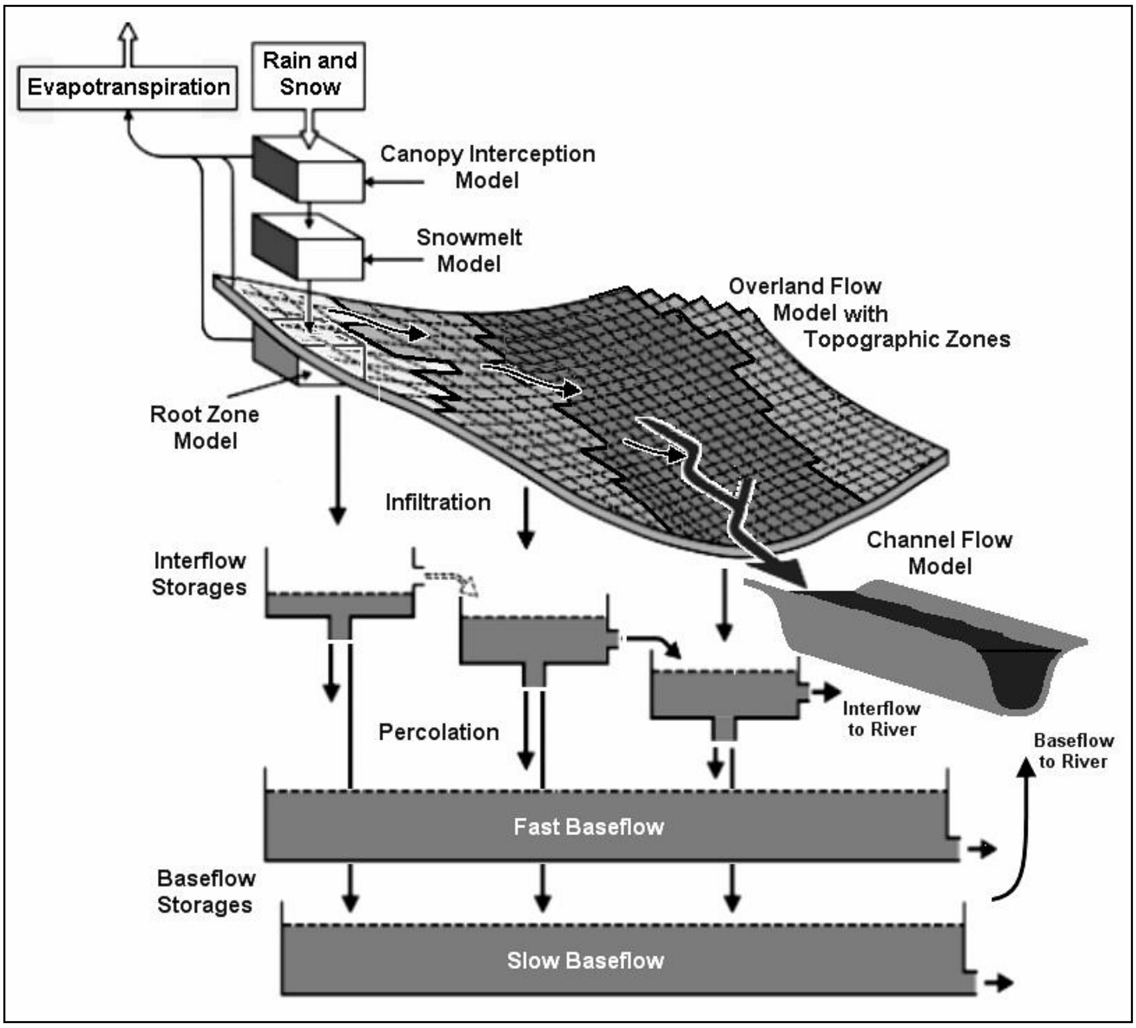


Figure 3.2: Schematic representation of the conceptual components in MIKE SHE hydrologic model (Source: DHI)

Basic Equations of MIKE SHE

Mathematical models consist of set of differential equations that are known to govern the flow with the most commonly used assumptions that the flow is one- or two-dimensional (horizontal, radial, vertical, etc.), the aquifer is homogeneous, isotropic and is infinite in extent and the borehole is of negligible in diameter.

(i) Unsaturated Flow

There are three options in MIKE SHE for calculating vertical flow in the unsaturated zone:

- the full Richards equation, which requires a tabular or functional relationship for both the moisture-retention curve and the effective conductivity,

- a simplified gravity flow procedure, which assumes a uniform vertical gradient and ignores capillary forces, and
- a simple two-layer water balance method for shallow water tables.

Richards equation in vertical direction:

The Richards equation represents the movement of water in unsaturated soils, and is attributed to Lorenzo A. Richards who published the equation in 1931. It is a nonlinear partial differential equation, which is often difficult to approximate since it does not have a closed-form analytical solution. Although attributed to Richards, it is established that this equation was actually discovered 9 years earlier by Lewis Fry Richardson in his book "Weather prediction by numerical process" published in 1922.

The transient state form of this flow equation, known commonly as Richards' equation writes in one-dimension (vertical):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(K(\theta)\frac{\partial \Psi}{\partial z} \right) + \frac{\partial K(\theta)}{\partial z} - S(z) \quad \text{……………………………………………….…} (3.1)$$

The dependent variables, θ and ψ, in Eq. (3.1) are related through the hydraulic conductivity function, $K(\theta)$, and the soil moisture retention curve, $\psi(\theta)$. Eq. (3.1) is general, in the sense that it is equally valid in both homogeneous and heterogeneous soil profiles, and there are no constraints on the hydraulic functions. Introducing the concept of soil water capacity by Eq. 3.2,

$$C = \frac{\partial \theta}{\partial \psi} \quad \text{…………………………………………………………..……………………..…} (3.2)$$

which is the slope on the soil moisture retention curve, then the tension-based version of equation is,

$$\frac{\psi}{h} = \frac{\partial}{\partial z}\left(K(\theta)\frac{\partial \Psi}{\partial z} \right) + \frac{\partial K(\theta)}{\partial z} \quad \text{…………………………………………………..…} (3.3)$$

This equation is usually referred to as Richards equation, which is named after L.A. Richards who first used it in 1931.

(ii) Saturated Flow

The governing equation for three-dimensional flow in saturated porous media which is used in MIKE SHE is

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.4)}$$

where, K_{xx}, K_{yy}, and K_{zz} = values of saturated hydraulic conductivity along the x, y, and z coordinate axes , which are assumed to be parallel to the principle axes of hydraulic conductivity tensor; h= potentiometric/hydraulic head (L); W= volumetric flux per unit volume representing sources and/or sinks of water, with $W<0.0$ for flow out of the groundwater system, and $W>0.0$ for flow into the groundwater system ; S_S= specific storage coefficient of the porous material.

Two special features of this apparently straightforward elliptic equation should be noted. First, the equation is non-linear when flow is unconfined and second, the storage coefficient is not constant but switches between the specific storage coefficient for confined conditions and the specific yield for unconfined conditions. The equation is called non-linear Bousinesq equation, which is the combination of the mass conservation and Darcy’s law for incompressible fluid and anisotropic porous media.

3.6 Basic Theory and Equation of MIKE 11 HD Model

MIKE 11, developed by DHI Water & Environment, is a modeling package for the simulation of surface runoff, flow, sediment transport and water quality in rivers, floodplains, channels and estuaries.

The hydrodynamic module (MIKE 11 HD) is commonly applied as a flood management tool simulating the unsteady flow in branched and looped river networks and quasi two-dimensional flow on floodplains. Once a model is established and calibrated, the impact of changes of artificial or natural origin on flood behavior can be quantified and displayed as changes in flood levels and discharges.

The MIKE 11 hydrodynamic module (HD) 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 which adapts according to the local flow conditions (in time and space). Advanced computational modules are included for description of flow over hydraulic structures, including possibilities to describe structure operation. The formulations can be applied to looped networks and quasi two-dimensional flow simulation on flood plains. The computational scheme is applicable for vertically homogeneous flow conditions extending from steep river flows to tidal influenced estuaries. The system has been used in numerous engineering studies around the world.

The MIKE 11 hydrodynamic is applied to compute water level, discharge and flow velocity. The MIKE11 HD solves the vertically integrated equations of conservation of energy and momentum called the “Saint Venant Equation” that describe the flow dynamic in a river system. A network editor assists the schematization of rivers and floodplains as a system of inter-connected branches. Flood levels and discharges as a function of time are calculated at specified points along the branches to describe the passage of flood flows through the model domain. Thus the Model takes into account the river connectivity, river cross-sections, flood plain level and observed discharge at inlet and stage at outlet locations of the modelled rivers. The observed discharge and stage applied respectively at the inlet and outlet are called boundary to the model. The runoff generated in the NAM model from rainfall occurring inside the basin is taken care of as inflows into the river system. MIKE 11 allows for two different types of bed resistance descriptions: Chezy, and Manning number.

Basic Equations of MIKE 11(HD)

MIKE 11 HD applied with the dynamic wave description solves the vertically integrated equations of conservation of continuity and momentum (the ‘Saint Venant´ equations). In the ‘Saint Venant´ equation flow is calculated as a function of space and time throughout the system which is governed by continuity and momentum equations.

The basic equations used in MIKE 11:

$$\frac{\partial Q}{\partial x}+\frac{\partial A}{\partial t}=0 \quad \text{...} \quad (3.5)$$

$$\frac{1}{A}\frac{\partial Q}{\partial t}+\frac{1}{A}\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right)+g\frac{\partial y}{\partial x}-g(S_o-S_f)=0 \quad \text{..............................} \quad (3.6)$$

Where,

t = time, x = the distance along the longitudinal axis of the sewer reach, flow-depth, y = flow-depth, A = the inactive (off-channel storage) cross-sectional area of flow, Q = lateral inflow or outflow, g = gravity constant, S = sewer or channel slope, S_f = friction slope due to boundary turbulent shear stress and determined, S_e = slope due to local severe expansion-contraction effects (large eddy loss)

Equation 3.5 is known as continuity equation and equation 3.6 is known as momentum equation. The two equations represent a complete unsteady flow hydrodynamic equation system therefore a dynamic model based on them is known as dynamic routing model or dynamic model.

3.7 Basic Theory of MIKE 11 NAM Model

Mike 11 NAM, the Rainfall Runoff Model is applied to estimate the runoff generated from rainfall occurring in the catchment by NAM method. NAM is a lumped conceptual model that considers rainfall, evaporation/ evapotranspiration, soil moisture and the important parameters relating to the basin character to compute run off, base flow and inter flow by simple water balance approach. The NAM hydrological model simulates the rainfall-runoff processes occurring at the catchment scale. NAM forms part of the rainfall-runoff (RR) module of the MIKE 11 river modelling system.

A mathematical hydrological model like NAM is a set of linked mathematical statements describing, in a simplified quantitative form, the behavior of the land phase of the hydrological cycle. NAM represents various components of the rainfall-runoff process by continuously accounting for the water content in four different and mutually interrelated storages. The NAM model can be characterized as a deterministic, lumped, conceptual model with moderate input data requirements.

The basic components are surface storage, lower zone or root zone storage, evapotranspiration, overland flow, inter flow, inter flow and overland flow routing, ground water recharge, soil moisture content and base flow.

The parameters are surface and root zone parameters, ground water parameters, snow module parameters and irrigation module parameters.

3.8 Methodology of the Study

Modelling of any physical phenomenon is an iterative development of a process. Model refinements are based on the availability and quality of data, hydrological understanding and scopes of the project. The general approach that has been followed in the current study can be summarized in the flowchart given in Figure 3.3.

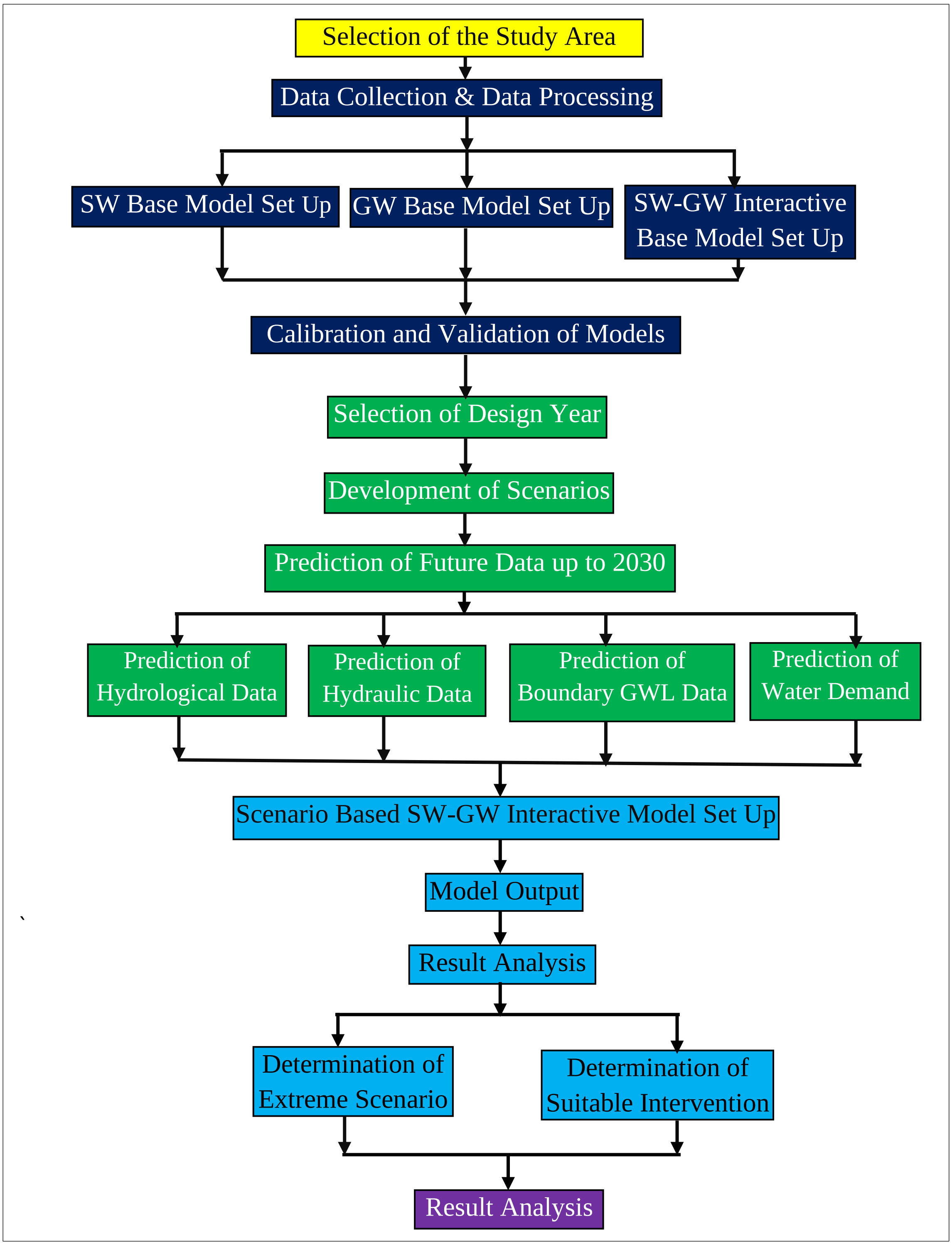


Figure 3.3: Flowchart of the overall methodology for this study

3.8.1 Selection of the Study Area

Rajshahi district is one of the most drought prone districts of Bangladesh (Chowdhury et al., 2018). Groundwater level in this area is successively falling at an alarming rate (Aziz et al., 2015). Groundwater recharge condition is very poor in Tanore, Godagari, Mohanpur and Baghmara upazilas and vulnerable for Boro rice (Aziz et al., 2015). Groundwater dependent irrigation system in the area has reached a critical phase (Adhikary et al., 2013) and GW level has dropped below the depth of the shallow tube wells in many places (Adhikary et al., 2013). The Bangladesh government is about to declare a "state of water emergency" in the drought prone Barind tract in the northwest of the country, where over-extraction of groundwater for rice farming and dwindling rainfall caused by climate change have combined to create a crisis (thethirdpole.net). These are the reasons for choosing this district as study area where sustainable GW is a major concern.

3.8.2 Data Collection and Data Processing

According to the model requirements, significant amount of data have been collected from Institute of Water Modelling (IWM), Bangladesh Water Development Board (BWDB), Bangladesh Agricultural Development Corporation (BADC) and Soil Resource Development Institute (SRDI). Only BWDB stations data has taken to prepare MIKE 11 and MIKE SHE model in current study. 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

(i) Data Requirements for MIKE SHE Hydrologic Model are as follows:

- Hydrometeorology of the study area i.e. precipitation, Evapotranspiration, stream water level data
- 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

(ii) Data Requirements for MIKE 11 Hydraulic Model are as follows:

- Existing river network
- Cross section data of rivers/khals
- Boundary water level data
- Boundary water flow data

After collecting data from different organizations, consistency of these data have been checked. Data processing is very much important because erroneous data may cause erroneous results. So, every types of data has been checked carefully. For instance, double mass analysis of rainfall data of station R 170 has been shown in Figure 3.4. Almost linear plot of double mass curve indicates consistent data of this station. Other double mass curve have been given in Appendix A.

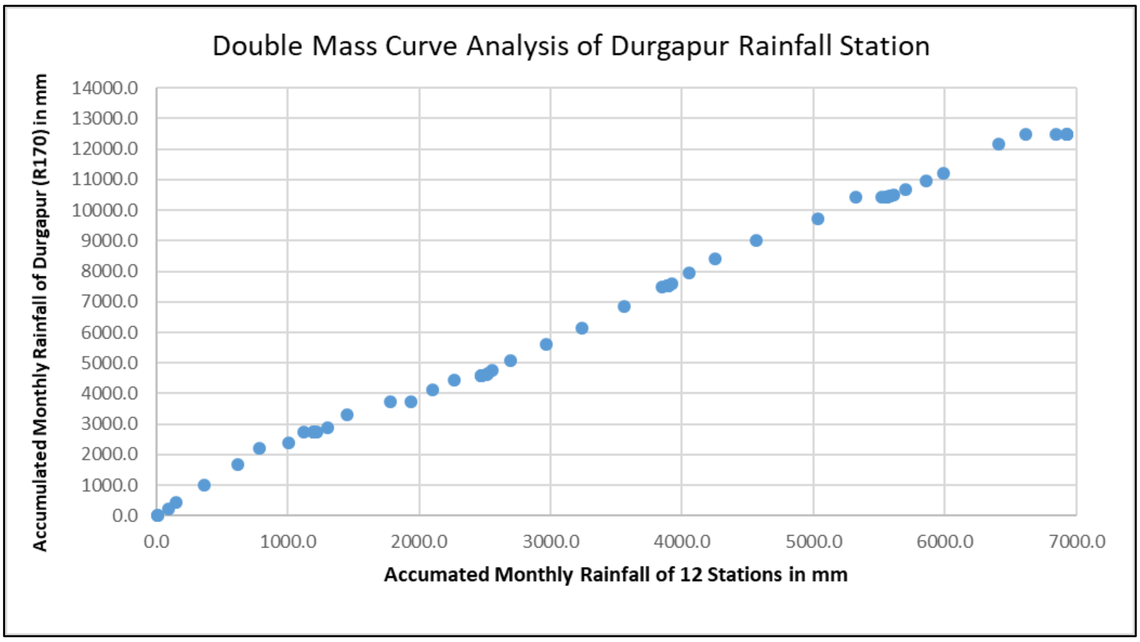


Figure 3.4: Double mass curve for rainfall data under rainfall station, R170 in Durgapur Upazila for the year 2012 to 2016

3.8.3 Base Model Set Up

The SW modelling approach consists of two major parts which are (1) hydrological model and (2) hydrodynamic model. The hydrological model has been set up using Rainfall-Runoff Module (NAM) of MIKE 11 modelling tool developed by Danish Hydraulic Institute (DHI). The hydrodynamic model of the project area has been set up using Hydrodynamic Module (HD) of the MIKE 11 tool. The study area is approximately 2400 square km and the model area will be larger than this to eliminate boundary error and to use observed water level and discharge stations of BWDB and IWM. The base model has been set up for 5 years (January, 2012 to December, 2016). Expected major outputs from this model are water level and discharge at every grid point within model area.

The groundwater model has been set up using MIKE SHE model of DHI. This model has been set up for 5 years (January, 2012 to December, 2016). Expected major outputs from this model are groundwater levels at every grid point within model area and water balance of the model area.

The MIKE 11(HD) and MIKE SHE models have been linked interactively and then it is capable of producing water balance and changing of storages in the form of groundwater recharge/discharge and showing fluctuations in water-table.

3.8.4 Calibration and Validation of Base Models

Surface water model has been calibrated for three years (January, 2012 to December, 2014) and have been validated for next 2 years (January, 2015 to December, 2016). After calibration and validation of surface water model, it needs to be coupled with groundwater model to understand the interaction between rivers and aquifers in the study area and to observe the influence of storage structures on surface water bodies. Then the coupled model (MIKE 11 and MIKE SHE) has been calibrated and validated with observed groundwater level data for the same calibration and validation period of surface water model. Main calibration parameter for MIKE-11(HD) model is Bed Resistance of stream channel (Manning's n) and for MIKE SHE model calibration parameters are horizontal hydraulic conductivity, vertical hydraulic conductivity, specific yield, storage co-efficient etc.

3.8.5 Selection of Design Year

For the development of future scenarios, design year has been selected based on statistical analysis. In the present study, design year has been selected based on return period of mean annual rainfall of the study area. The mean annual rainfall has been obtained from the average of 10 stations falls in the study area. Observed annual rainfall for a period of 47 years (1970-2016) has been considered for statistical analysis. According to the recommendation of FAP25 study, data has been fitted to 3-parameter Log Normal distribution to find out the average and extreme dry year. The statistical software HYMOS 4.0 has been used for this purpose. From this analysis 1990 year has been selected as a design year of average hydrological condition and 2014 and 1994 have been selected for design year of dry (5 years of return period) and extreme dry conations (10 years of return period) respectively.

3.8.6 Development of Scenarios

In order to sustain groundwater resources up to year 2030 we have to foresee future condition of groundwater resources under different Scenarios. For this reason, there are ten (10) Scenario s have been chosen to understand future groundwater level considering rainfall, evaporation, boundary groundwater level and water demand as driving forces. Summary of these scenarios is given in Table 5.4. Rainfall and Evaporation date for 2017 to 2030 have been collected from Global Circulation Model HADCM3 using Climate Editor Tool of Mike 11 software. GWL for 2017-2030 have been generated based on selected design year considering four boundary conditions. Agricultural water demand data has been calculated from 2017 to 2030 according to the National Water Management Plan (NWMP) of WARPO and municipal water demand has been calculated from projected future population data of BBS. After development of scenarios with the help of SW-GW interactive model, most extreme and suitable scenario has been identified for this study area up to 2030.

3.8.7 Prediction of Data up to Year 2030

For prediction model of MIKE SHE, required data that has been projected are described in this article from year 2017 to 2030.

(i) Prediction of Hydrological Data

Precipitation

Monthly precipitation data for 2017 to 2030 have been collected from Global Circulation Model HADCM3 using Climate Editor Tool of Mike 11 software. Emission scenario has been chosen for this analysis is SRA2 which is based on the assumption that a very heterogenous world with continuously incresing global population and regionally oriented economic growth that is more fragmented and slower than in other storyline.

Evapotranspiration

Monthly evapotranspiration data for 2017 to 2030 have been collected from Global Circulation Model HADCM3 using Climate Editor Tool of Mike 11 software. Emission scenario has been chosen for this analysis is SRA2 which is based on the assumption that a very heterogenous world with continuously incresing global population and regionally oriented economic growth that is more fragmented and slower than in other storyline.

(ii) Prediction of Hydraulic Data

River water level

For projection of groundwater levels up to 2030, it is considered in this study that river water level data follows the same time series plotted for year 2016 that has to be extended up to 2030.

(iii) Prediction of Boundary GWL Data

Groundwater level at model boundary

Projected groundwater level data for eight (8) boundary wells are very important variables of the MIKE SHE hydrologic model. For projected groundwater level of the model boundary wells, four (4) boundary conditions named as “Boundary Condition 01”, “Boundary Condition 02”, “Boundary Condition 03” and “Boundary Condition 04” have been considered.

Boundary Condition 01: Assumption is, same groundwater level of hydrological condition of the year 2016 (base condition) individual model boundary wells will be continued over the years up to 2030.

Boundary Condition 02: Assumption is, same groundwater level of hydrological condition of the year 1990 (average condition of 2.33 years return period) individual model boundary wells will be continued over the years up to 2030.

Boundary Condition 03: Assumption is, same groundwater level of hydrological condition of the year 2014 (dry condition of 5 years return period) individual model boundary wells will be continued over the years up to 2030.

Boundary Condition 04: Assumption is, same groundwater level of hydrological condition of the year 1994 (extreme dry condition of 10 years return period) individual model boundary wells will be continued over the years up to 2030.

(iv) Prediction of Water Demand

In order to support the food requirement of the increased population, crop production needs to be increased bringing potential areas under irrigation through optimum utilization of the available water resources. It is important to assess future water requirement to see whether it exceeds the safe yield limit of the aquifer and creates any environmental degradation. Future water demand has been assessed for irrigation and domestic use following the methodology as mentioned in this section.

Irrigation water demand

Upazila wise crop water requirement for different cropping pattern has been assessed by IWM under the referenced project according to 2012 survey (IWM, 2012) has shown in Appendix-C and considered as input data for the study. These data has used in this study for base irrigation demand in the year 2016.

According to National Water Management Plan (NWMP), irrigation demands are expected to increase potentially by at least a quarter over the next 25 years (WARPO, 2001). From 2016 to 2030, 3 sets of crop demand increment were taken that exponentially increased from 1.0 in 2016 to values of (i) no increment; (ii) 1% yearly increment of present demand; (iii) 1.5% yearly increment demand; (iii) 2% yearly increment demand and (v) 2.5% yearly increment of present demand respectively in 2030 is shown in Figure 3.5. 2016 is considered as the base year (present demand year). To attain 1%, 1.5% , 2% and 2.5% yearly incremental demand, demand of base year has been multiplied by 1.010, 1.015, 1.020 and 1.025 respectively. Land use (crop coverage area) expansion within the gross area is considered as key reason for the increment of water demand.

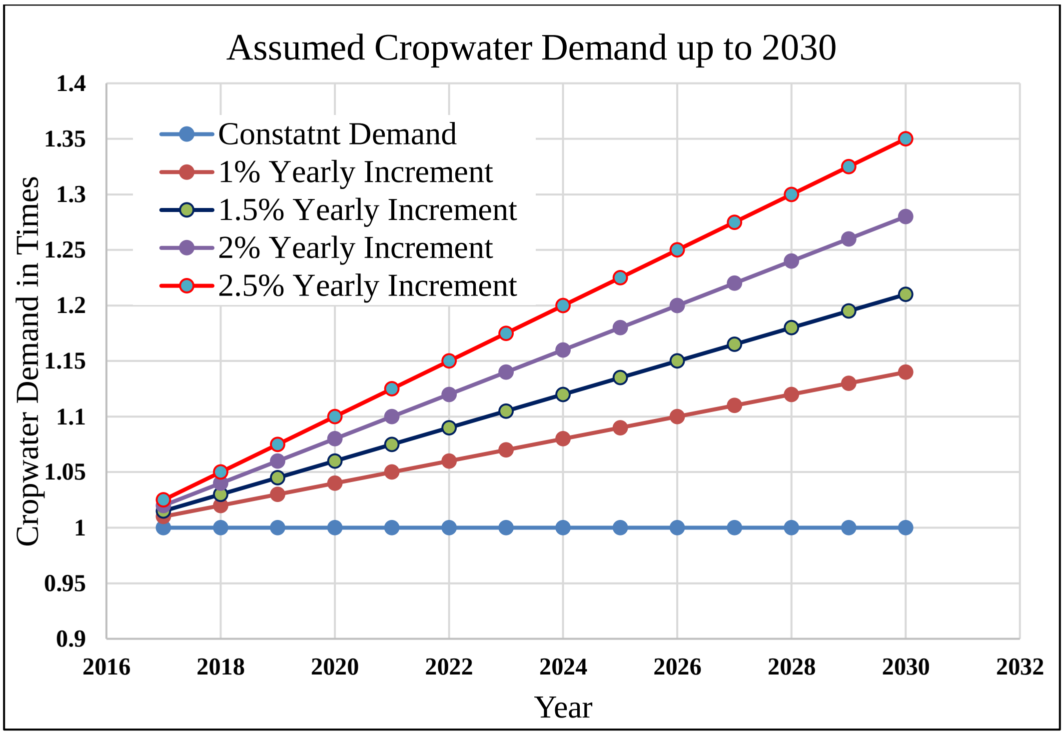


Figure 3.5: Irrigation demands considered in the models (for 2017-2030)

Domestic and Municipal water demand

In Bangladesh, about 97% of total potable water is met up from groundwater sources. It is understood from the field survey that domestic and municipal water source of the study area is solely groundwater based. Therefore, assessment of domestic and municipal water requirement is important to see the abstraction effect on groundwater table.

According to the NWMP report, per capita gross water demand for municipal town and rural areas are 166 lpcd and 30 lpcd respectively (NWMP, 2000). The gross water demand of municipal town includes 119 lpcd net domestic water demand, 20% of it as a system loss, 10% as gross commercial demand and 15% as industrial demand. On the other hand it has 50% returned flow from the commercial demand and 75% returned flow from industrial demand, thus the net water demand for municipal town becomes 76 lpcd. The gross water demand for rural areas doesn’t include any loss and commercial and industrial demand. Thus the net water demand for rural areas is same as the gross water demand.

In Bangladesh, the population census is carried out in ten years interval. Last population was enumerated in the year 2011 and published by the BBS (2012) which is the only sources of population data. In this study, A govt. report titled “Population Projection *of Bangladesh, Dynamics and Trends (2011-2061)” by BBS under Ministry of Planning has* *been taken as an authentic source for projection of population of Rajshahi district up to 2030.*

The projected population is estimated by the following equation:

$$P_p = P_b\,(1 + r)^{n} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \text{(3.7)}$$

Where P_p = projected population in the year n

P_b = Base population

r = rate of natural increase of population per year

n = number of years being considered

Domestic and municipal water requirement for future condition is assessed based on the population projected to the year 2030. Upazila wise projected population and future water demand for rural and urban areas are given in Table-3.1, Table 3.2 and Table 3.3. In Table 3.1, population has been predicted Upazila-wise within the study area. In Table 3.2, municipal water demand has been calculated up to 2030 in m^3/day unit to understand Upazila-wise water demand for domestic purposes in future within study period. In Table 3.3, municipal water demand has been calculated up to 2030 in mm/day unit to make this demand applicable for groundwater model. From this table it is clear that municipal water demand is very low compared to high agricultural water demand.

Table 3.1: Upazila-wise Projected Population up to 2030

Year	**Bagha**	**Baghmara**	**Charghat**	**Durgapur**	**Godagari**	**Mohanpur**	**Paba**	**Puthia**	**Tanore**	**Rajshahi**
2012	186780	359665	209704	188465	335590	172418	318626	210416	194028	456098
2013	189414	364736	212661	191123	340322	174849	323119	213382	196764	462529
2014	192084	369879	215659	193818	345120	177315	327675	216391	199538	469050
2015	194793	375094	218700	196550	349987	179815	332295	219442	202351	475664
2016	197539	380383	221784	199322	354921	182350	336980	222536	205205	482371
2017	199574	384301	224068	201375	358577	184229	340451	224829	207318	487339
2018	201630	388259	226376	203449	362270	186126	343958	227144	209454	492359

Year	Bagha	Baghmara	Charghat	Durgapur	Godagari	Mohanpur	Paba	Puthia	Tanore	Rajshahi
2019	203706	392258	228707	205544	366002	188043	347501	229484	211611	497430
2020	205805	396299	231063	207662	369772	189980	351080	231848	213790	502553
2021	207924	400380	233443	209801	373580	191937	354696	234236	215993	507730
2022	209525	403463	235241	211416	376457	193415	357427	236039	217656	511639
2023	211139	406570	237052	213044	379356	194904	360179	237857	219332	515579
2024	212764	409701	238877	214684	382277	196405	362953	239688	221020	519549
2025	214403	412855	240717	216337	385220	197917	365747	241534	222722	523549
2026	216054	416034	242570	218003	388186	199441	368564	243394	224437	527581
2027	217112	418073	243759	219071	390088	200418	370370	244586	225537	530166
2028	218176	420121	244953	220145	392000	201400	372185	245785	226642	532764
2029	219245	422180	246153	221224	393921	202387	374008	246989	227753	535374
2030	220319	424249	247360	222308	395851	203379	375841	248199	228869	537998

Table 3.2: Upazila-wise Municipal Water Demand in m3/day up to 2030

Year	**Bagha**	**Baghmara**	**Charghat**	**Durgapur**	**Godagari**	**Mohanpur**	**Paba**	**Puthia**	**Tanore**	**Rajshahi**
2012	7664	12465	8083	6898	12696	6089	13558	7274	8313	34663
2013	7772	12640	8197	6995	12875	6175	13749	7376	8430	35152
2014	7882	12819	8312	7094	13056	6262	13943	7480	8549	35648
2015	7993	12999	8430	7194	13240	6350	14140	7586	8669	36150
2016	8105	13183	8548	7295	13427	6440	14339	7693	8792	36660
2017	8189	13318	8636	7371	13565	6506	14487	7772	8882	37038
2018	8273	13456	8725	7447	13705	6573	14636	7852	8974	37419
2019	8359	13594	8815	7523	13846	6641	14787	7933	9066	37805
2020	8445	13734	8906	7601	13989	6709	14939	8015	9159	38194
2021	8532	13876	8998	7679	14133	6778	15093	8097	9254	38587
2022	8597	13982	9067	7738	14242	6830	15209	8160	9325	38885
2023	8663	14090	9137	7798	14351	6883	15326	8223	9397	39184
2024	8730	14199	9207	7858	14462	6936	15444	8286	9469	39486
2025	8797	14308	9278	7918	14573	6989	15563	8350	9542	39790
2026	8865	14418	9350	7979	14685	7043	15683	8414	9616	40096
2027	8909	14489	9395	8018	14757	7078	15760	8455	9663	40293
2028	8952	14560	9441	8058	14830	7112	15837	8497	9710	40490
2029	8996	14631	9488	8097	14902	7147	15915	8538	9758	40688
2030	9040	14703	9534	8137	14975	7182	15993	8580	9805	40888

Table 3.3: Upazila-wise Municipal Water Demand in mm/day up to 2030

Year	Bagha	Baghmara	Charghat	Durgapur	Godagari	Mohanpur	Paba	Puthia	Tanore	Rajshahi
2012	0.041	0.034	0.049	0.035	0.027	0.037	0.040	0.038	0.028	0.761
2013	0.042	0.035	0.050	0.035	0.027	0.038	0.040	0.038	0.029	0.772
2014	0.043	0.035	0.051	0.036	0.027	0.038	0.041	0.039	0.029	0.782
2015	0.043	0.035	0.051	0.036	0.028	0.039	0.042	0.039	0.029	0.793
2016	0.044	0.036	0.052	0.037	0.028	0.040	0.042	0.040	0.030	0.805
2017	0.044	0.036	0.053	0.037	0.029	0.040	0.043	0.040	0.030	0.813
2018	0.045	0.037	0.053	0.038	0.029	0.040	0.043	0.041	0.030	0.821
2019	0.045	0.037	0.054	0.038	0.029	0.041	0.043	0.041	0.031	0.830
2020	0.046	0.037	0.054	0.038	0.029	0.041	0.044	0.042	0.031	0.838
2021	0.046	0.038	0.055	0.039	0.030	0.042	0.044	0.042	0.031	0.847
2022	0.046	0.038	0.055	0.039	0.030	0.042	0.045	0.042	0.032	0.853
2023	0.047	0.038	0.056	0.039	0.030	0.042	0.045	0.043	0.032	0.860
2024	0.047	0.039	0.056	0.040	0.030	0.043	0.045	0.043	0.032	0.867
2025	0.048	0.039	0.056	0.040	0.031	0.043	0.046	0.043	0.032	0.873
2026	0.048	0.039	0.057	0.040	0.031	0.043	0.046	0.044	0.033	0.880
2027	0.048	0.040	0.057	0.041	0.031	0.044	0.046	0.044	0.033	0.884
2028	0.048	0.040	0.057	0.041	0.031	0.044	0.047	0.044	0.033	0.889
2029	0.049	0.040	0.058	0.041	0.031	0.044	0.047	0.044	0.033	0.893
2030	0.049	0.040	0.058	0.041	0.032	0.044	0.047	0.045	0.033	0.897

From this above calculation it has found that average domestic and municipal water requirement from 2012 to 2030 is 0.05 mm/day for all Upazilas except Rajshahi

City Corporation where demand is 0.85 mm/day. For simplicity and for low demand compared to crop demand, a constant demand of 0.05 mm/day and 0.85mm/day have been applied in groundwater model for all Upazilas and Rajshahi city corporation respectively to address population and municipal demand.

Total Water Requirement

The total water requirement for the study area is the sum of the water requirement for irrigation, domestic and municipal water use. Upazilla wise irrigation water requirement is estimated based on the percentage of crop coverage within the Upazilla and domestic & municipal water requirement is estimated based on the present population of the Upazilla. The total water requirement for the study area for future condition has been estimated following the procedure as mentioned in the above sections. It can be noted that in the present situation, the Domestic and Municipal water requirement is very negligible portion of total water requirement, actually the irrigation water requirement dominates the total water requirement. Water demand for other sectors are not considered in this study due to their negligible contribution in total water demand.

3.8.8 Result and Analysis

Yearly minimum and maximum groundwater level have been analyzed for all upazilas and most emphasis has been given to identify the extreme scenario on minimum groundwater level. All these mentioned scenarios show decreasing trend of groundwater levels within the study period. After generation of possible future scenarios, extreme scenario has been identified. So, in this study, innervations have been applied to this extreme scenario to sustain future groundwater resources up to 2030. Attempts have been made to stop the rate of declining groundwater levels and to increase the trends of groundwater levels of the study area. Three interventions have been applied and they are (i) Structural, (ii) Non-Structural and (iii) Combined Interventions.

3.9 Summary

Theory and methodology is the backbone of any research work. If the methodology is sound and clear it is expected that the study result based on this methodology will also be sound. So in this chapter background theory and overall methodology of this study have been reviewed. Short description of each section of methodology is described here and further description and analysis based on this methodology has been discussed in the following chapter.

CHAPTER 4

STUDY AREA AND MODEL SET UP

4.1 General

In any research work, knowing the details of the study area is very important. Relevant information of the study area helps to understand the overall situation of the study area. It helps to find existing and future problems and suitable solution to overcome these problems more practically. Before model set up, sound knowledge of the study area is necessary. Proper set up of the models are also important to extract good results. Solution to counter problems will be based on model output, so model set up should be appropriate so that it can simulate the real scenario of the study area as close as possible. For this reason, these two important issues are discussed in this chapter.

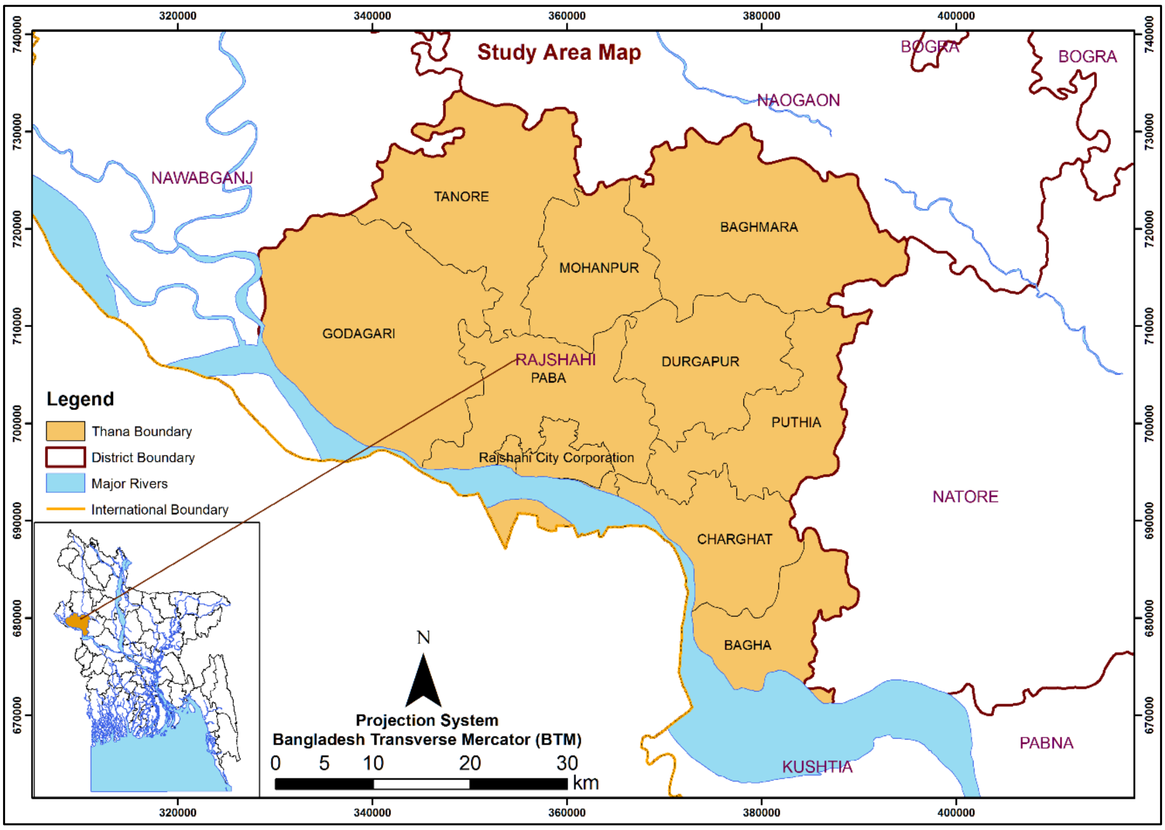


Figure 4.1: Map of Study Area (Rajshahi District in Bangladesh)

4.2 Study Area

Rajshahi District area is around 2407.01 sq km, located in between 24°07' and 24°43' north latitudes and in between 88°17' and 88°58' east longitudes. It is bounded by Naogaon district on the north, West Bengal state of India, Kushtia district and Ganges river on the south, Natore district on the east, Nawabganj on the west. Map of study area has been shown in Figure 4.1.

(i) Climate of the area:

Rajshahi's climate is classified as tropical. The summers are much rainier than the winters in Rajshahi. This climate is considered to be Aw (Tropical wet and dry or savanna climate; with the driest month having precipitation less than 60 mm (2.4 in) and less than 4% of the total annual precipitation) according to the Köppen-Geiger climate classification. The average annual temperature in Rajshahi is 25.8 °C. About 1419 mm of precipitation falls annually. Precipitation is the lowest in December, with an average of 2 mm. The greatest amount of precipitation occurs in July, with an average of 301 mm. At an average temperature of 29.4 °C, June is the hottest month of the year. The lowest average temperatures in the year occur in January, when it is around 18.5 °C. Between the driest and wettest months, the difference in precipitation is 299 mm. The variation in temperatures throughout the year is 10.9 °C. Summary of these information is tabulated in Table 4.1 and shown in Figure 4.2 and 4.3.

Table 4.1: Average Temperature and rainfall statistics of the study area

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Avg. Temperature (°C)	18.5	20.6	25.7	28.8	29.1	29.4	28.9	29.1	29.1	27.6	23.5	19.4
Avg. Min. Temperature (°C)	11.6	13.3	18	21.7	23.5	25.5	25.9	26.2	25.9	23.4	17.6	12.8
Avg. Max. Temperature (°C)	25.4	28	33.5	35.9	34.8	33.3	32	32	32.3	31.9	29.5	26.1
Avg. Precipitation / Rainfall (mm)	13	15	27	39	129	272	301	261	234	112	14	2

Source: (climate-data.org)

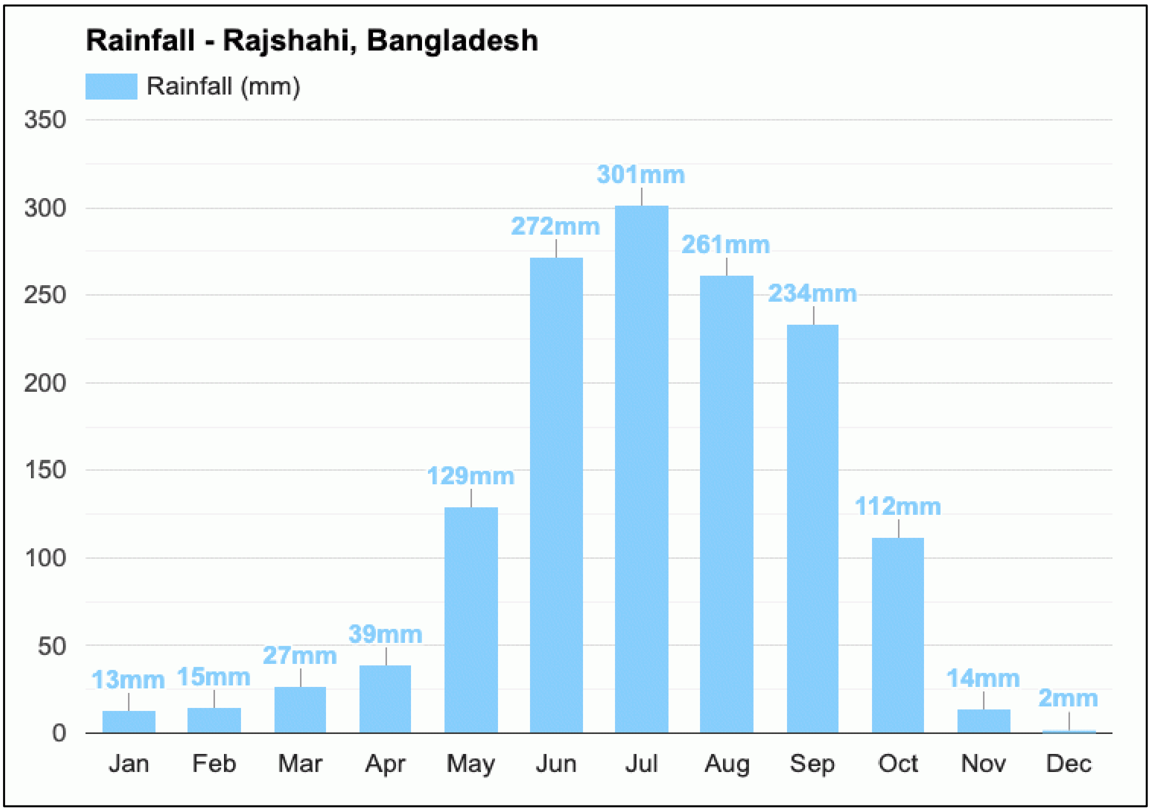


Figure 4.2: Diagram of average monthly rainfall of Rajshahi District (Source: climate-data.org)

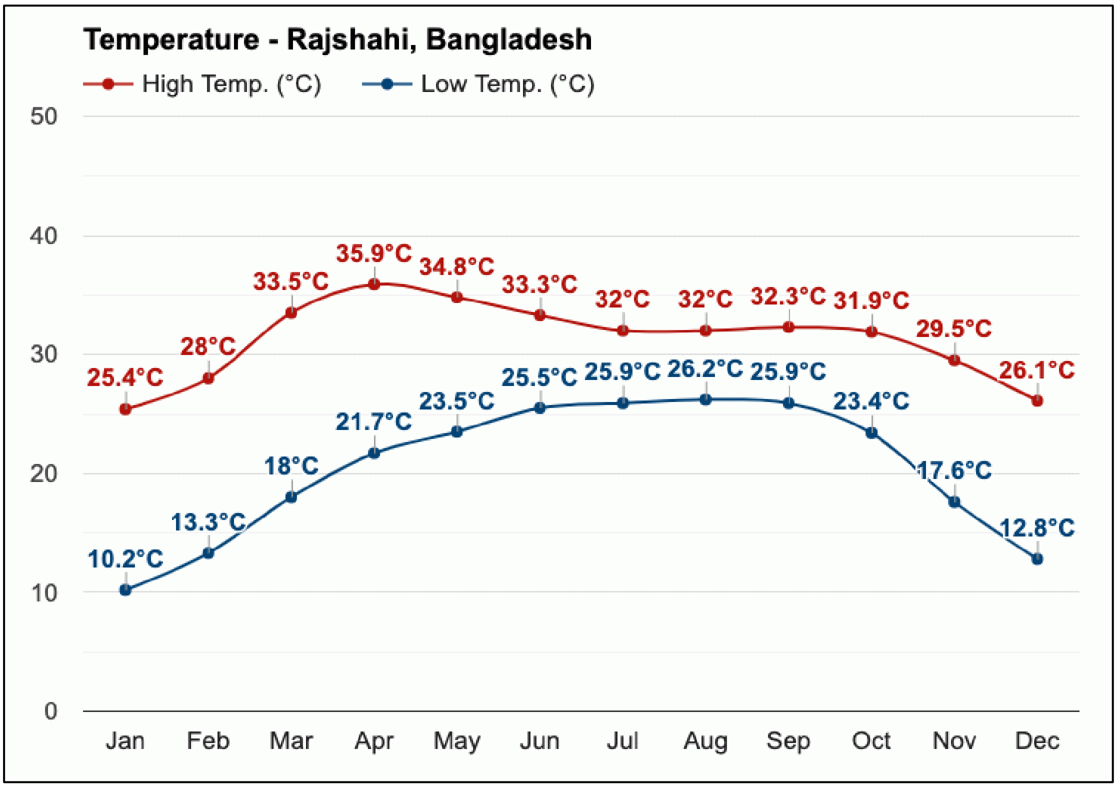


Figure 4.3: Diagram of average maximum and minimum temperature of Rajshahi District (Source: weather-atlas.com)

(ii) Topography of the study area:

The topography of the study area varies from 9.72mPWD to 46.85mPWD. Almost 13% of study area has elevation greater than 25.00mPWD. Slope of this area varies from 0 to 1.35 degree. This area remains flood free because of its high elevation. Topography of the study area is shown in Figure 4.4.

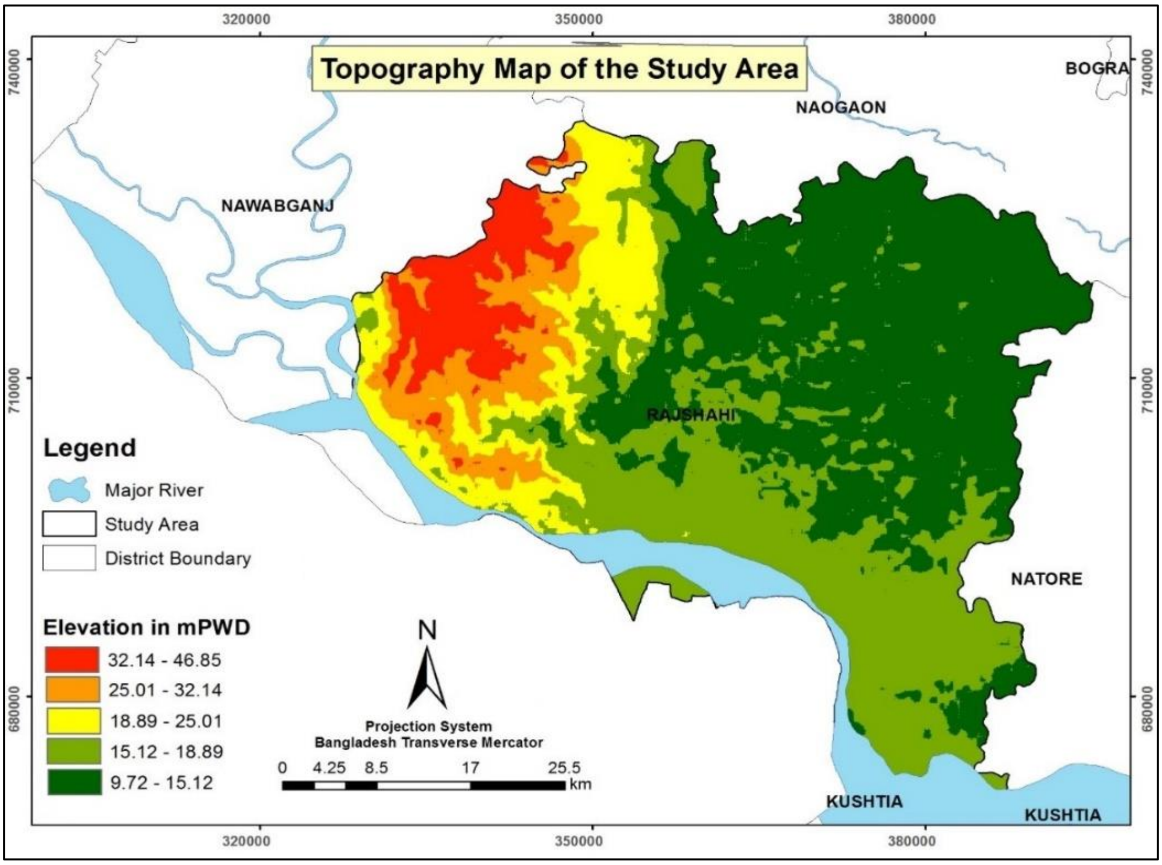


Figure 4.4: Topography of the study area

(iii) Geomorphology and hydrogeological setting:

Hydrogeological parameters of an area are generally governed by the lithostratigraphy and prevailing tectonic activities of that area which is a part of regional geological setting, physiography and geomorphology.

(iv) Study area and regional geological setting:

The present geomorphologic setting of the study area is the result of tectonic adjustment within the Bengal Basin. Tectonically Bangladesh is lying on the Indian Plate and occupies the major part of the Bengal Basin. Geological data indicates that the area is traversed by a basement-controlled faults named Tanor fault. The study area experienced lateral discontinuities of terrace materials indicate that the Barind Terrace is large elevated block. The blocks are bordered by raised shelf type terrain due to step faulting along eastern and western margins. The Barind Terrace has significant effect on both the terrestrial and subsurface geological environment that ultimately influences the ground water regimes of the area.

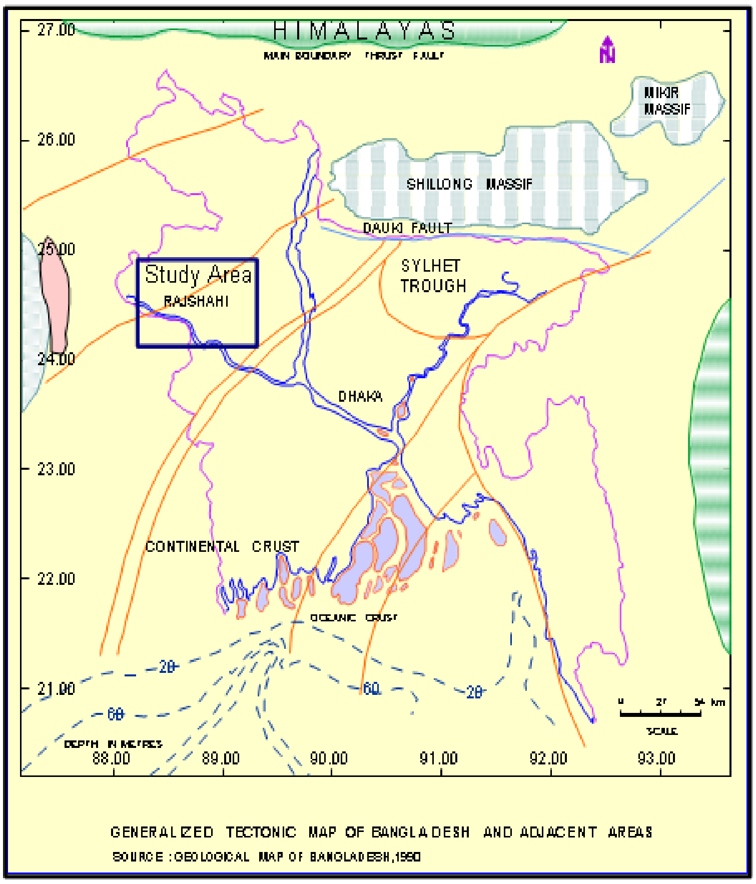


Figure 4.5: Generalized Tectonic Map of Bangladesh and Adjacent Area (Source GSB, 1990**)**

4.3 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.

(i) Precipitation:

There are twelve BWDB rainfall stations (Table 4.2) that have influence in the study area as well as model area shown in Figure 4.6. Station wise data is recorded by BWDB on daily basis from 1970 to 2016. Missing data are filled up by taking average of the data of stations surrounding the station in question. It is assumed that the normal rainfalls of surrounding stations are within 10 to 12% of that concerned station (Subramanya, 1994). Accurate prediction of hydrological models requires accurate spatial and temporal distribution of rainfall observation network. For this reason, distribution of rainfall station within model boundary has been shown in Figure 4.6. Quality checking of rainfall data includes visual inspection of plots, preparation of double mass curves, estimation of yearly mean values, and comparison of monthly values.

Table 4.2: Details of rainfall stations within/around the Rajshahi district

Station ID	**Station Name**	**Data Availability**
R003	Atrai	1970 - 2016
R023	Natore	1970 - 2016
R219	Tanore	1970 - 2016
R170	Durgapur	1970 - 2016
R172	Godagari	1970 - 2016
R184	Lalpur	1970 - 2016
R185	Manda	1970 - 2016
R190	Nachol	1970 - 2016
R195	Chapai Nawabganj	1970 - 2016
R204	Puthia	1970 - 2016
R205	Rajshahi	1970 - 2016
R212	Sardah	1970 - 2016

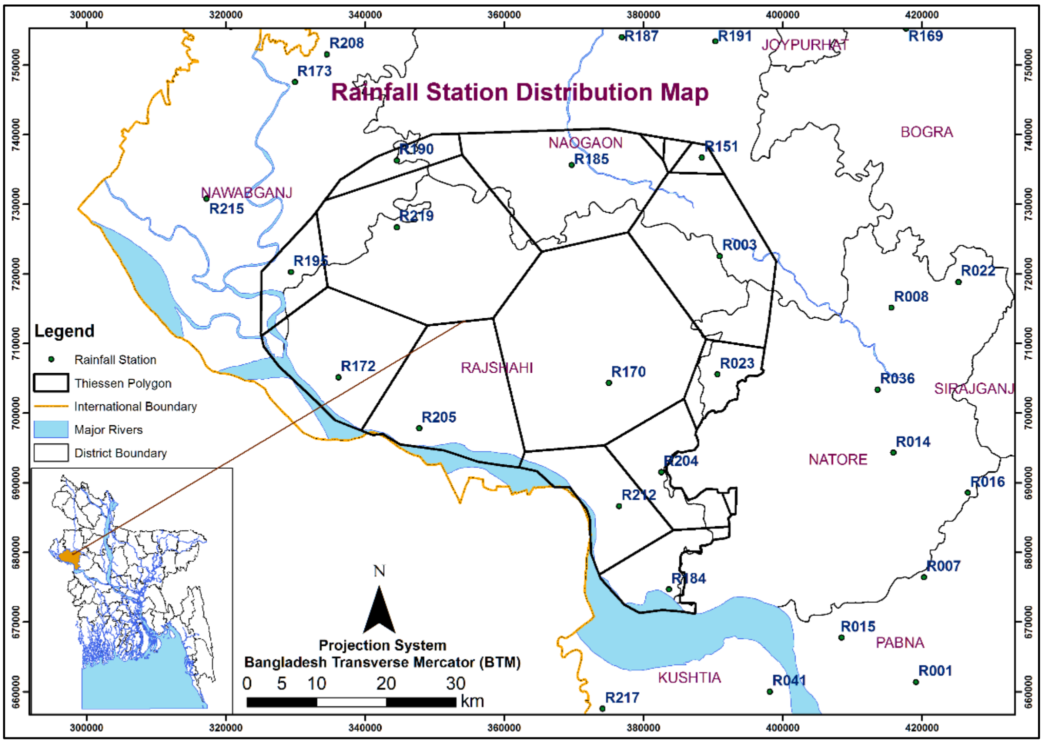


Figure 4.6: Rainfall station distribution within/around the Rajshahi district (source: BWDB)

(ii) Evapotranspiration:

Evapotranspiration data have collected directly from the referenced IWM study (IWM, 2013). According to the collected data, BWDB maintains only one evaporation station in the study area. Station ID is E 29 and available data has been found from 1969 to 2016. 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, 2013). From 1969 to 2016 data, annual evaporation value in the study area is around 1080mm (about 3 mm/day). As such, data from one station has been used for the whole study area.

(iii)Hydrogeological setting:

Based on so far available hydro-stratigraphic data and reports it appears that within the exploited depth one-aquifer unit exists in the study area. However, there is a clay layer but not continuous within this aquifer. The upper part of this aquifer is composed of grey and light brown colored very fine-to-fine sand with lenses of fine to medium grained sand and occasionally with clay, silt and trace mica lenses. The lower part of this aquifer is considered as principal source of groundwater production in the study area. The lower part of this aquifer has composed of medium to coarse-grained sand with occasional fine sediment lenses. The geometry and confining properties of both of this aquifer are variable with its location in the study area and controlled by local subsurface geology. According to UNDP (UNDP, 1982) report the study area aquifer systems has the transmissivity value ranges from 500 m^2 /day to 1500 m^2 /day. Steep gradient of groundwater elevation exists in the study area which may have maximum outflow situation and direction is towards the Padma River.

(iv) 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 30 groundwater observation wells of BWDB is selected in/around the study area is shown in Figure 4.7 and Figure 4.8. Among them 8 observation wells are on the study area boundary, which have used as boundary condition and 22 observation wells are inside the study area which can be used for calibration purpose.

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.

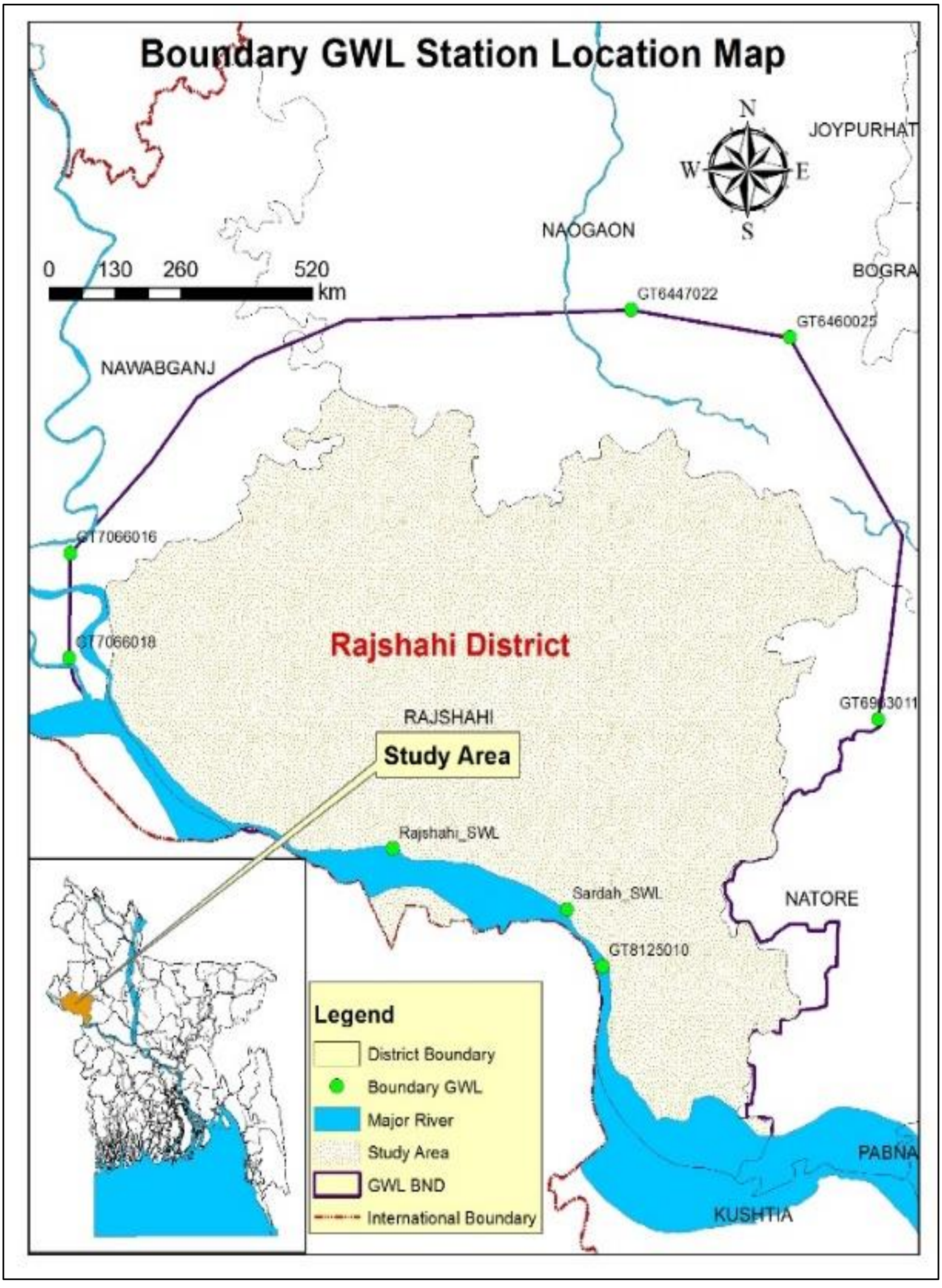


Figure 4.7: Selected Groundwater observation wells (Boundary Wells) under BWDB within/around the Rajshahi district (Source: BWDB)

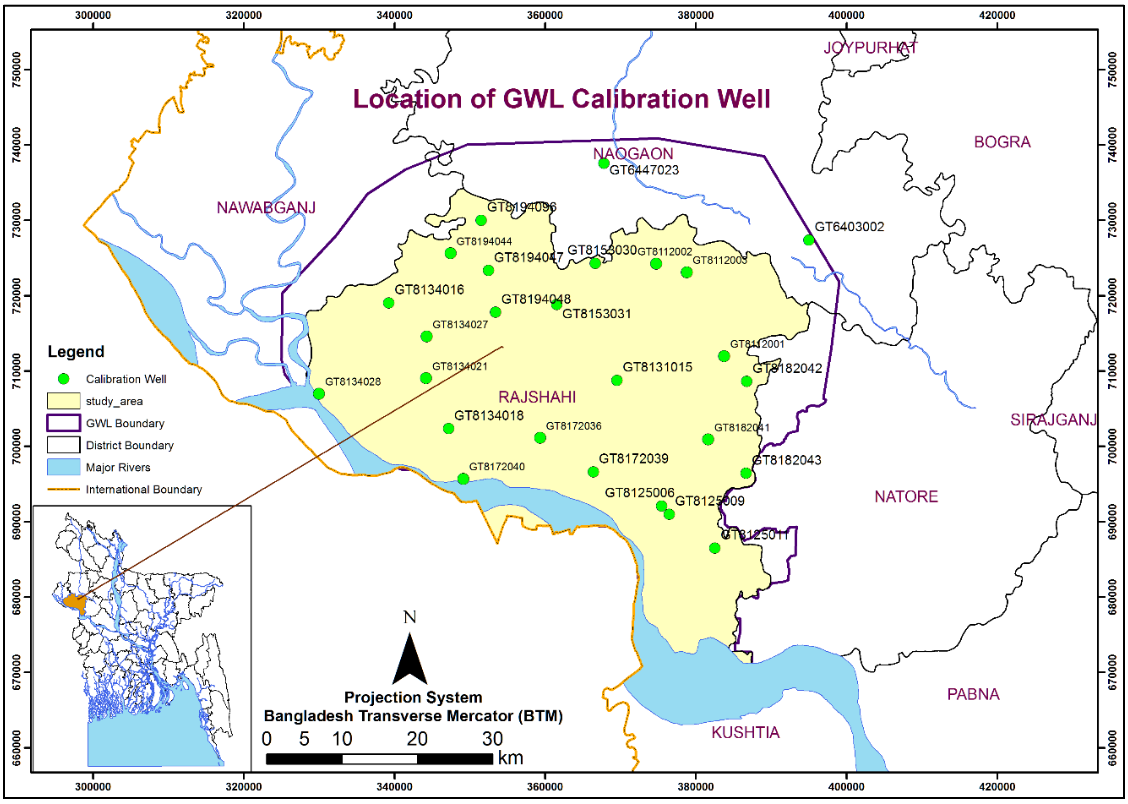


Figure 4.8: Selected Groundwater observation wells (Calibration Wells) under BWDB within/around the Rajshahi district

Existing trend of groundwater levels (1986 to 2016) have been analyzed and decreasing trends are found in almost all groundwater observation wells. Trend analysis has been carried out to understand the current situation of groundwater in this study area. A sample trend analysis graph has been given in Figure 4.9 and rest of these analysis have been arranged in **Appendix-B.** From yearly average trend analysis of station ID GT8125009 it is found that maximum groundwater level falls 6.3cm/year on the other hand minimum groundwater level falls 15.cm/year.

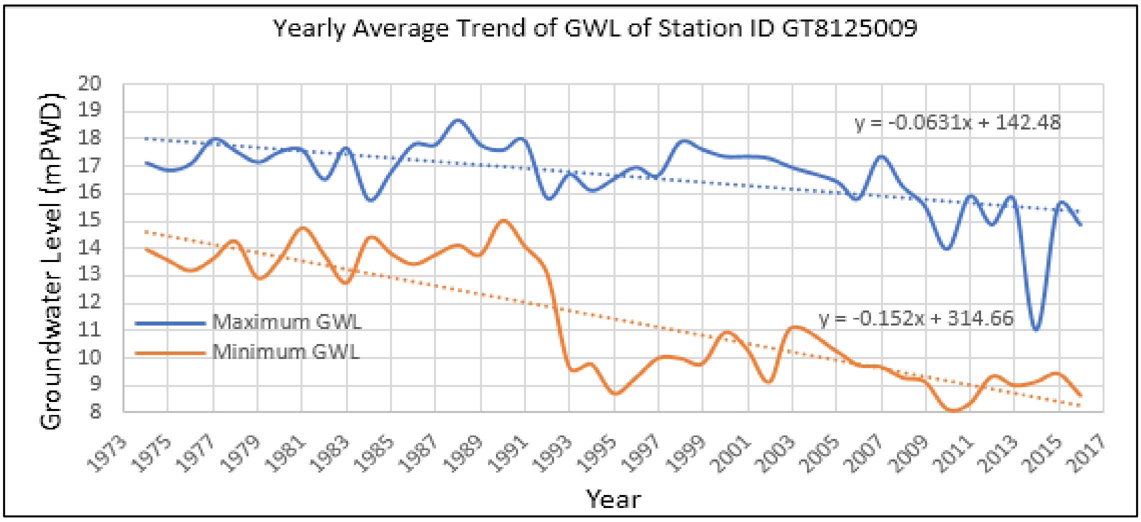


Figure 4.9: Yearly average trend of GWL at GT8125009 for the year 1974 to 2016

(v) Abstraction due to Water Use

In the study area abstraction data is not available. To overcome this limitation, water abstraction data for 2012 to 2016 have been estimated. Main assumption behind this estimation that the irrigation and domestic 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 including domestic population data, abstraction obtained. 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 and domestic 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. Domestic water demand depends on population and their consumption pattern of that area.

(vi) River system:

There are ten rivers in this district, totaling around 146 km in length. Major rivers of the study area are Ganges, Mahananda, Baral and Sib-Barnai. Moreover, there are several minor rivers in this area. Most of the rivers of this region flow from very steep to flat ground.

(vii) River water level:

Some major rivers and a list of beels are the main surface water sources in the study area. Major Rivers passing through the study area are Ganges, Mahananda, Baral and Sib-Barnai. Among all rivers, Ganges is contributing major role and dominating surface water resources. Water level is recorded five times daily at these locations. These water level data has collected and processed for the period of 2005 to 2012. Collected data has checked by plotting hydrograph. The river water level data for other locations has generated by linear interpolation or extrapolation. River water level hydrograph of Ganges at Sardah station is shown in Figure 4.10.

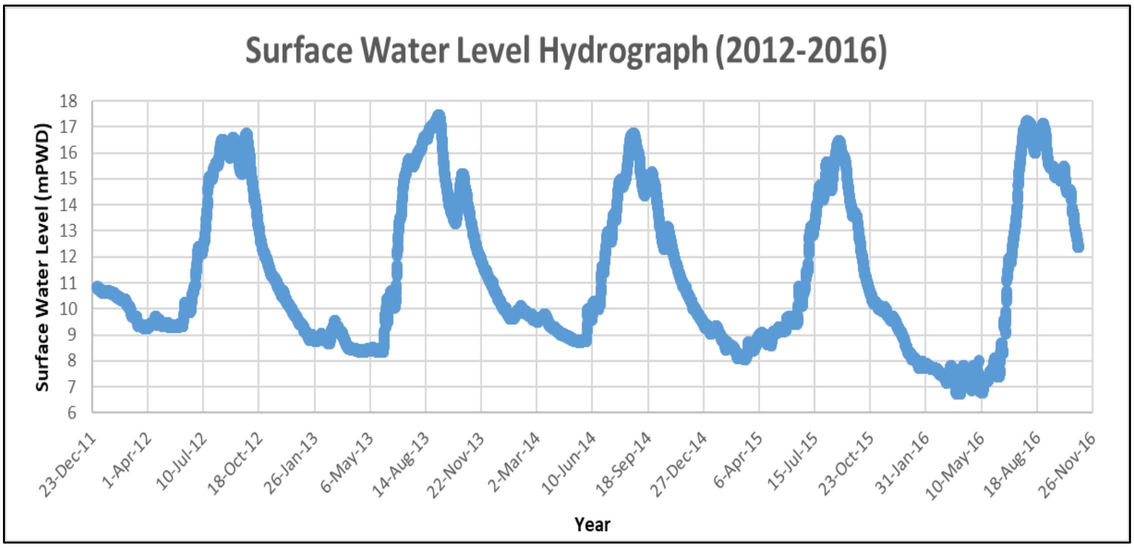


Figure 4.10: River water level hydrograph for river Ganges at Sardah station (Source: BWDB)

(viii) Soil condition:

There are six types of soil profiles available in the study area according to the SRDI map. Grey Terrace Soils silt over clay sub layer is found in high elevated areas where lower elevated areas are dominated by Calc. dark grey and calc. brown floodplain soil grey clay and Calcareous dark grey floodplain soils with lime kankar soil. Details of the soil profile is shown in Figure 4.11.

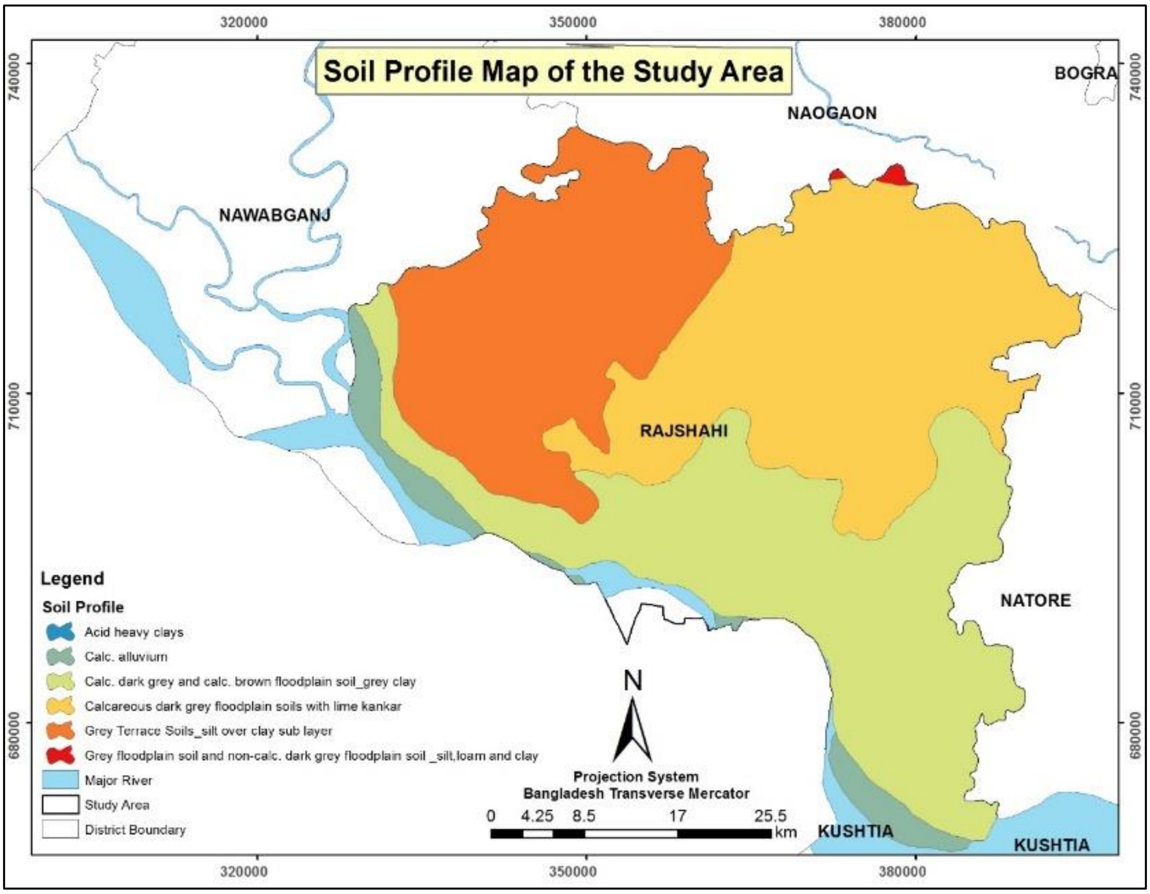


Figure 4.11: Soil profile map of the study area (Source: SRDI)

(ix)Lithology of the study area:

A general-purpose subsurface lithology of the study area has been prepared by IWM through analyzing sedimentary structure, its grain size, hydraulic properties, its thickness and depth. Same litho-logical layers have been taken for this study to prepare MIKE SHE hydrologic model. A sample hydro-stratigraphic cross sections (Section S2-N2: Figure 4.13) show similar lithological pattern that is used in this study. The plan for hydro-stratigraphic cross sections are shown in Figure 4.12. Rest of the cross sections (10) have been shown as Figure C1 to C10 in Appendix-C. Hydro-stratigraphic cross sections show that the thickness of upper soil thickness is large enough which impedes groundwater recharge. It is also clear from hydro-stratigraphic cross sections that land slope is very steep in this region which allows water to runoff rather than infiltration.

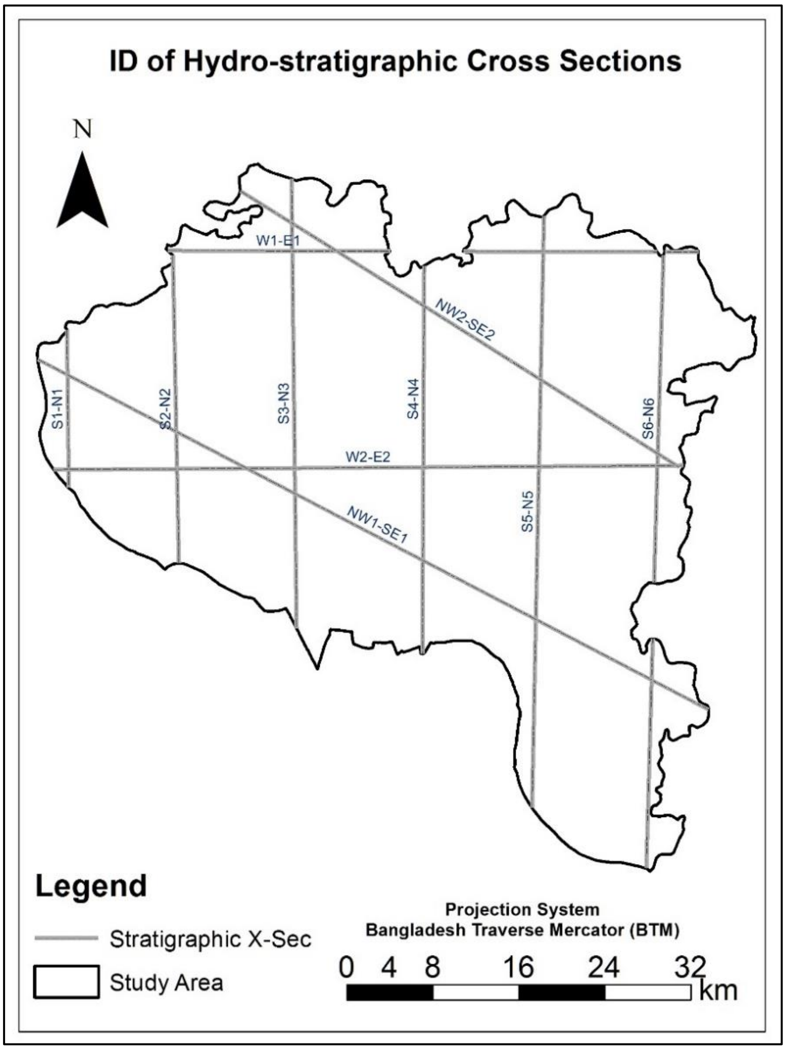


Figure 4.12: Plan of hydrostat graphic sections

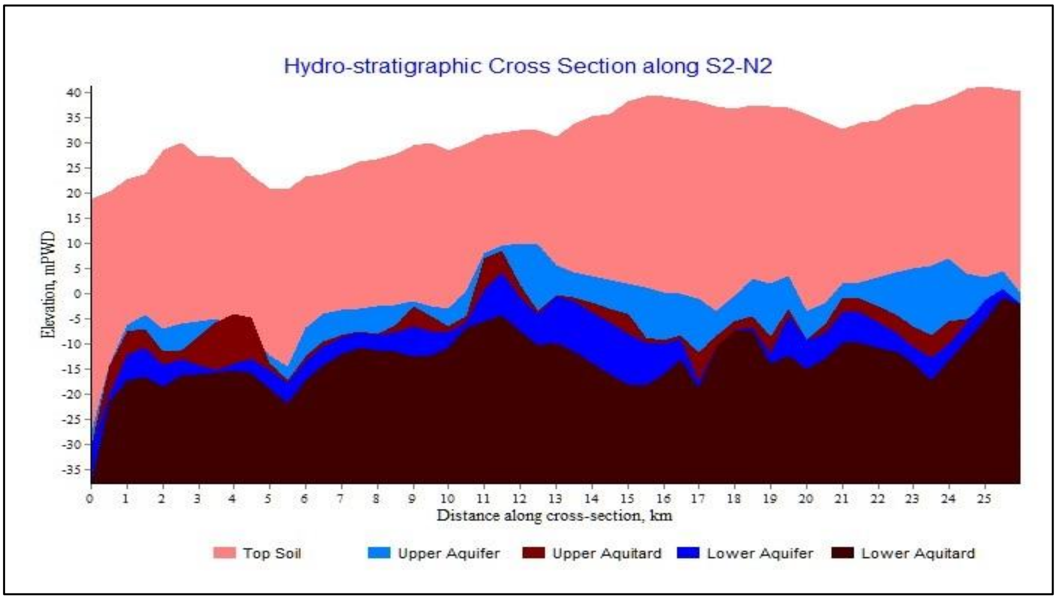


Figure 4.13: Hydro-stratigraphic Cross Section S2-N2 along South to North

(x) Aquifer properties:

Aquifer tests have been performed in accordance with IWM developed data base to understand the aquifer geometry and aquifer characteristics which include vertical & horizontal hydraulic conductivity and specific yield. These properties have been used as main parameters in groundwater model for assessing groundwater resource base and development potential. It is found that in Rajshahi district area horizontal hydraulic conductivity mostly varies from 28 m/day to 65 m/day. High hydraulic conductivity indicates that the aquifer is highly permeable. Aquifer properties data have been collected from a research project of IWM titled "*Determination of Hydro-geological Parameter for Different Regions of Bangladesh (North-West Region: Phase-I)"* and tabulated in Table 4.3.

Table 4.3: Aquifer Properties in Rajshahi district

District: Rajshahi	**T (m^2/day)**	**K (m/day)**	**Sy**
Bagha	1500	45	0.12
Baghmara	1275	28	0.07
Charghat	700	29	0.03
Durgapur	1800	46	0.09
Godagari	1150	29	0.09
Mohanpur	1213	33	0.13
Paba	1500	53	0.01
Puthia	1530	49	0.03
Tanore	2000	65	0.03

(Source: IWM, BWDB)

(xi) Agricultural practice in the study area:

In the project area, main crops are rice-paddy, jute, wheat, potato, oilseeds and variety of vegetables and they grow in rain fed and irrigated condition. Boro, Wheat, potato, oilseeds and winter vegetables are the main Rabi (November to March) crops, while Kharif-I (April to June) crops are HYV Aus, B. Aus, Jute, Kaon, Til and summer vegetables and Kharif-II (July to October) grow HYV Aman, Local Variety Aman and rainy season vegetables. Sugarcane grows in very small scale. Nowadays some fruit trees are also growing. The following major cropping patterns prevail within the project area based on secondary data:

1. HYV Aman followed by potato followed by Maize
2. HYV Aman followed by potato followed by HYV Boro
3. HYV Aman followed by mustard followed by HYV Aus
4. HYV Aus / Jute followed by HYV Aman followed by wheat

5. HYV Aman followed by HYV Boro
6. HYV Aman followed by wheat
7. HYV Aman followed by potato
8. HYV Aman followed by rabi vegetables
9. HYV Aman followed by Maize
10. HYV Aman followed by pulses
11. Local variety Aman followed by wheat/potato/maize
12. Fruit trees

Drought and inadequate irrigation facilities are the major limitations to intensive land use and optimum crop production.

(xii) Irrigation System and Coverage:

Scarcity of rainfall from November to May, and scatter and insufficient rains in the months of September and October, irrigation is essential for intensive use of cultivable land. Though surface water is available at near the outfall of the Mohananda river into the Ganges and in the Ganges River, large pumping plants are required for pumping from the river. Moreover, the water levels of the rivers in some reaches go down beyond the suction limit of low lift pumps becoming the problems of pumping from river. The study area in major part is undulating and is not suitable for flood irrigation. Even then, pumping from the rivers and conserving water by small water control structures now practice limited surface water irrigation. Main dependence for irrigation is on ground water. Groundwater is being extracted for irrigation mainly by deep tubewells and very few shallow tubewells. The irrigation coverage by each DTW is in the range of 12 ha - 25 ha, the average is being 23.68 ha per DTW. Irrigation coverage by each STW is in the range of 1.0 ha-5.0 ha. The average is 2.42 ha per STW and the average coverage per LLP is 5.63 ha.

4.4 Groundwater Model Set Up

The groundwater model up to a depth of 80m for the study area was developed using MIKE SHE hydrologic modelling tools to understand the groundwater flow dynamics and to assess the groundwater resources under the present and various development scenarios. Model was developed covering entire study area with grids size of 1000m×1000m. After satisfactory calibration and verification of the model, the model has been applied for various development options to identify suitable cropping options for groundwater resources.

The model has been calibrated using data for the period 2012 to 2014. In order to get further reliability, calibrated model has also been validated using the recent data of 2015 to 2016. Finally taking the calibrated and validated parameters the model has been applied for various development scenarios by assigning future abstractions and corresponding land use patterns and thus to achieve the objectives set forth in the study particularly comparison of groundwater resources for different cropping pattern. The model area spreads over 9 Upazilas of Rajshahi district having an area about 2400 sq km. The model area is higher than the study area. It is shown in Figure 4.14. This has been done in order to have less boundary impact.

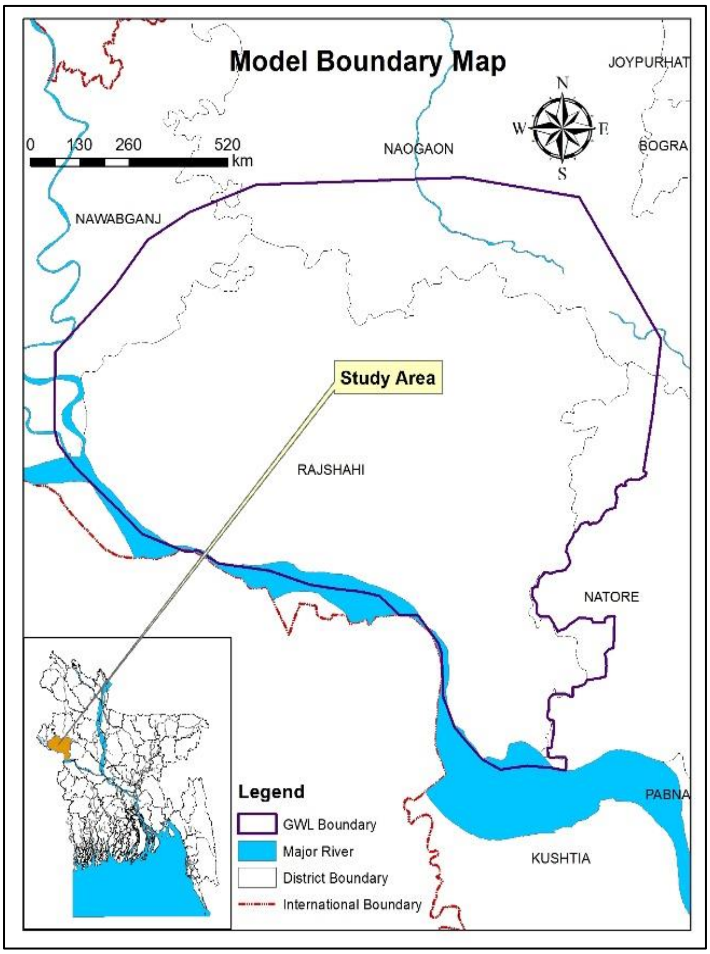


Figure 4.14: Model area for MIKE SHE hydrologic model

(i) Model build-up:

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 evapotranspiration, unsaturated zone, saturated zone, overland flow and river systems. Brief descriptions of the groundwater model setup are given below.

(ii) 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 (1st January 2012 to 31st December 2030). However, simulation periods of the calibration, validation and prediction models were different and user specified.

(iii) Model domain and grid size

The study area has been discretized into 1000m x 1000m square grids as shown in Figure 4.15. The model has 3233 grid cells. The grid cells are the basic units to provide all the

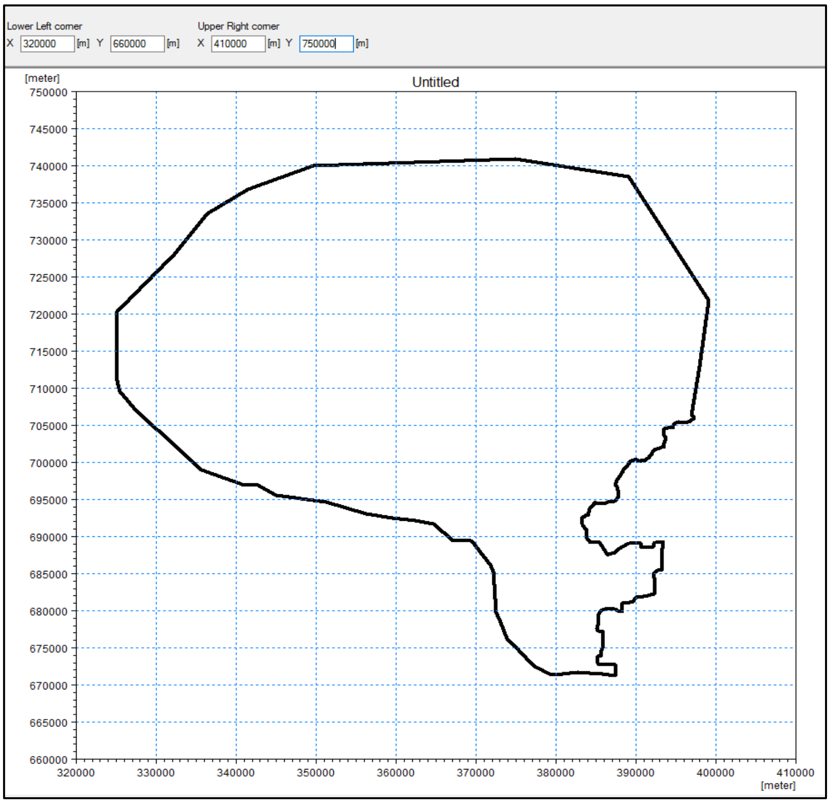

Lower Left corner
X 320000 [m] Y 660000 [m]
Upper Right corner
X 410000 [m] Y 750000 [m]

Figure 4.15: Model domain and grid size of MIKE SHE

spatial and temporal data as input and to obtain corresponding data as output. Upazila wise grid numbers within the study area is given in Table 4.4. A geographical limit of the study area is shown in Table 4.5.

Table 4.4: Grid cells used for model setup

Upazilas of the Rajshahi District	**Numbers of Grid Cells (area: 1 km2)**		
	Upazila wise	**Study area**	**Model area**
Godagari	472	2378	3233
Charghat	165		
Tanore	295		
Durgapur	195		
Paba	280		
Puthia	193		
Baghmara	363		
Bagha	184		
Mohanpur	163		

Geographical limit of the model area falls between 410000 m East, 66000 m North to 320000 m East, 750000 m North in Bangladesh Transverse Mercator (BTM) projection system.

(iv)Topography:

A well-prepared digital elevation model (DEM) is essential for visualizing the floodplain topography and for accurate Modelling. A DEM of 30 m resolution has been developed to define the topography of the study area and used in the model. Topographic data for the study area has been extracted from USGS Earth Explorer.

(v) Precipitation and evapotranspiration:

Rainfall data is very essential input for the model. There are twelve (12) 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. The rainfall data for the relevant stations have been collected from BWDB office. After checking the consistency of these data, the time series input files for precipitation have been computed, projected for future scenarios and incorporated in the model. To account for the spatial variation in rainfall, the time series data for each station has been assigned to thiessen polygon is shown in Figure 4.16.

Time series data for the potential Evapotranspiration are given as input to the model. The evaporation data of Rajshahi station, used in the model is discussed earlier.

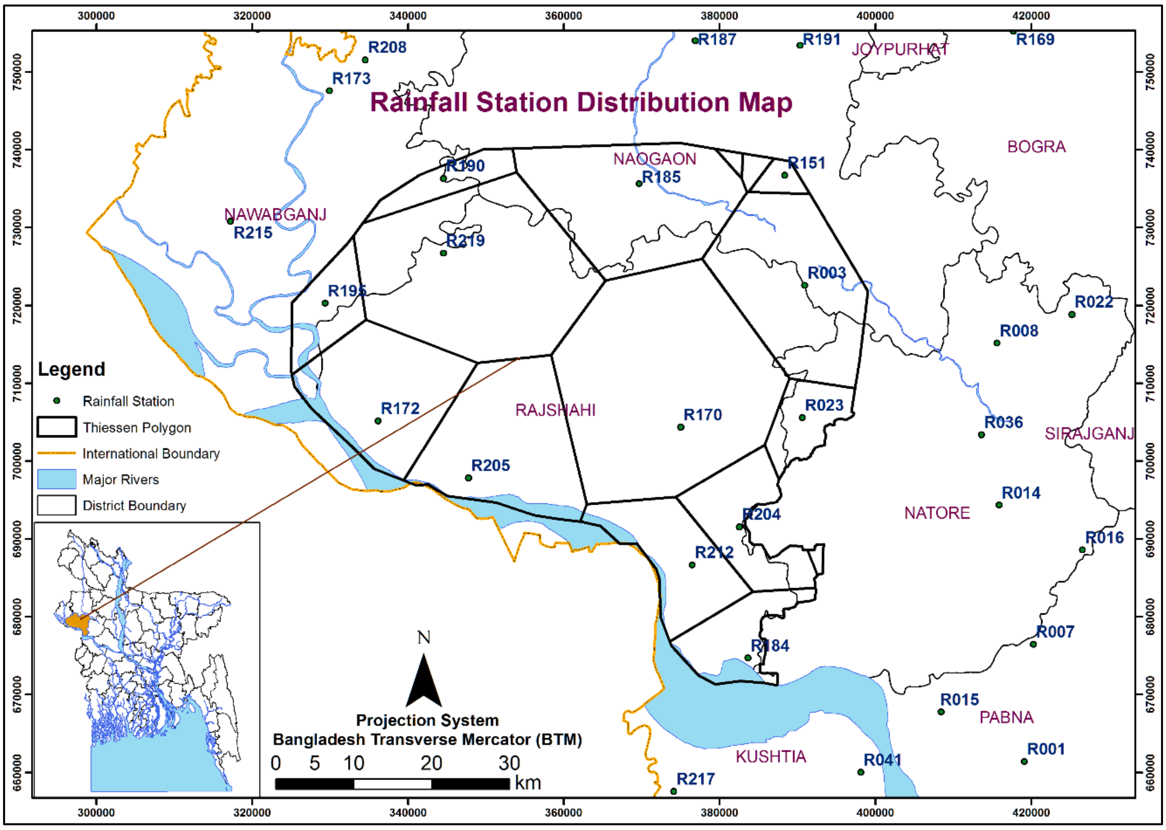


Figure 4.16: Thiessen polygons for individual rainfall station in the study area

(vi) Land use and vegetation:

Land use and vegetation are used in the model to calculate actual Evapotranspiration depending on the actual crops grown in the study area. The major part of the study area is agricultural land. It has homestead and water bodies also. Under the IWM mentioned project, spatial distribution of crops has been determined from a comprehensive field campaign. However, for the model input, these cropping types and cropping pattern have further been simplified considering the major crops that require irrigation water.

(vii) River systems:

The river systems are included in the model described earlier. The river model is coupled with the groundwater model.

(viii) 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 surface runoff, to be routed down-gradient towards the river system. Overland water starts flowing when it exceeds the specified detention storage. Detention storage can be specified either as spatially distributed or as constant. Initial water depth on the ground surface is also required as input data that can also be distributed or constant. The study area is dominated by agricultural land and the main crops are different varieties of paddy. Overland flows are governed by the roughness of topography.

A lower value of roughness has been considered in the model since the area is mainly of agricultural land. A Manning number (M) 10 has been specified describing the surface roughness. Since the area is dominantly agricultural, a constant value has been considered for the entire area. Exchange of overland flow and groundwater flow occurs when a soil becomes completely saturated and at the same time there is pond water on the ground surface. Like river-aquifer exchange, leakage coefficient along with hydraulic conductivity is taken for overland-groundwater exchange.

(ix) Litho-logic layers and corresponding properties:

Same lithologic layers with aquifer properties that is discussed in Article 4.9 have used to prepare MIKE SHE hydrologic model. Horizontal hydraulic conductivity has taken for top soils & aquitard as per developed data base of IWM incorporated into calibrated model under referenced project (IWM, 2012).

(x) Initial condition of groundwater level:

Initial conditions in terms of potential heads of groundwater have been specified in the model is shown in Figure 4.17. Potential heads of the monitoring wells are used to generate initial condition contour map and it is taken applicable for all the layers alike.

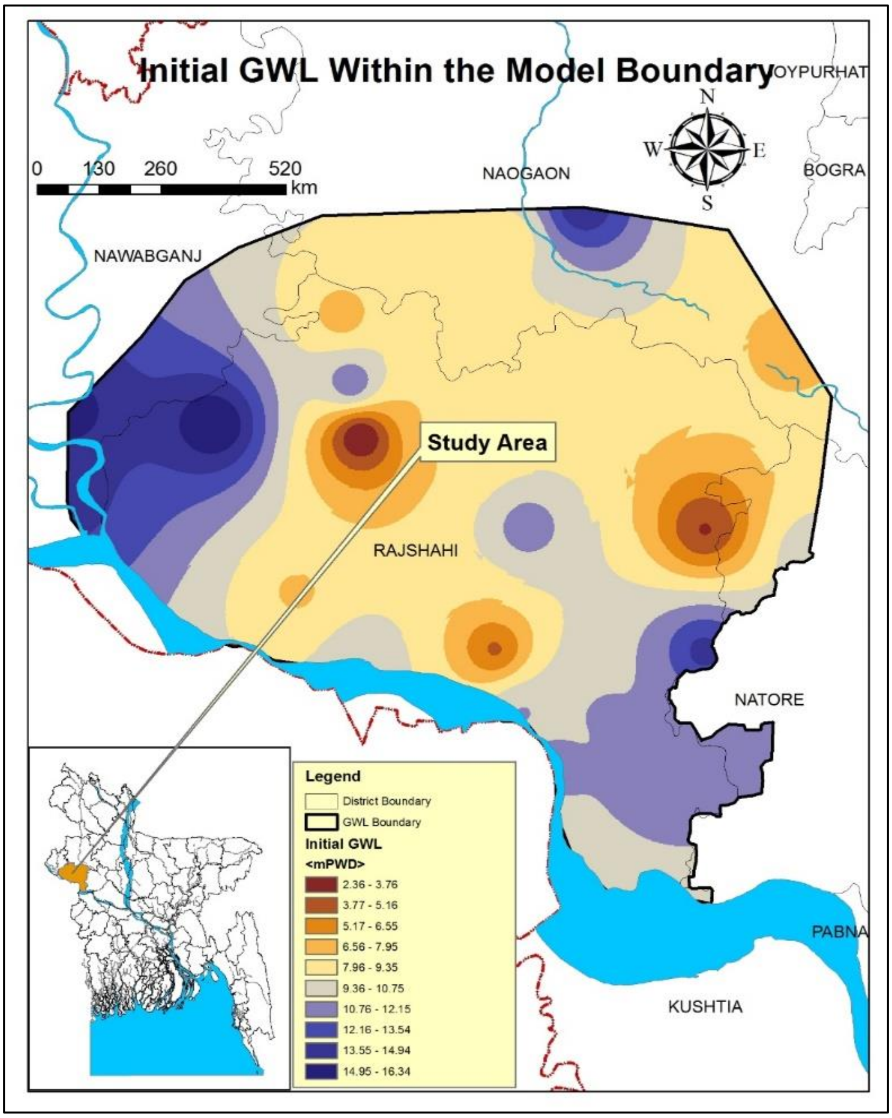


Figure 4.17: Initial groundwater level for the model on 01 January, 2012

(xi)Boundary condition:

Boundary condition must be specified for all the layers along the boundary of the model area. In total 8 monitoring wells are available along boundary line of the study area. Two (2) boundary conditions for boundary groundwater level discussed before, are used in the model. The layers are leaky in nature and thus interconnected. Therefore, the same boundary condition is applied in all the layers.

(xii) Model calibration parameters

Model calibration parameters for groundwater model are horizontal hydraulic conductivity, vertical hydraulic conductivity, specific yield, storage co-efficient.

These parameters are applied on the 3 defined layers as top soil, aquitard and aquifer. Horizontal hydraulic conductivity is considered to be the same value. Specific yield and storage co-efficient is taken directly from the referenced project (Hydrogeological Parameters of North-West Regions of Bangladesh, IWM). Mainly vertical hydraulic conductivity is calibrated with the range of one-fourth (1/4) to one-twentieth (1/20) of the horizontal hydraulic conductivity.

4.5 Surface Water Model Set Up

The SW modelling approach consists of two major parts which are (1) hydrological model and (2) hydrodynamic model. The hydrological model will be setup using Rainfall-Runoff Module (NAM) of MIKE 11 modelling tool developed by Danish Hydraulic Institute (DHI) of the MIKE 11 tool. Major data requirements for NAM module are rainfall and evaporation and for MIKE 11(HD) module are water level, discharge, cross-section of stream channel/khals etc. In this study required data for NAM and MIKE 11(HD) have been collected from IWM. In Figure 4.18 network file along river system within the model area has been shown.

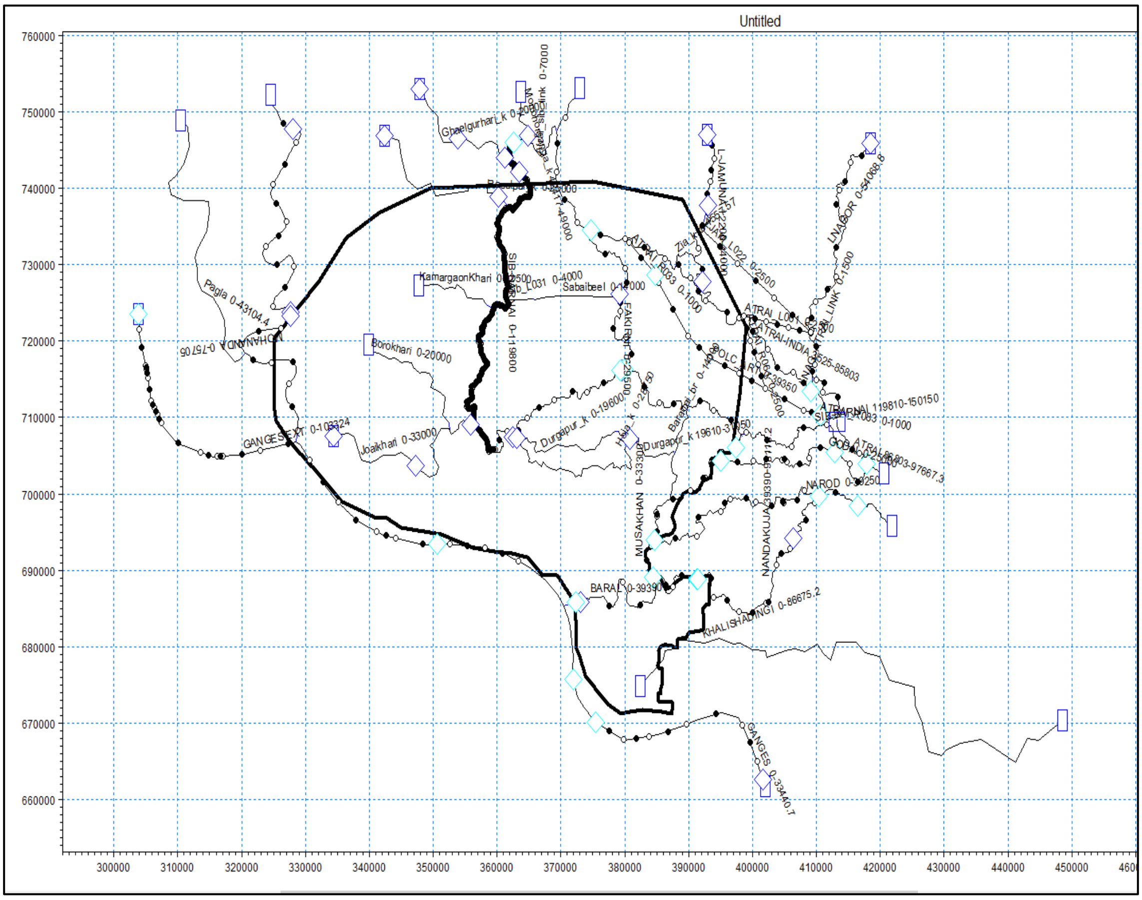


Figure 4.18: River network within model area in Mike 11(HD)

(i) Major rivers within the Surface Water model area:

The study area hasn’t enough major rivers but there are some major rivers surrounding its area. Some of the name of rivers/khals are given below in a list and shown in Figure 4.19. Name of Rivers in the Study Area:

S.N.	RiverName	S.N.	RiverName
1	Atrai	15	Little Jamuna
2	Atrai-Sib Link	16	Little Nagor-Atrai Link
3	Baral	17	Little Nagor
4	Baranai Branch	18	Mohanada
5	Borokhari	19	Monohorganga Khal
6	Durgapur Khal	20	Musakhan
7	Fakirni	21	Nandakuja
8	Ganges	22	Narod
9	Ghaelgurhari Khal	23	Pagla
10	Godai	24	Rasulpur Khal
11	Hoja Khal	25	Sabaibeel
12	Joai Khari	26	Sib-Barnai
13	Kamargaon Khari	27	Zia Khal
14	Khalishadingi	28	Pangal

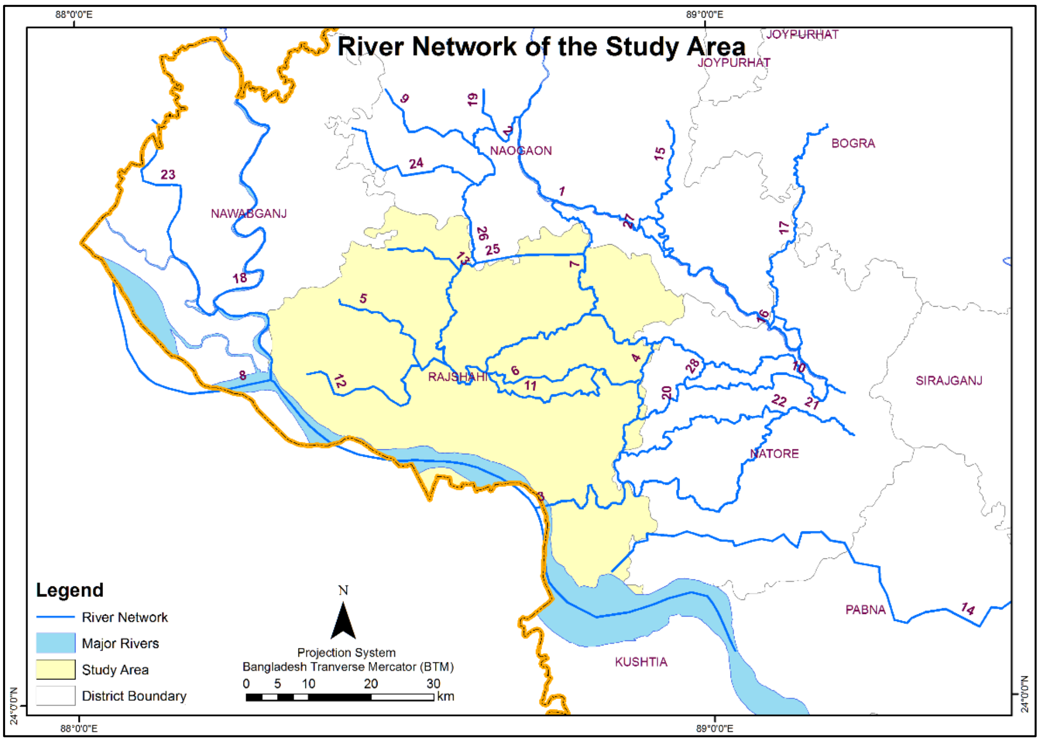
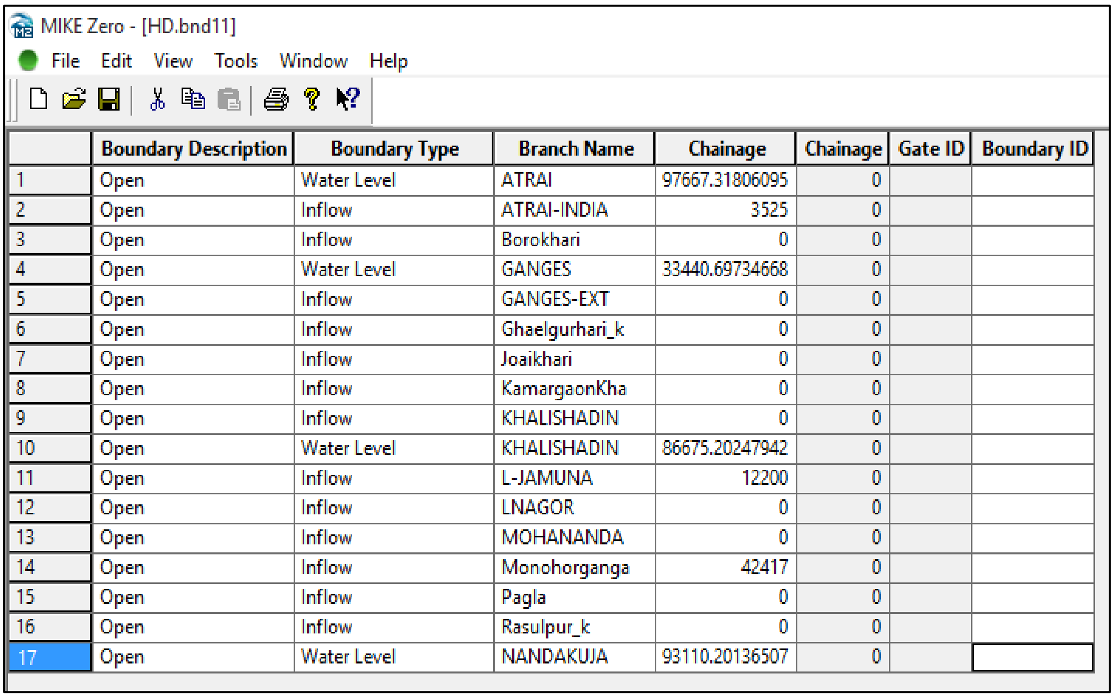


Figure 4.19: River network of the study area and surrounding

(ii) Boundary stations and calibration parameter:

There are 17 boundary stations have been selected for MIKE 11(HD) model. Among them 4 stations are water level stations and rest of them are discharge stations. Boundary stations are shown in Figure 4.20. Main calibration parameter for MIKE-11(HD) model is Bed Resistance of stream channel (Manning's n)



	Boundary Description	Boundary Type	Branch Name	Chainage	Chainage	Gate ID	Boundary ID
1	Open	Water Level	ATRAI	97667.31806095	0		
2	Open	Inflow	ATRAI-INDIA	3525	0		
3	Open	Inflow	Borokhari	0	0		
4	Open	Water Level	GANGES	33440.69734668	0		
5	Open	Inflow	GANGES-EXT	0	0		
6	Open	Inflow	Ghaelgurhari_k	0	0		
7	Open	Inflow	Joaikhari	0	0		
8	Open	Inflow	KamargaonKha	0	0		
9	Open	Inflow	KHALISHADIN	0	0		
10	Open	Water Level	KHALISHADIN	86675.20247942	0		
11	Open	Inflow	L-JAMUNA	12200	0		
12	Open	Inflow	LNAGOR	0	0		
13	Open	Inflow	MOHANANDA	0	0		
14	Open	Inflow	Monohorganga	42417	0		
15	Open	Inflow	Pagla	0	0		
16	Open	Inflow	Rasulpur_k	0	0		
17	Open	Water Level	NANDAKUJA	93110.20136507	0		

Figure 4.20: Boundary stations of SW model

4.6 Surface Water - Groundwater Interaction

The aquifers are often fed by seepage from rivers, ponds and other water bodies or may discharge through seepage to feed rivers, ponds and water bodies. Two conditions may exist that determine how groundwater use has an effect on the surface water resources. These conditions are an interconnected river and aquifer, where the river is losing water to the aquifer and an interconnected river in which the river is gaining water from the groundwater.

In the first condition river losses will increase in response to groundwater pumping. In the second condition, river gains will decrease in response to groundwater pumping. In either case, groundwater pumping will result in a depletion of surface water. At high river stage, there is a direct lateral flow from the river to the aquifer induced by head difference. When the river stage is below the groundwater level the flow reverses and groundwater discharge from the aquifer to the rivers base flow.

Due to natural discharge and withdrawal for irrigation and domestic purposes the groundwater level in April attains the lowest level. As soon as the irrigation stopped, there is a rise of groundwater level due to recovery of groundwater and there is a sharp rise after June with the beginning of rainfall because about 30% of total rainfall goes to aquifer as recharge (Karim, 1972).

4.7 Summary

Mathematical modelling tools are used in this study to simulate the existing and future complex scenarios simply. Before model setup, it is necessary to know every details of the study area so that actual scenario of study area can be simulated in the model. Detail analysis of the study area also helps to find sustainable solution of existing problems which are applicable in field level.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 General

Proper calibration and validation of the base model for the study area are the prerequisite for future scenario development. So, emphasis has been given to this fact and tried to calibrate and validate this Surface Water-Groundwater integrated model as good as possible. After completion of calibration and validation of the base model, optional run has been performed based on assumed scenarios and most extreme scenario and suitable intervention have been found out.

5.2 Calibration and Validation of the SW and GW Models

Model calibration is the process of adjustment of the model parameters and forcing within the margins of the uncertainties to obtain a model representation of the processes of interest that satisfies pre-agreed criteria (Goodness-of-Fit). Model validation is in reality an extension of the calibration process. Its purpose is to assure that the calibrated model properly assesses all the variables and conditions which can affect model results and demonstrate the ability to predict field observations for periods/conditions separate from the calibration effort.

5.2.1 Calibration and Validation of SW Model

The MIKE 11 model has been calibrated and validated with observed data. This model has been calibrated for 3 years (January to December of 2012 to 2014) and has been validated for next 2 years (January to December of 2015 to 2016). Summary table of calibration and validation has been shown in Table 5.1. Main calibration parameter for MIKE-11(HD) model is Bed Resistance of stream channel (Manning’s n). Calibration and validation of surface water model for surface water level at Chapai-Nawabganj Station on Mohananda River is shown in Figure 5.1. From this figure it is observed that superimposed observed and simulated results are almost identical which indicates good calibration and validation of this model at this station. Figure 5.2 shows calibration and validation of surface water model for surface water level at Singra Station on Atrai River. This superimposed graph also indicates good model performance at this station. Plots of other stations are shown in Appendix-D.

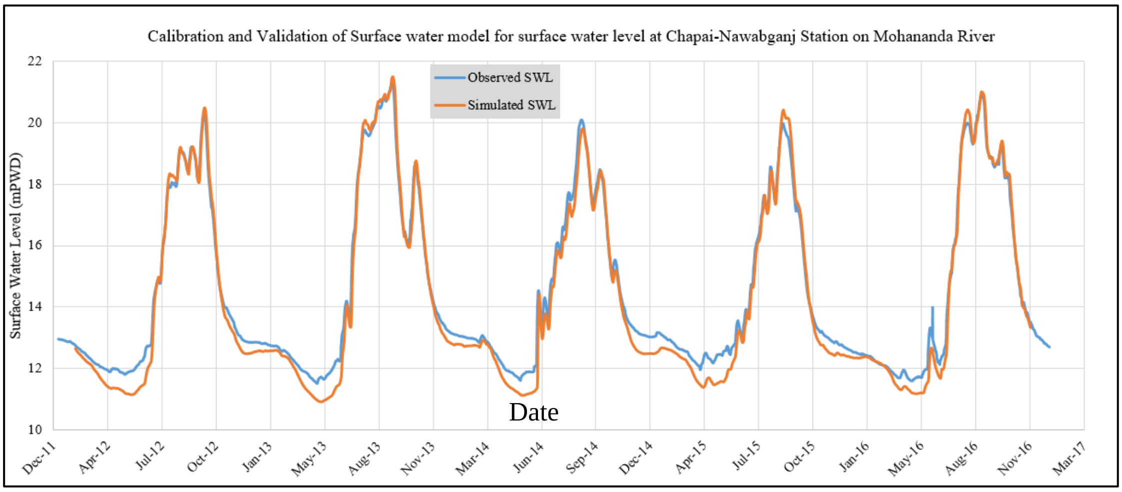


Figure 5.1: Calibration and Validation of Surface water model for surface water level at Chapai-Nawabganj Station on Mohananda River

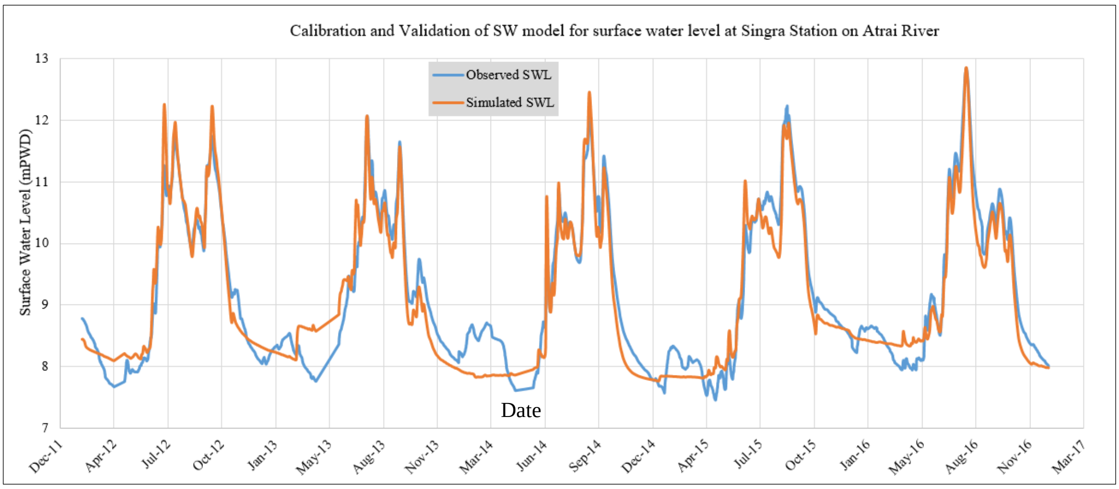


Figure 5.2: Calibration and Validation of Surface water model for surface water level at Singra Station on Atrai River

Table 5.1: Summary Table of Calibration and Validation

Model Type	**Calibration Year**	**Validation Year**
SW	Jan 2012-Dec 2014	Jan 2015-Dec 2016
SW-GW	Jan 2012-Dec 2014	Jan 2015-Dec 2016

5.2.2 Calibration and Validation of SW-GW Integrated Model

SW-GW integrated model has been calibrated for 3 years (January to December of 2012 to 2014) and has been validated for next 2 years (January to December of 2015 to 2016). The calibration process is an iterative process, where the focus in mainly on the groundwater observations, and on when they have reached a reasonable fit with the observed data. The first step model calibration is the identification of the calibration targets. The second step consists of determining the acceptable range of errors between simulated and measured calibrated targets. At the third step, trial and error and inverse simulations have been performed until simulated parameters are within the acceptable range of errors.

The model consists of three layers, each one represented by 3233 active cells. This equates to a possible 3x3233 input variables that can be altered to achieve the calibration target. The calibration has been based on the comparison between the calculated and observed head on original observation well data rather than interpolated values because of the uncertainty involved in the interpolation process. Calibration and Validation of groundwater model for groundwater level at Charghat Upazila (GT 8125009), Puthia Upazila (GT 8182042) and Durgapur Upazila (GT 8131015) are shown in Figure 5.3, 5.4 and 5.6 respectively. From visual observation, almost all the groundwater levels show good correlation with simulated results. Observed raw data of groundwater levels were not consistent in many cases and there were lots of data gaps which needed to be processed.

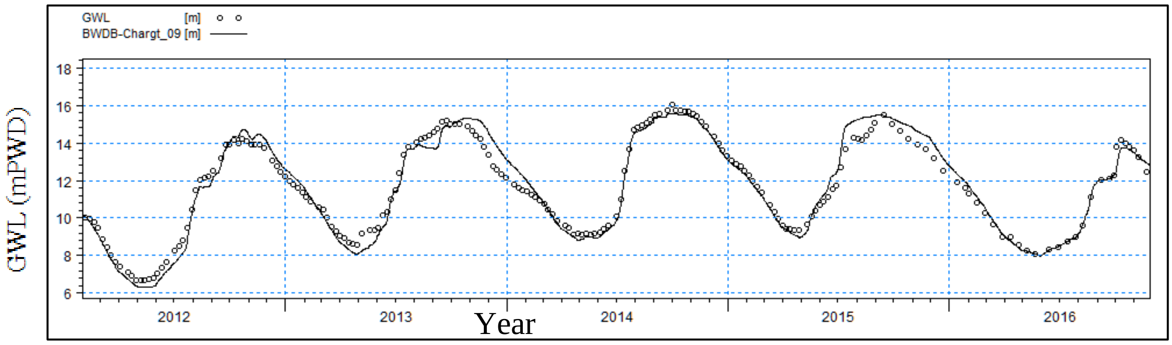


Figure 5.3: Calibration and Validation of model for groundwater level at Charghat Upazila

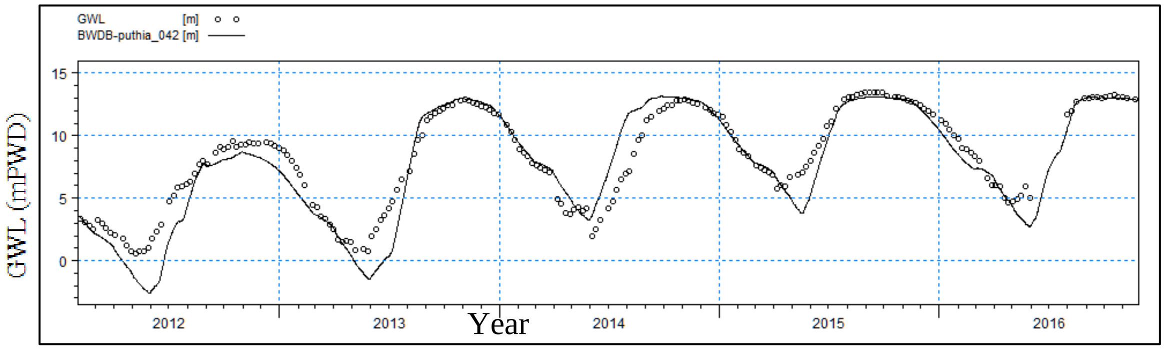


Figure 5.4: Calibration and Validation of model for groundwater level at Puthia Upazila

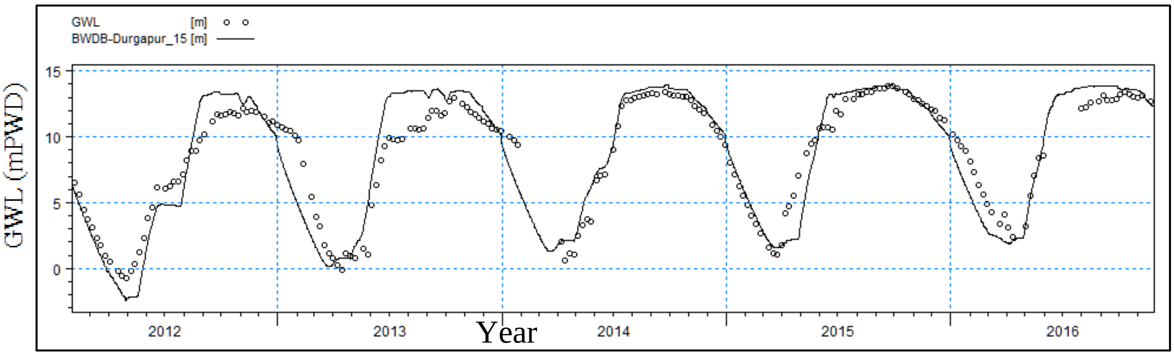


Figure 5.5: Calibration and Validation of model for groundwater level at Durgapur Upazila

5.3 Selection of Design Year for Scenario Development

For groundwater and surface water resource assessment, rainfall data were analyzed to estimate the rainfall event for different return period. In selecting design event, most weight was given for 50% dependable of annual rainfall, because this is considered most generally significant for irrigation requirement considerations and also irrigation projects are normally planned considering design year of average hydrological conditions. Accordingly, analysis concentrated on rainfall event for 2.33–year return period (avg. year) and find out the corresponding year which was selected as design year. But in this study sustainability of groundwater resources is major concern that’s why design year based on dry condition will be given more priority. So, extreme dry year (5 years and 10 years return periods) has been estimated to assess the resources at extreme drought condition.

Due to the randomness of rainfall events, in the present study, design year has been selected based on return period of mean annual rainfall of the study area. The mean annual rainfall has been obtained from the average of 10 stations falls in the study area. Observed annual rainfall for a period of 47 years (1970-2016) has been considered for statistical analysis. According to the recommendation of FAP25 study, data has been fitted to 3-parameter Log Normal distribution to find out the average and extreme dry year. The statistical software HYMOS 4.0 has been used for this purpose. The results of the analysis are presented in Table 5.1 and Table 5.2. From this analysis 1990 year has been selected as a design year of average hydrological condition and 2014 and 1994 have been selected for design year of dry and extreme dry conations respectively.

Table 5.2: Return Period for Different Distribution

Distribution	**Return Period in Years**						
	2.00	2.33	5.00	10.00	20.00	50.00	100.00
Normal	1484.67	1438.39	1266.01	1151.60	1057.15	950.87	880.03
2PLog Normal	1486.90	1440.70	1266.40	1148.76	1050.45	938.53	863.15
3PLogNormal	1490.28	1460.52	1271.39	1154.14	1055.89	943.78	868.11
Pearson	1489.48	1443.08	1267.55	1148.68	1049.10	935.50	858.85
LogPearson	1491.68	1445.39	1267.97	1145.74	1042.03	922.23	840.49
Gumbel EV1	1527.36	1484.39	1297.71	1145.67	999.82	811.04	669.57

Table 5.3: Selection of Design Year Based on Statistical Analysis

Analyzed Year	Annual Mean Area Rainfall (mm)	Selected Design Year	Analyzed Year	Annual Mean Area Rainfall (mm)	Selected Design Year
1970.00	1479.03		1993.00	1594.28	
1971.00	2025.07		1994.00	1150.75	Extreme Dry Event of Return Period 1 in 10 Years
1972.00	1192.95		1995.00	1702.21	
1973.00	1763.93		1996.00	1261.67	
1974.00	1548.16		1997.00	1354.29	
1975.00	1221.2		1998.00	1866.24	
1976.00	1544.95		1999.00	1753.39	
1977.00	1830.35		2000.00	1839.11	
1978.00	1433.51		2001.00	1626.21	
1979.00	1375.36		2002.00	1590.19	
1980.00	1615.5		2003.00	1392.88	
1981.00	1609.65		2004.00	1576.77	
1982.00	1029.05		2005.00	1595.42	

Analyzed Year	Annual Mean Area Rainfall (mm)	Selected Design Year	Analyzed Year	Annual Mean Area Rainfall (mm)	Selected Design Year
1983.00	1362.7		2006.00	1066.61	
1984.00	1583.75		2007.00	1354.76	
1985.00	1393.31		2008.00	1189.69	
1986.00	1742.95		2009.00	1160.39	
1987.00	1688.22		2010.00	1260.15	
1988.00	1845.82		2011.00	1743.06	
1989.00	1409.59		2012.00	1061.72	
1990.00	1470.21	Average hydrologic condition of Return Period 1 in 2.33 Years	2013.00	1047.45	
1991.00	1655.12		2014.00	1273.27	Dry Event of Return Period 1 in 5 Years
1992.00	1060.24		2015.00	1568.62	
			2016.00	1847.93	

5.4 Formulation of Future Scenarios

Rajshahi district is one of the most draught prone areas in Bangladesh. Groundwater levels in this study area have been declining alarmingly. In order to sustain groundwater resources up to year 2030 we have to foresee future condition of groundwater resources under different Scenarios. For this reason, there are ten (10) Scenario s have been chosen to understand future groundwater level. It also helps to find out the most extreme and less vulnerable scenario and hence suitable interventions can be applied to sustain groundwater resources as well as.

These 10 scenarios are tabulated in Table 5.3. Further details of these scenarios have been discussed later in this article 5.4. Rainfall, evaporation, boundary groundwater level, agricultural and domestic water demands have been considered as the driving forces to formulate these scenarios.

Table 5.4: Summary Table of all scenarios

Scenario No.	Rainfall and Evaporation	Boundary Groundwater Level	Agricultural Water Demand	Domestic Water Demand
1	Same as base year 2016	Same as base year 2016	Same as base year 2016	Same as base year 2016
2	Generated from GCM	Same as base year 2016	Same as base year 2016	Same as base year 2016
3	Generated from GCM	Same as base year 2016	Demand increases by 1% annually	Predicted population based on BBS
4	Generated from GCM	Same as base year 2016	Demand increases by 1.5% annually	Predicted population based on BBS
5	Generated from GCM	GWL of average years return period (1990)	Demand increases by 1% annually	Predicted population based on BBS
6	Generated from GCM	GWL of average years return period (1990)	Demand increases by 1.5% annually	Predicted population based on BBS
7	Generated from GCM	GWL of dry condition of five years return period (2014)	Demand increases by 1% annually	Predicted population based on BBS
8	Generated from GCM	GWL of dry condition of five years return period (2014)	Demand increases by 1.5% annually	Predicted population based on BBS
9	Generated from GCM	GWL of dry condition of ten years return period (1994)	Demand increases by 2% annually	Predicted population based on BBS
10	Generated from GCM	GWL of dry condition of ten years return period (1994)	Demand increases by 2.5% annually	Predicted population based on BBS

Details of these above mentioned ten scenarios are discussed below:

Scenario 1: It is the base scenario. In this scenario crop water demand, rainfall, evaporation, domestic water demand and groundwater level of boundary wells of base year 2016 has been assumed constant up to year 2030.

Scenario 2: Same as scenario 01 except rainfall and evaporation data have been generated from 2016 to 2030 from GCM model of HADCM3 under emission scenario SRA2 with the help of Climate change editor module of MIKE software.

Scenario 3: Same as scenario 2 except crop water demand of the base year 2016 has been increased annually by 1% up to year 2030. Groundwater level of boundary wells of base year 2016 has been assumed constant up to year 2030.

Scenario 4: Same as scenario 3 except crop water demand of the base year 2016 has been increased annually by 1.5% up to year 2030. Groundwater level of boundary wells of base year 2016 has been assumed constant up to year 2030.

Scenario 5: Same as scenario 3 except boundary groundwater level of the average condition of hydrological year of 1990 (2.33 years of return period) has been assumed constant up to year 2030.

Scenario 6: Same as scenario 4 except boundary groundwater level of the average condition of hydrological year of 1990 (2.33 years of return period) has been assumed constant up to year 2030.

Scenario 7: Same as scenario 3 except boundary groundwater level of the dry condition of hydrological year of 2014 (5 years of return period) has been assumed constant up to year 2030.

Scenario 8: Same as scenario 4 except boundary groundwater level of the dry condition of hydrological year of 2014 (5 years of return period) has been assumed constant up to year 2030.

Scenario 9: In this scenario crop water demand of the base year 2016 has been increased annually by 2% up to year 2030. Rainfall and evaporation data have been generated from 2016 to 2030 from GCM model of HADCM3 under emission scenario SRA2 with the help of Climate change editor module of MIKE software. Boundary groundwater level of the extreme dry condition of hydrological year of 1994 (10 years of return period) has been assumed constant up to year 2030.

Scenario 10: Same as scenario 09 except crop water demand of the base year 2016 has been increased annually by 2.5% up to year 2030.

5.5 Determination of the Most Extreme Scenario from Different Scenarios

Due to randomness of rainfall distribution and cropping pattern, extreme scenario has been selected by analyzing data of Upazila instead of district. Yearly minimum and maximum groundwater level have been analyzed for all Upazilas and most emphasis has been given to identify the worst and less vulnerable on minimum groundwater level. At first Upazila wise analysis has been done for all scenarios to find out which scenario is most extreme and which is good among these ten scenarios. It is expected that extreme and less vulnerable of one Upazila may not be extreme or good for every Upazila of Rajshahi. Therefore extreme scenario for maximum number of Upazilas has been selected for the whole Rajshahi district.

Upazila wise analysis of all scenarios have been shown in Figure 5.6 to 5.10 and in Table 5.5 to 5.12.

From this analysis shown in Table 5.5, S-10 and S-02 scenario have been selected as extreme and less vulnerable among 10 scenarios for Paba Upazila. For determining extreme and less vulnerable scenarios, yearly lowest and highest values of GWL under different scenarios have been analyzed from 2017 to 2030. Graphical representation of these two scenarios show that during wet period both these scenarios give almost similar result and in dry season the extreme scenario varies by more than 2m from other scenario in some years which is shown in Figure 5.6. For this reason, dry period characteristics of groundwater levels under assumed scenarios have been considered to find out extreme scenario.

Table 5.5: Yearly Minimum GWL of Paba Upazila

Year	S- 01	S- 02	S- 03	S- 04	S- 05	S- 06	S- 07	S- 08	S- 09	S- 10	Max GWL	Scenario	Min GWL	Scenario
2017	11.57	12.08	12.04	12.04	11.32	11.30	10.10	10.13	11.79	11.78	12.08	S- 02	10.10	S- 07
2018	11.47	12.28	12.22	12.19	11.75	11.70	11.04	11.06	11.76	11.73	12.28	S- 02	11.04	S- 07
2019	11.32	12.18	12.07	11.98	11.66	11.60	10.90	10.92	11.34	11.31	12.18	S- 02	10.90	S- 07
2020	11.12	11.99	11.79	11.69	11.51	11.40	10.41	10.41	11.00	10.89	11.99	S- 02	10.41	S- 07
2021	11.11	11.95	11.69	11.60	11.38	11.28	10.31	10.31	10.63	10.51	11.95	S- 02	10.31	S- 08
2022	11.02	11.81	11.55	11.37	11.27	11.15	11.37	11.38	10.31	10.18	11.81	S- 02	10.18	S- 10
2023	10.88	11.69	11.36	11.19	11.13	10.91	12.32	12.33	10.01	9.82	12.33	S- 08	9.82	S- 10
2024	10.75	11.55	11.16	10.94	10.92	10.73	12.62	12.64	9.69	9.48	12.64	S- 08	9.48	S- 10
2025	10.74	11.54	11.10	10.84	10.79	10.57	12.84	12.85	9.56	9.28	12.85	S- 08	9.28	S- 10
2026	10.63	11.38	10.90	10.62	10.74	10.43	12.59	12.59	9.45	9.07	12.59	S- 08	9.07	S- 10
2027	10.53	11.24	10.71	10.39	10.64	10.31	12.11	12.12	9.35	8.96	12.12	S- 08	8.96	S- 10
2028	10.36	11.10	10.47	10.15	10.44	10.13	11.47	11.47	9.27	8.83	11.47	S- 07	8.83	S- 10
2029	10.26	11.06	10.36	9.94	10.38	10.00	10.95	10.97	9.21	8.81	11.06	S- 02	8.81	S- 10
2030	10.22	10.91	10.18	9.76	10.26	9.84	10.42	10.41	9.19	8.89	10.91	S- 02	8.89	S- 10

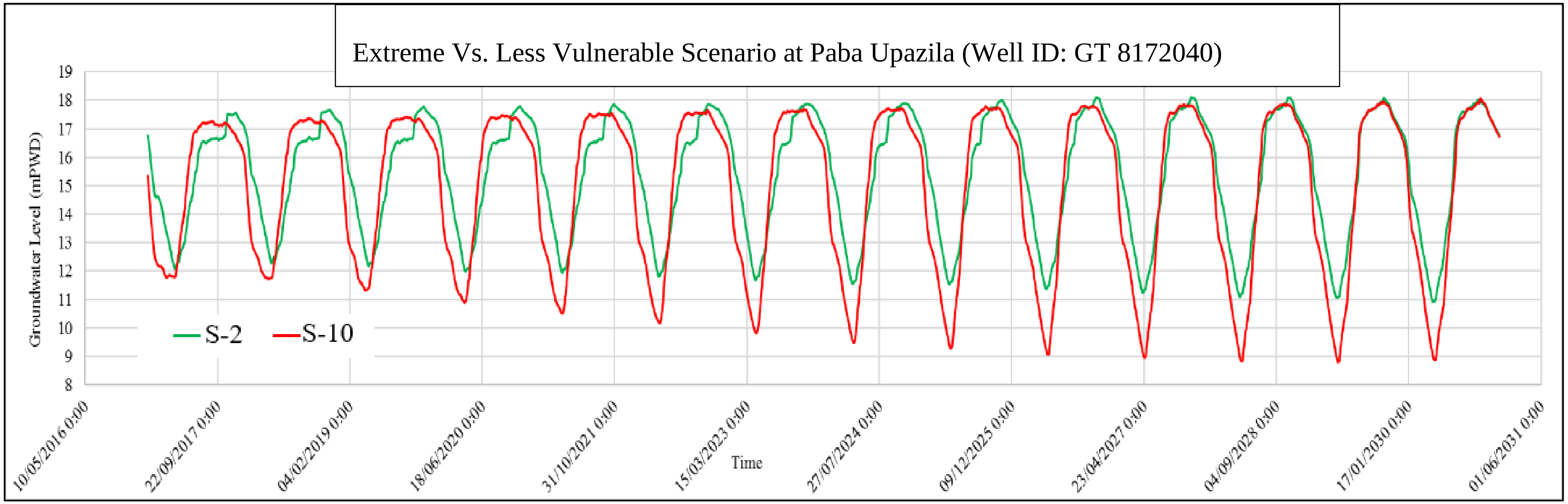


Figure 5.6: Extreme vs less vulnerable scenarios at Paba Upazila

Table 5.6: Yearly Minimum GWL of Charghat Upazila

Year	S- 01	S- 02	S- 03	S- 04	S- 05	S- 06	S- 07	S- 08	S- 09	S- 10	Max GWL	Scenario	Min GWL	Scenario
2017	8.49	9.04	8.99	8.96	9.01	8.98	8.96	8.98	8.86	8.84	9.04	S- 02	8.49	S- 01
2018	8.54	9.16	9.06	9.02	9.09	9.05	9.02	9.03	8.95	8.85	9.16	S- 02	8.54	S- 01
2019	8.55	9.17	9.03	8.95	9.07	9.01	8.96	8.96	8.82	8.77	9.17	S- 02	8.55	S- 01
2020	8.53	9.15	8.95	8.83	8.99	8.85	8.83	8.84	8.70	8.58	9.15	S- 02	8.53	S- 01
2021	8.56	9.19	8.88	8.80	8.97	8.82	8.79	8.79	8.62	8.49	9.19	S- 02	8.49	S- 10
2022	8.56	9.19	8.85	8.72	8.87	8.75	8.68	8.68	8.53	8.32	9.19	S- 02	8.32	S- 10

Year	S- 01	S- 02	S- 03	S- 04	S- 05	S- 06	S- 07	S- 08	S- 09	S- 10	Max GWL	Scenario	Min GWL	Scenario
2023	8.56	9.20	8.82	8.61	8.85	8.65	8.58	8.58	8.36	8.17	9.20	S- 02	8.17	S- 10
2024	8.54	9.16	8.74	8.50	8.77	8.54	8.45	8.46	8.24	8.00	9.16	S- 02	8.00	S- 10
2025	8.56	9.21	8.71	8.40	8.74	8.48	8.35	8.36	8.15	7.89	9.21	S- 02	7.89	S- 10
2026	8.56	9.21	8.64	8.34	8.68	8.36	8.31	8.31	8.04	7.85	9.21	S- 02	7.85	S- 10
2027	8.56	9.21	8.58	8.25	8.60	8.29	8.23	8.23	7.91	7.83	9.21	S- 02	7.83	S- 10
2028	8.52	9.17	8.50	8.11	8.54	8.15	8.10	8.11	7.85	7.74	9.17	S- 02	7.74	S- 10
2029	8.55	9.22	8.48	8.07	8.52	8.10	8.08	8.08	7.85	7.71	9.22	S- 02	7.71	S- 10
2030	8.55	9.21	8.36	7.99	8.39	8.03	8.00	8.00	7.82	7.65	9.21	S- 02	7.65	S- 10

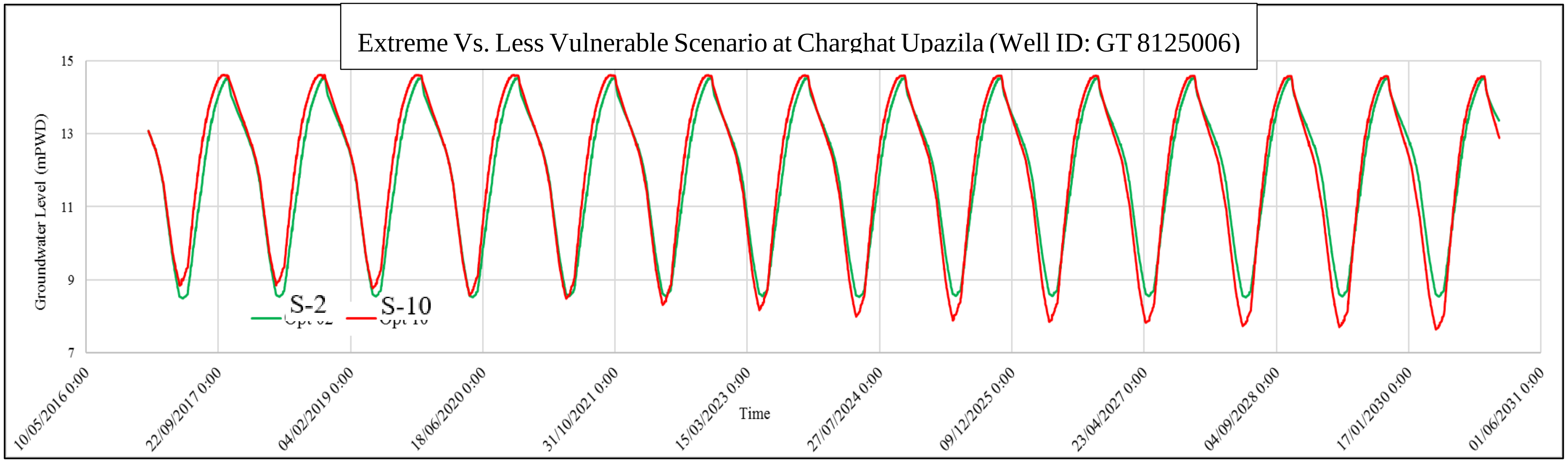


Fig. 5.7: Extreme vs less vulnerable scenarios at Charghat Upazila

Table 5.7: Yearly Minimum GWL of Mohanpur Upazila

Year	S- 01	S- 02	S- 03	S- 04	S- 05	S- 06	S- 07	S- 08	S- 09	S- 10	Max GWL	Scenario	Min GWL	Scenario
2017	2.34	2.92	2.70	2.55	2.88	2.85	2.90	2.78	2.82	2.87	2.92	S- 02	2.34	S- 01
2018	2.80	3.12	3.17	3.05	3.17	3.12	2.97	3.08	3.09	2.88	3.17	S- 05	2.80	S- 01
2019	3.18	3.20	3.47	3.09	3.07	3.40	3.17	3.38	3.12	3.16	3.47	S- 03	3.07	S- 05
2020	2.87	3.15	3.17	3.18	3.12	3.07	3.19	2.93	3.22	3.12	3.22	S- 09	2.87	S- 01
2021	3.44	3.59	3.29	3.13	3.24	3.20	3.11	3.21	3.10	3.11	3.59	S- 02	3.10	S- 09
2022	2.75	3.21	3.14	3.18	3.03	2.92	3.01	3.11	3.22	3.05	3.22	S- 09	2.75	S- 01
2023	3.19	3.32	3.36	3.13	3.16	3.28	2.92	2.92	2.90	2.86	3.36	S- 03	2.86	S- 10
2024	2.73	3.23	2.91	2.89	3.16	2.85	3.10	3.05	3.02	2.78	3.23	S- 02	2.73	S- 01
2025	3.16	3.38	3.19	2.90	3.28	3.12	2.89	2.79	3.16	2.90	3.38	S- 02	2.79	S- 08
2026	2.75	3.28	2.92	3.07	3.12	3.18	3.10	2.93	2.90	2.67	3.28	S- 02	2.67	S- 10
2027	3.01	3.20	2.93	2.89	3.14	2.80	2.98	2.94	2.87	2.63	3.20	S- 02	2.63	S- 10
2028	2.88	3.27	3.06	2.90	3.16	2.91	2.95	2.86	2.81	2.64	3.27	S- 02	2.64	S- 10
2029	3.24	3.29	3.08	3.00	3.02	2.87	2.95	2.90	2.70	2.63	3.29	S- 02	2.63	S- 10
2030	2.92	3.35	3.13	2.73	2.82	2.90	2.76	2.89	2.79	2.68	3.35	S- 02	2.68	S- 10

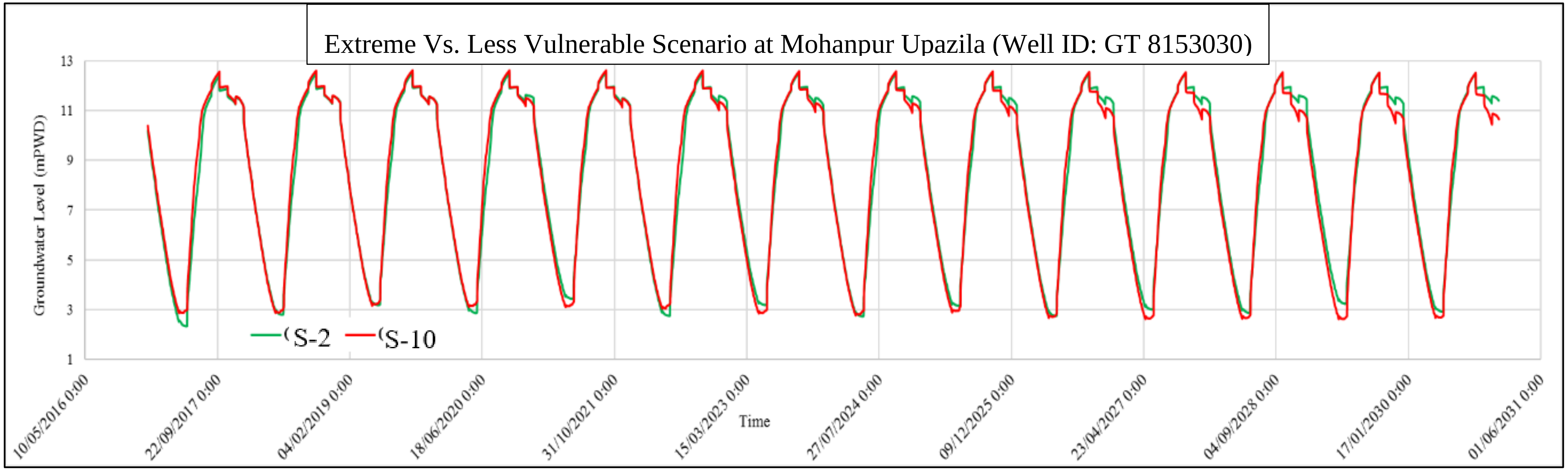


Fig. 5.8: Extreme vs less vulnerable scenarios at Mohanpur Upazila

Table 5.8: Yearly Minimum GWL of Durgapur Upazila

Year	S- 01	S- 02	S- 03	S- 04	S- 05	S- 06	S- 07	S- 08	S- 09	S- 10	Max GWL	Scenario	Min GWL	Scenario
2017	1.69	2.24	2.23	2.23	2.25	2.23	2.32	2.23	2.23	2.25	2.32	S- 07	1.69	S- 01
2018	2.01	2.96	3.00	2.90	3.03	2.94	2.95	2.99	2.93	2.86	3.03	S- 05	2.01	S- 01
2019	2.11	3.17	3.11	3.08	3.16	3.18	3.16	3.16	3.05	3.03	3.18	S- 06	2.11	S- 01
2020	2.24	3.63	3.17	3.17	3.25	3.45	3.16	3.11	3.11	3.17	3.63	S- 02	2.24	S- 01
2021	2.19	3.15	3.50	3.16	3.41	3.40	3.16	3.11	3.15	3.18	3.50	S- 03	2.19	S- 01
2022	2.19	3.62	3.15	3.30	3.17	3.04	3.11	3.17	3.00	3.18	3.62	S- 02	2.19	S- 01

Year	S- 01	S- 02	S- 03	S- 04	S- 05	S- 06	S- 07	S- 08	S- 09	S- 10	Max GWL	Scenario	Min GWL	Scenario
2023	2.23	3.54	3.38	2.96	3.15	3.38	3.03	3.15	2.96	2.85	3.54	S- 02	2.23	S- 01
2024	2.23	3.31	3.39	3.07	3.16	3.15	3.11	3.41	2.98	3.16	3.41	S- 08	2.23	S- 01
2025	2.08	3.33	3.16	2.95	3.12	2.98	2.95	2.95	2.90	2.80	3.33	S- 02	2.08	S- 01
2026	2.15	3.63	3.03	2.99	3.12	3.18	2.96	2.93	2.89	2.89	3.63	S- 02	2.15	S- 01
2027	2.11	3.53	2.96	2.93	3.12	3.02	2.93	3.18	2.92	2.93	3.53	S- 02	2.11	S- 01
2028	2.24	3.40	3.41	3.02	3.17	2.98	3.02	3.18	2.93	2.93	3.41	S- 03	2.24	S- 01
2029	2.16	3.37	3.11	2.92	3.30	3.18	3.10	2.96	2.92	2.80	3.37	S- 02	2.16	S- 01
2030	2.19	3.53	2.99	3.15	3.03	3.14	3.14	2.93	2.93	2.88	3.53	S- 02	2.19	S- 01

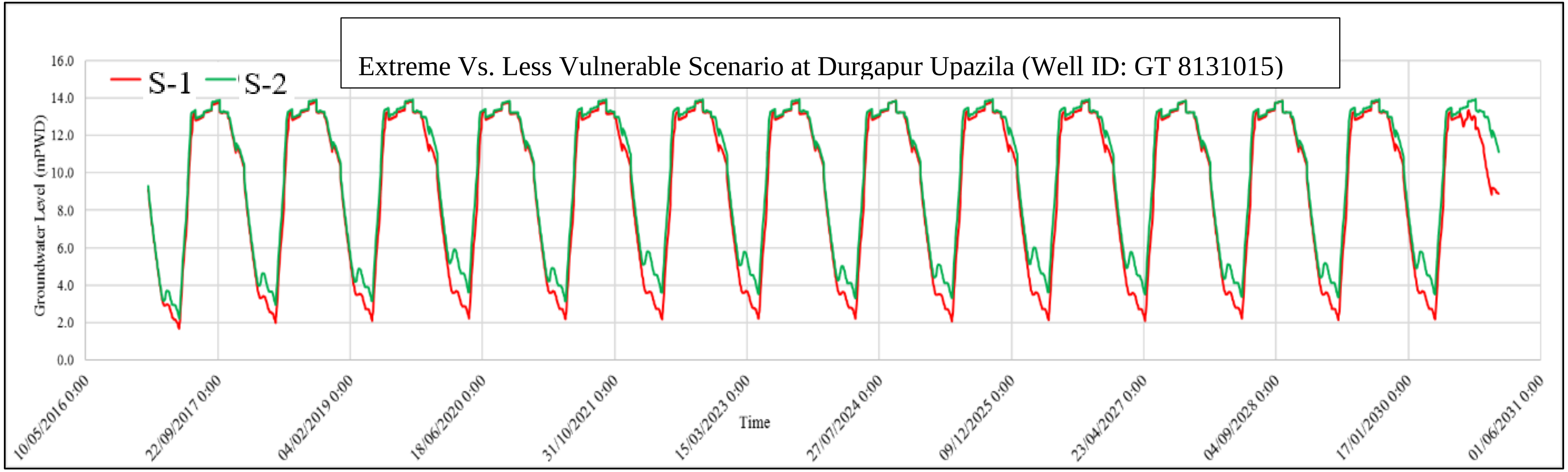


Figure 5.9: Extreme vs less vulnerable scenarios at Durgapur Upazila

Table 5.9: Yearly Minimum GWL of Tanore Upazila

Year	S- 01	S- 02	S- 03	S- 04	S- 05	S- 06	S- 07	S- 08	S- 09	S- 10	Max GWL	Scenario	Min GWL	Scenario
2017	5.75	5.75	5.74	5.72	5.74	5.72	5.72	5.72	5.70	5.70	5.75	S- 01	5.70	S- 10
2018	5.75	5.96	5.85	5.84	5.85	5.84	5.84	5.84	5.81	5.76	5.96	S- 02	5.75	S- 01
2019	5.60	6.00	5.84	5.79	5.85	5.79	5.79	5.79	5.71	5.66	6.00	S- 02	5.60	S- 01
2020	5.41	5.93	5.73	5.64	5.73	5.64	5.64	5.64	5.56	5.43	5.93	S- 02	5.41	S- 01
2021	5.37	5.87	5.64	5.53	5.65	5.53	5.53	5.53	5.40	5.35	5.87	S- 02	5.35	S- 10
2022	5.32	5.85	5.54	5.39	5.55	5.39	5.39	5.39	5.31	5.17	5.85	S- 02	5.17	S- 10
2023	5.29	5.83	5.40	5.31	5.40	5.31	5.31	5.31	5.14	4.98	5.83	S- 02	4.98	S- 10
2024	5.25	5.78	5.35	5.17	5.35	5.17	5.17	5.17	4.97	4.75	5.78	S- 02	4.75	S- 10
2025	5.22	5.76	5.29	5.04	5.29	5.04	5.04	5.04	4.78	4.49	5.76	S- 02	4.49	S- 10
2026	5.19	5.74	5.19	4.89	5.19	4.89	4.89	4.89	4.57	4.22	5.74	S- 02	4.22	S- 10
2027	5.16	5.73	5.09	4.74	5.09	4.74	4.74	4.74	4.34	3.94	5.73	S- 02	3.94	S- 10
2028	5.13	5.69	4.97	4.55	4.97	4.55	4.55	4.55	4.10	3.64	5.69	S- 02	3.64	S- 10
2029	5.10	5.69	4.87	4.37	4.87	4.37	4.37	4.37	3.87	3.33	5.69	S- 02	3.33	S- 10
2030	5.08	5.66	4.75	4.20	4.75	4.20	4.20	4.20	3.62	3.02	5.66	S- 02	3.02	S- 10

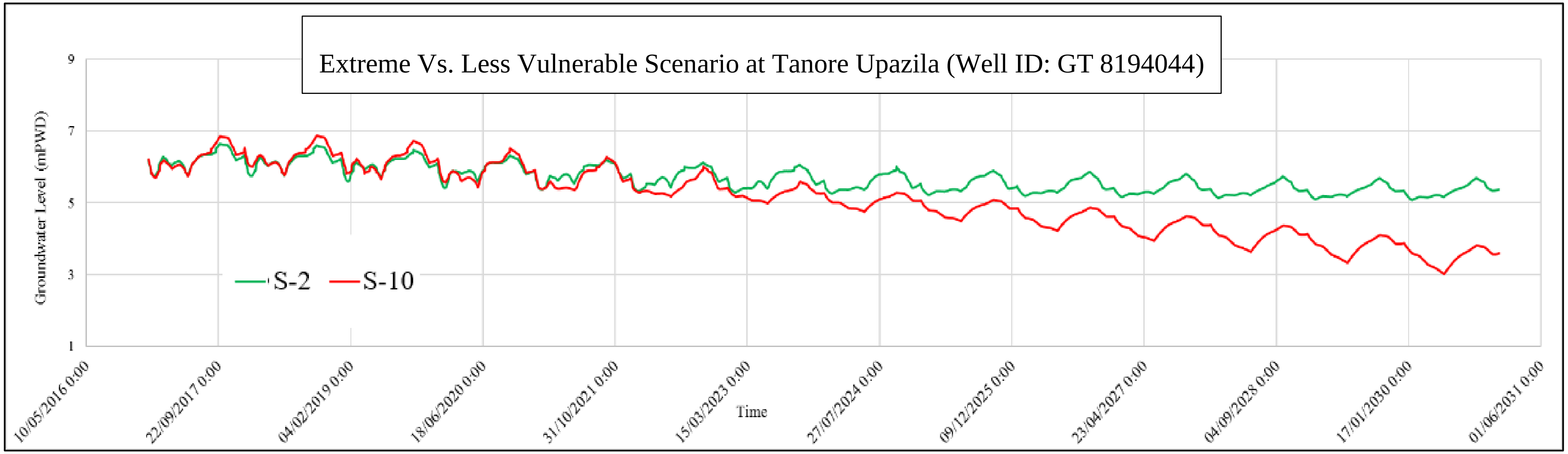


Figure 5.10: Extreme vs less vulnerable scenarios at Tanore Upazila

Table 5.10: Yearly Minimum GWL of Puthia Upazila (GT8182043)

Year	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10	Max GWL	Scenario	Min GWL	Scenario
2017	8.73	8.73	8.73	8.73	8.72	8.72	8.80	8.80	8.68	9.42	9.42	S- 10	8.68	S- 09
2018	6.29	6.30	6.29	6.30	6.17	6.17	6.82	6.81	5.61	9.42	9.42	S- 10	5.61	S- 09
2019	7.84	7.89	7.84	7.89	7.79	7.79	8.12	8.11	6.69	9.34	9.34	S- 10	6.69	S- 09
2020	9.35	9.35	9.35	9.35	9.38	9.34	7.91	7.91	8.56	9.22	9.38	S- 05	7.91	S- 08
2021	9.05	9.04	9.05	9.05	8.67	8.67	8.34	8.34	8.16	9.09	9.09	S- 10	8.16	S- 09
2022	8.75	9.26	9.25	9.25	8.91	8.90	7.88	7.88	9.42	8.91	9.42	S- 09	7.88	S- 07

Year	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10	Max GWL	Scenario	Min GWL	Scenario
2023	8.66	9.27	9.27	9.27	9.55	9.55	8.29	8.29	9.42	8.82	9.55	S- 05	8.29	S- 07
2024	8.57	9.25	9.24	9.23	9.53	9.51	7.90	7.90	9.35	8.69	9.53	S- 05	7.90	S- 07
2025	8.51	9.20	9.18	9.17	9.46	9.45	7.60	7.60	9.22	8.60	9.46	S- 05	7.60	S- 07
2026	8.49	9.17	9.15	9.15	9.38	9.37	7.65	7.64	9.09	8.53	9.38	S- 05	7.64	S- 08
2027	8.41	9.10	9.07	9.05	9.27	9.27	7.89	7.89	8.92	8.51	9.27	S- 05	7.89	S- 07
2028	8.29	9.02	8.99	8.97	9.24	9.23	8.32	8.31	8.83	8.52	9.24	S- 05	8.29	S- 01
2029	8.24	8.93	8.89	8.88	9.19	9.17	8.69	8.70	8.70	8.53	9.19	S- 05	8.24	S- 01
2030	8.22	8.91	8.86	8.85	9.13	9.09	8.95	8.94	8.61	8.58	9.13	S- 05	8.22	S- 01

Table 5.11: Yearly Minimum GWL of Godagari Upazila (GT8134016)

Year	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10	Max GWL	Scenario	Min GWL	Scenario
2017	20.79	20.78	20.75	20.74	20.75	20.73	20.74	20.74	20.72	20.66	20.79	S- 01	20.66	S- 10
2018	20.85	20.81	20.76	20.73	20.76	20.73	20.72	20.73	20.66	20.64	20.85	S- 01	20.64	S- 10
2019	20.86	20.84	20.77	20.76	20.78	20.76	20.76	20.76	20.76	20.76	20.86	S- 01	20.76	S- 06
2020	20.85	20.83	20.73	20.73	20.73	20.72	20.68	20.72	20.67	20.68	20.85	S- 01	20.67	S- 09
2021	20.89	20.87	20.80	20.79	20.80	20.79	20.79	20.79	20.79	20.78	20.89	S- 01	20.78	S- 10
2022	20.89	20.88	20.81	20.80	20.81	20.80	20.80	20.80	20.79	20.80	20.89	S- 01	20.79	S- 09
2023	20.90	20.88	20.80	20.80	20.80	20.80	20.80	20.80	20.80	20.80	20.90	S- 01	20.80	S- 04
2024	20.86	20.85	20.75	20.75	20.75	20.74	20.74	20.74	20.75	20.74	20.86	S- 01	20.74	S- 07
2025	20.90	20.88	20.80	20.79	20.80	20.80	20.80	20.79	20.80	20.80	20.90	S- 01	20.79	S- 04
2026	20.90	20.89	20.80	20.80	20.80	20.79	20.80	20.80	20.80	20.81	20.90	S- 01	20.79	S- 06
2027	20.91	20.88	20.79	20.79	20.79	20.79	20.79	20.80	20.80	20.81	20.91	S- 01	20.79	S- 03
2028	20.87	20.86	20.74	20.73	20.74	20.74	20.74	20.73	20.74	20.75	20.87	S- 01	20.73	S- 08
2029	20.90	20.88	20.79	20.78	20.79	20.79	20.79	20.79	20.80	20.82	20.90	S- 01	20.78	S- 04
2030	20.92	20.89	20.79	20.79	20.79	20.78	20.78	20.78	20.80	20.84	20.92	S- 01	20.78	S- 08

Table 5.12: Yearly Minimum GWL of Bagmara Upazila (GT8194044)

Row Labels	Min of 1	Min of 2	Min of 3	Min of 4	Min of 5	Min of 6	Min of 7	Min of 8	Min of 9	Min of 10	Max GWL	Scenario	Min GWL	Scenario
2017	5.75	5.75	5.74	5.72	5.74	5.72	5.72	5.72	5.70	5.70	5.75	S- 01	5.70	S- 10
2018	5.75	5.96	5.85	5.84	5.85	5.84	5.84	5.84	5.81	5.76	5.96	S- 02	5.75	S- 01
2019	5.60	6.00	5.84	5.79	5.85	5.79	5.79	5.79	5.71	5.66	6.00	S- 02	5.60	S- 01
2020	5.41	5.93	5.73	5.64	5.73	5.64	5.64	5.64	5.56	5.43	5.93	S- 02	5.41	S- 01
2021	5.37	5.87	5.64	5.53	5.65	5.53	5.53	5.53	5.40	5.35	5.87	S- 02	5.35	S- 10
2022	5.32	5.85	5.54	5.39	5.55	5.39	5.39	5.39	5.31	5.17	5.85	S- 02	5.17	S- 10
2023	5.29	5.83	5.40	5.31	5.40	5.31	5.31	5.31	5.14	4.98	5.83	S- 02	4.98	S- 10
2024	5.25	5.78	5.35	5.17	5.35	5.17	5.17	5.17	4.97	4.75	5.78	S- 02	4.75	S- 10
2025	5.22	5.76	5.29	5.04	5.29	5.04	5.04	5.04	4.78	4.49	5.76	S- 02	4.49	S- 10
2026	5.19	5.74	5.19	4.89	5.19	4.89	4.89	4.89	4.57	4.22	5.74	S- 02	4.22	S- 10
2027	5.16	5.73	5.09	4.74	5.09	4.74	4.74	4.74	4.34	3.94	5.73	S- 02	3.94	S- 10
2028	5.13	5.69	4.97	4.55	4.97	4.55	4.55	4.55	4.10	3.64	5.69	S- 02	3.64	S- 10
2029	5.10	5.69	4.87	4.37	4.87	4.37	4.37	4.37	3.87	3.33	5.69	S- 02	3.33	S- 10
2030	5.08	5.66	4.75	4.20	4.75	4.20	4.20	4.20	3.62	3.02	5.66	S- 02	3.02	S- 10

From this analysis shown in Table 5.6, S-10 and S-02 scenario have been selected as extreme and less vulnerable among 10 scenarios for Charghat Upazila. For determining extreme and less vulnerable scenarios, yearly lowest and highest values of GWL under different scenarios have been analyzed from 2017 to 2030. Graphical representation of these two scenarios show that during wet period both these scenarios give almost similar result and in dry season the extreme scenario varies by more than 1m from other scenario in some years which is shown in Figure 5.7. For this reason, dry period characteristics of groundwater levels under assumed scenarios have been considered to find out extreme scenario.

From this analysis shown in Table 5.7, S-10 and S-02 scenario have been selected as extreme and less vulnerable among 10 scenarios for Mohanpur Upazila. For determining extreme and less vulnerable scenarios, yearly lowest and highest values of GWL under different scenarios have been analyzed from 2017 to 2030. Graphical representation of these two scenarios show that during wet period both these scenarios give almost similar result and in dry season the extreme scenario varies by less than 0.5m from other scenario in some years which is shown in Figure 5.8. For this reason, dry period characteristics of groundwater levels under assumed scenarios have been considered to find out extreme scenario.

From this analysis shown in Table 5.8, S-01 and S-02 scenario have been selected as extreme and less vulnerable among 10 scenarios for Durgapur Upazila. For determining extreme and less vulnerable scenarios, yearly lowest and highest values of GWL under different scenarios have been analyzed from 2017 to 2030. Graphical representation of these two scenarios show that during wet period both these scenarios give almost similar result and in dry season the extreme scenario varies by more than 2m from other scenario in some years which is shown in Figure 5.9. For this reason, dry period characteristics of groundwater levels under assumed scenarios have been considered to find out extreme scenario.

From this analysis shown in Table 5.9, S-10 and S-02 scenario have been selected as extreme and less vulnerable among 10 scenarios for Tanore Upazila. For determining extreme and less vulnerable scenarios, yearly lowest and highest values of GWL under different scenarios have been analyzed from 2017 to 2030. Graphical representation of these two scenarios show that during wet period both these scenarios give almost similar result and in dry season the extreme scenario varies by more than 2m from other scenario in some years which is shown in Figure 5.10. For this reason, dry period characteristics of groundwater levels under assumed scenarios have been considered to find out extreme scenario.

From this analysis shown in Table 5.10, S-07 and S-05 scenario have been selected as extreme and less vulnerable among 10 scenarios for Puthia Upazila. For determining extreme and less vulnerable scenarios, yearly lowest and highest values of GWL under different scenarios have been analyzed from 2017 to 2030.

From this analysis shown in Table 5.11, S-10 and S-01 scenario have been selected as extreme and less vulnerable among 10 scenarios for Godagari Upazila. For determining extreme and less vulnerable scenarios, yearly lowest and highest values of GWL under different scenarios have been analyzed from 2017 to 2030.

From this analysis shown in Table 5.12, S-10 and S-02 scenario have been selected as extreme and less vulnerable among 10 scenarios for Bagmara Upazila. For determining extreme and less vulnerable scenarios, yearly lowest and highest values of GWL under different scenarios have been analyzed from 2017 to 2030.

From Upazila wise analysis it is clear that scenario 10 and scenario 02 are most extreme and less vulnerable scenarios respectively in almost all of the Upazilas in Rajshahi district. A summary table of above analysis is given in Table 5.13.

Superposition of groundwater levels simulated for all these scenarios also show that scenario 10 is the most extreme scenario among all. Figure5.11 shows comparative analysis of all Scenario s at GT 8172040 station of Paba Upazila.

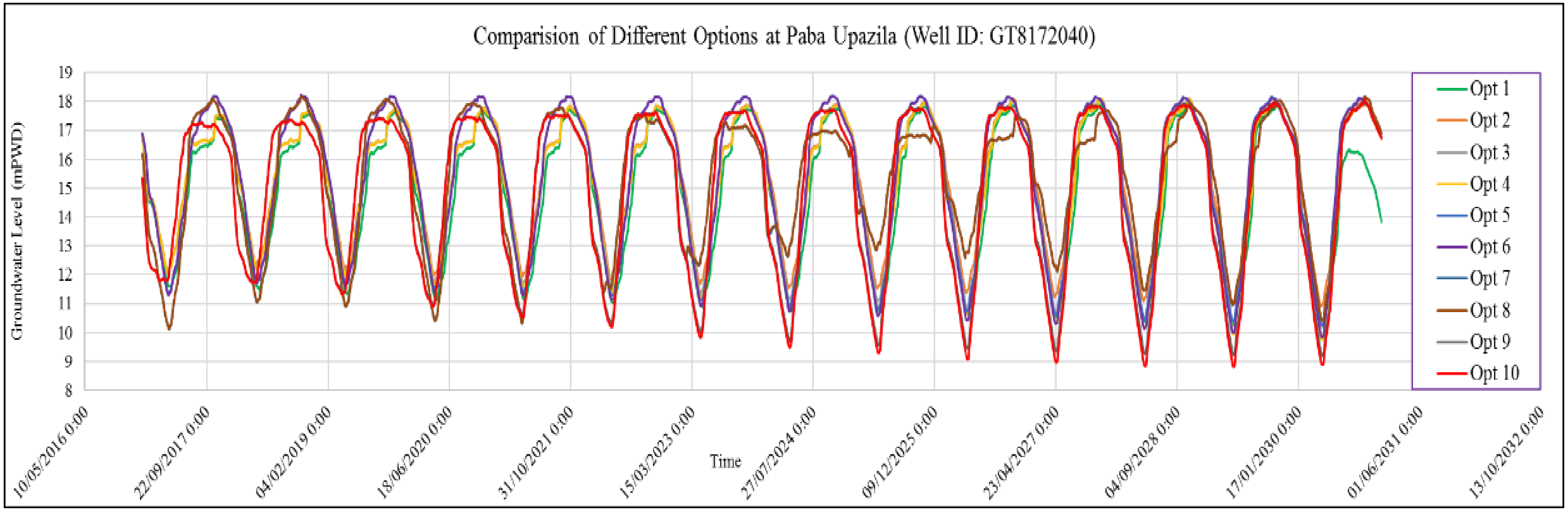


Figure 5.11: Sample graph showing all Scenario s at GT 8172040 station of Paba Upazila.

Table 5.13: Upazila wise extreme and less vulnerable scenarios

Upazila	Extreme Scenario	Less Vulnerable Scenario
Paba	S-10	S-02
Charghat	S-10	S-02
Mohanpur	S-10	S-02
Durgapur	S-01	S-02
Tanore	S-10	S-02
Puthia	S-07	S-05
Godagari	S-10	S-01
Bagmara	S-10	S-02

5.6 Application of Interventions to Counter Extreme Scenario

All these mentioned Scenario s show decreasing trend of groundwater levels within the study period. After generation of possible future scenarios, Scenario 10 has been simulated the extreme future scenario and Scenario 02 has been identified as less vulnerable scenario among the other Scenarios. So, in this study, innervations have been applied to this extreme scenario to sustain future groundwater resources up to 2030. Attempts have been made to stop the rate of declining groundwater levels and to increase the trends of groundwater levels of the study area.

Three interventions have been applied and they are (i) Non-Structural, (ii) Structural and (iii) Combined Interventions.

(i) Non-Structural Intervention:

Production of rice requires huge amount of groundwater for irrigation purposes during non-monsoon period (December to May), which lead to progressive lowering of groundwater table. Around 90% of the irrigation water comes from groundwater sources in Bangladesh. To achieve food security, Bangladesh has increased Boro rice production substantially at the cost of unsustainable groundwater depletion that will hinder water and food security in the long run.

Intervention 01: So, in this intervention area of Boro rice field is replaced by Wheat which requires around half of water required by rice.

(ii) Structural Intervention:

Intervention 02: So, in this intervention, control structures have been introduced in major khaal/kharies to regulate dry season flow of surface water to increase seepage and percolation and recharge groundwater within the area of influence.

(iii) Combined Intervention:

Intervention 03: Combination of interventions of 1 and 2 have been applied.

5.6.1 Result from Non-Structural Intervention

Before application of Non-Structural intervention, it is necessary to explore the extent of Boro rice field. Total area of Boro rice field within Rajshahi district is approximately 724 km^2 which is about one third of the study area. Figure of Boro rice field extent and Upazila wise distribution of Boro rice filed in percentage have been given in Figure 5.12 and Table 5.14 respectively. From Table 5.14, it is clear that Tanore, Godagari, Baghmara and Mohanpur are the Boro dominant Upazilas of Rajshahi district.

Replacement of Boro rice by Wheat has significantly improved the water stressed situation within this study area. Almost all of the wells of the Upazilas have been responded positively towards this intervention. Wise use of groundwater in the dry season could be a better solution towards sustainability of this scarce resource.

Upazila-wise recovery of groundwater levels of some of the wells are shown below. Graphical representation of extreme scenario vs intervention 01at Godagari, Paba, Baghmara and Mohanpur Upazila is shown in Figure 5.13 to 5.16. In these graphs, extreme scenario is represented by red line and intervention 01 is represented by green line. Groundwater level simulated under extreme scenario shows significant recovery due to application of intervention 01.

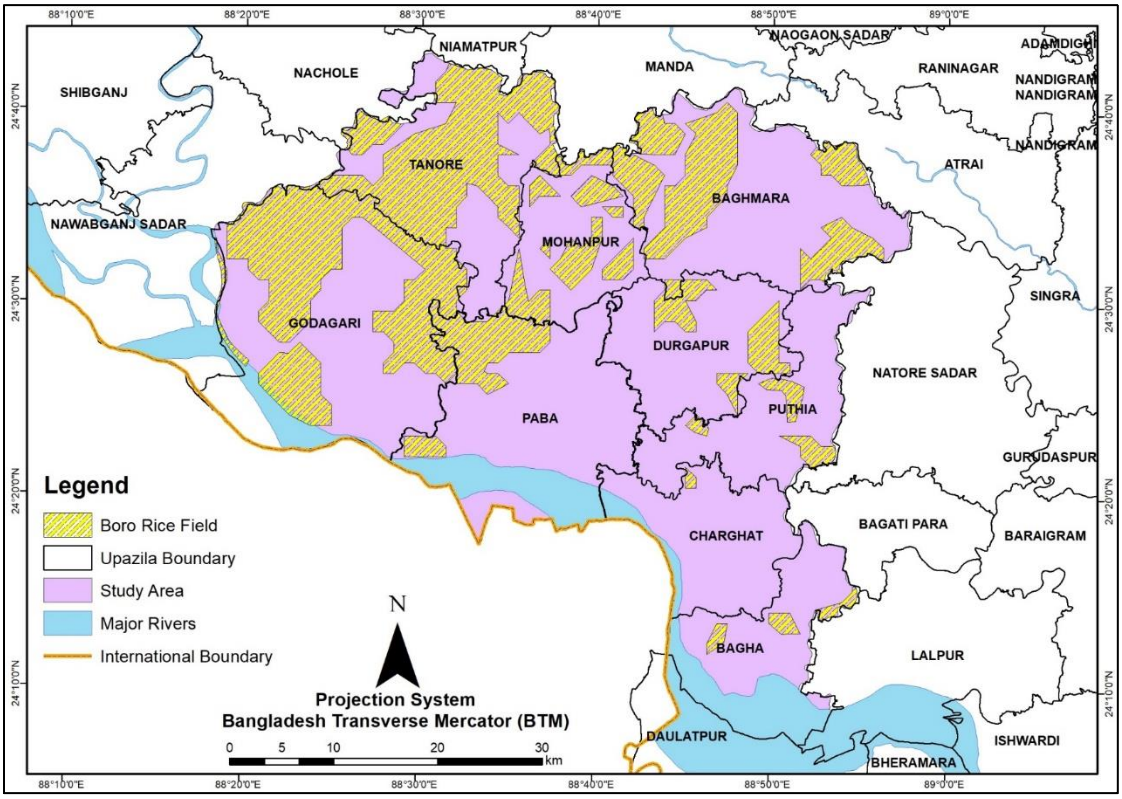


Figure 5.12: Extent of Boro rice field within Rajshahi district.

Table 5.14: Upazila-wise distribution of Boro rice field

Upazila Name	Upazila Area Km^2	Boro Rice Field Km^2	% Coverage of Each Upazila
Tanore	298.36	182.67	61.2
Godagari	493.54	222.65	45.1
Baghmara	367.9	136.9	37.2
Mohanpur	163.32	57.38	35.1
Paba	303.06	56.5	18.6
Durgapur	200.06	36.75	18.4
Puthia	192.55	18.13	9.4
Bagha	193.76	11.49	5.9
Charghat	175.28	1.44	0.8

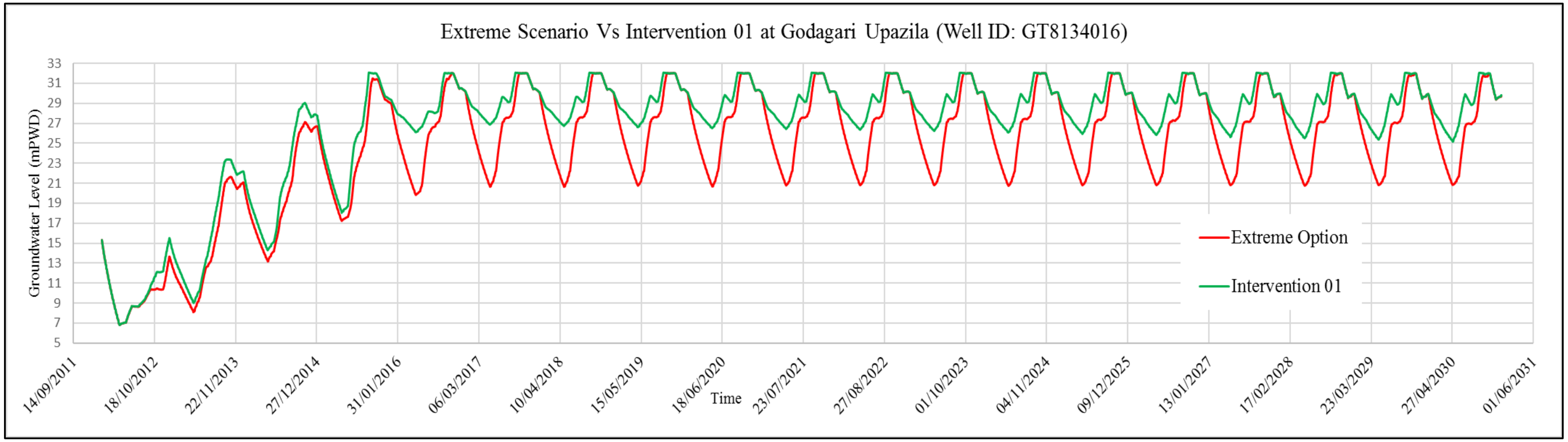


Figure 5.13: GWL of Extreme scenario vs. Intervention 01 at Godagari Upazila (Well ID: GT8134016)

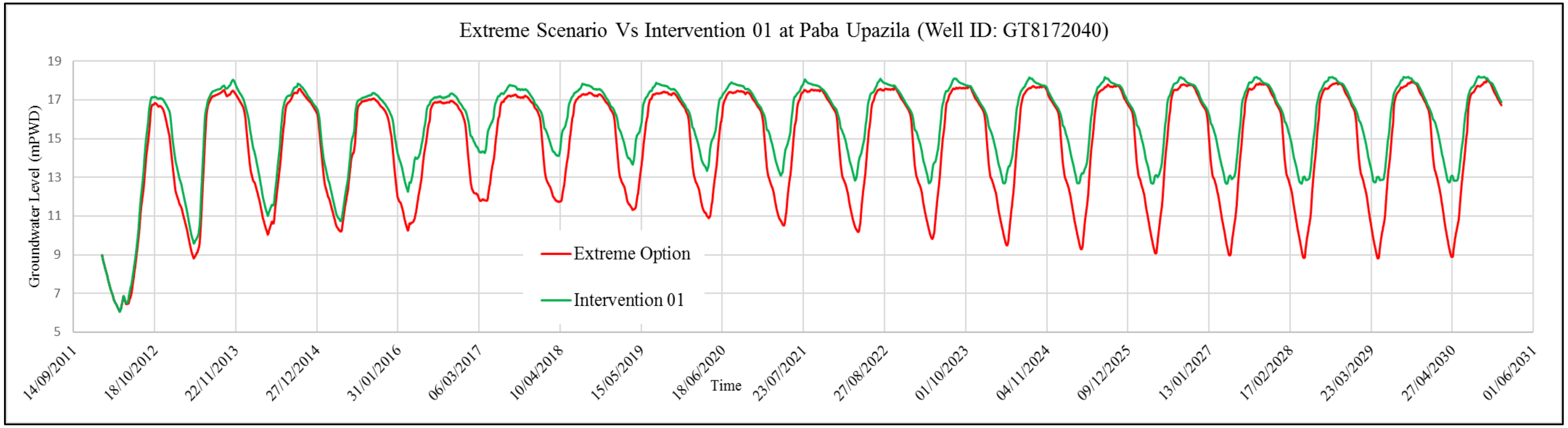


Figure 5.14: GWL of Extreme scenario vs. Intervention 01 at Paba Upazila (Well ID: GT8172040)

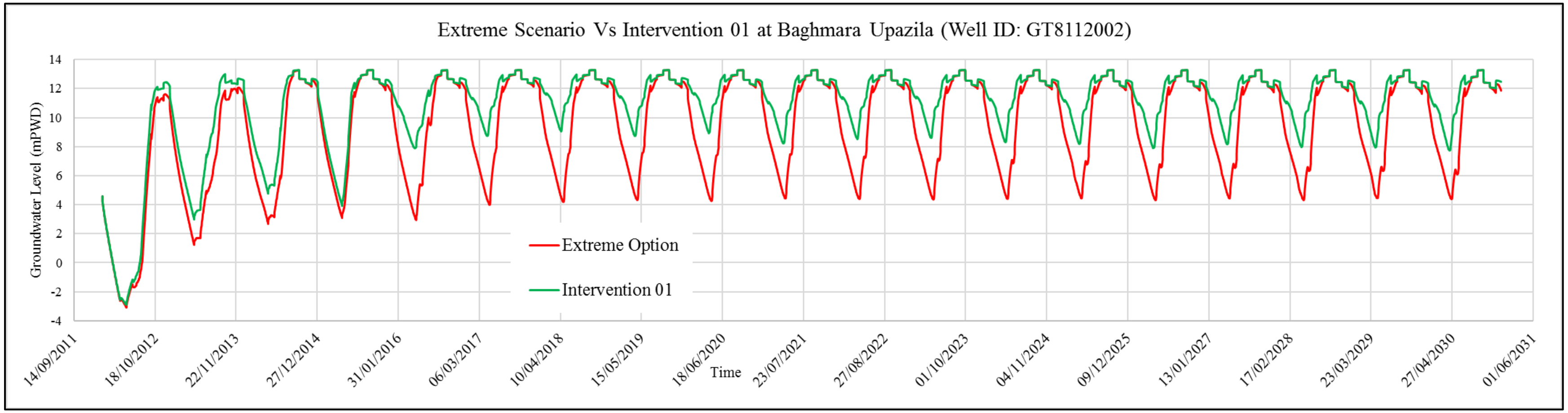


Figure 5.15: GWL of Extreme scenario vs. Intervention 01 at Baghmara Upazila (Well ID: GT8112002)

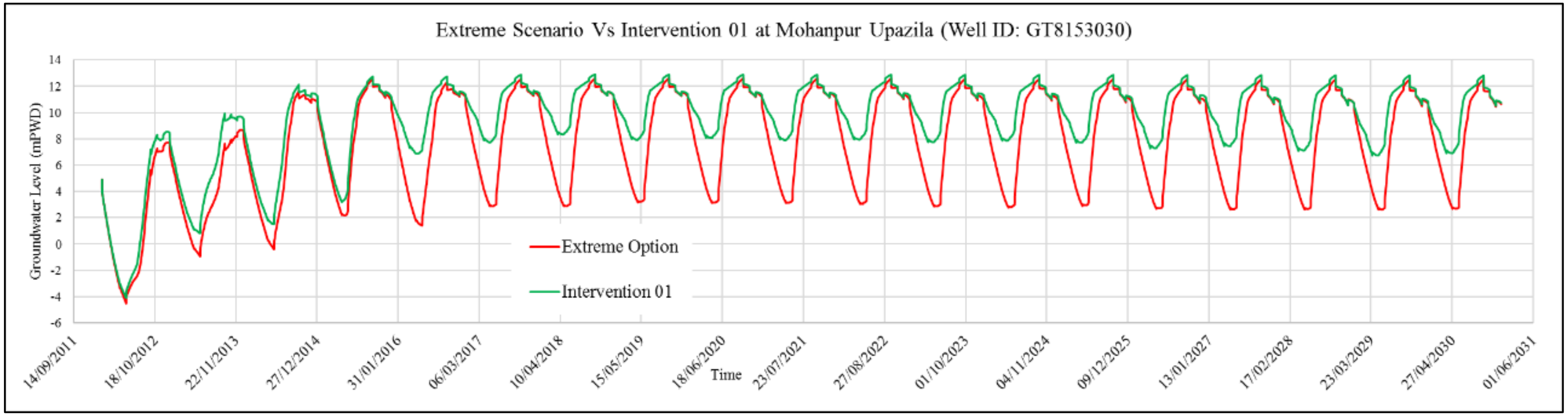


Figure 5.16: GWL of Extreme scenario vs. Intervention 01 at Mohanpur Upazila (Well ID: GT8153030)

5.6.2 Result from Structural Intervention:

In this intervention, 3 control strictures have been applied in rainfed kharis/khals only without creating any obstruction in rivers to store water in dry period. Structures applied on Rasulpur Khal, Joai Khari and Kamargaon Khari. Since Boro Khari in connected to Kamargaon Khari, it will be under regulation of control structure which are shown in Figure 5.17. Gates of these structures will be remained closed from November to April when groundwater stress is maximum. Rest of the months of the year, gates will be fully open. This stored water will boost groundwater resources and excess stored water could be used for irrigation purposes by constructing irrigation canals or by other means.

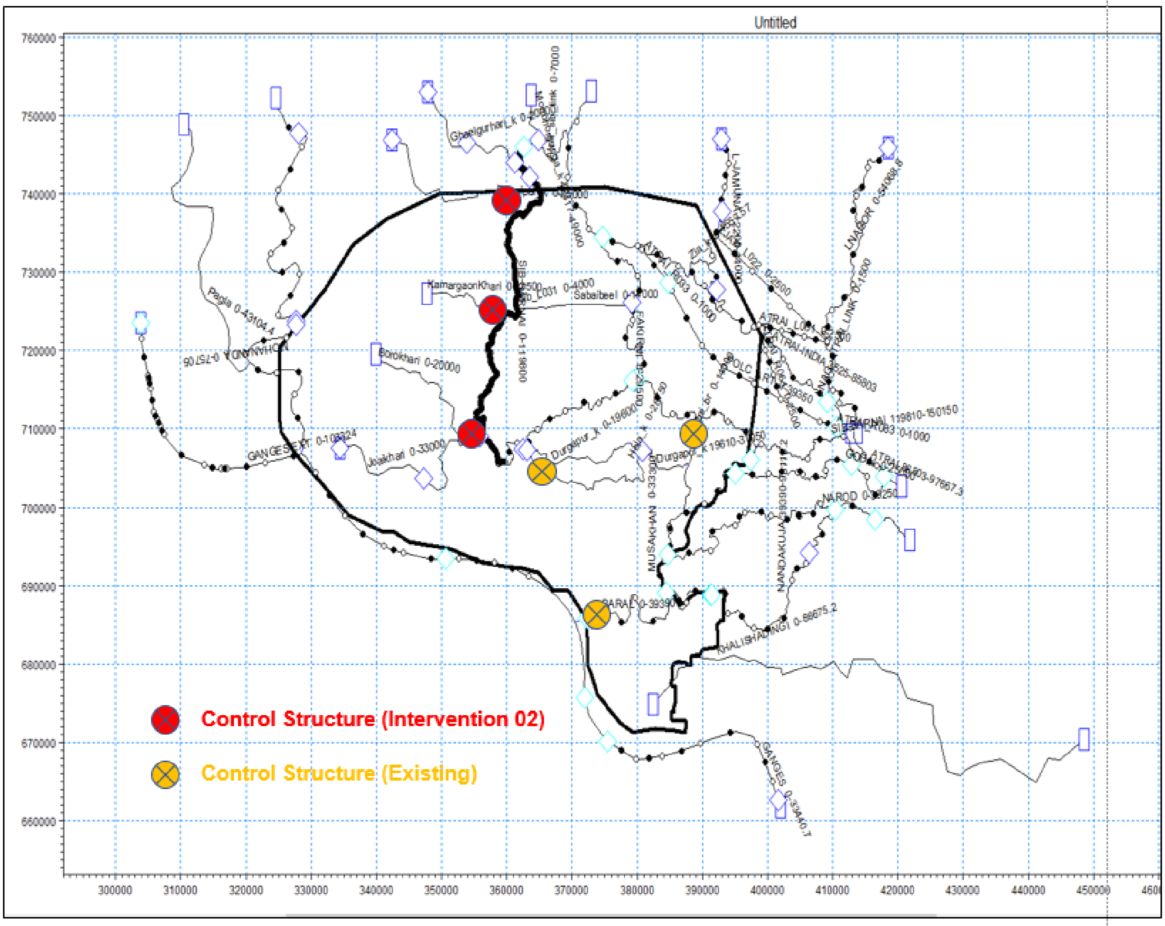


Figure 5.17: Location of proposed and existing structures within Rajshahi district.

But these controlling structures introduced in small kharis and khals to store water in dry season against extreme scenario have shown insignificant result. Some improvement of groundwater resources in dry season have seen in Godagari, Tanore Upazilas and specific areas where control structures are introduced. Rest of the Upazilas insignificantly response to this intervention.

5.6.3 Result from Combined Intervention

In this intervention, intervention 01 and intervention 02 have been applied to get best output to counter worst scenario. Since Intervention 02 is less sensitive, combining with Intervention 01 this intervention has shown vary little improvement than Intervention 01.

5.7 Depth of Phreatic Surface under Different Scenarios and Interventions

The phreatic surface or water table is the surface where the water pressure head is equal to the atmospheric pressure (where gauge pressure = 0). It may be visualized as the "surface" of the subsurface materials that are saturated with groundwater in a given vicinity. Depth of this surface is measured from existing ground level. Since 27 April 2028 has been found the driest event for this whole study area, depth to phreatic surface of different Scenarios and interventions have been shown below for this particular date to visualize specially the improvement of groundwater table after application of different interventions. It helps to understand the future availability of GW due to lowering of GWL.

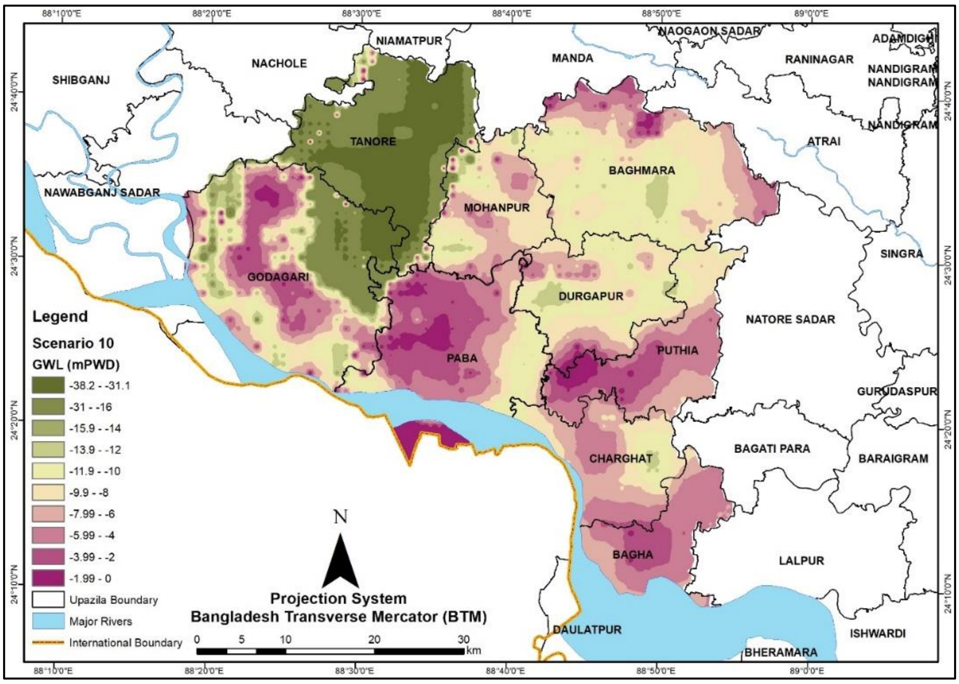


Figure 5.18: Depth of phreatic surface of extreme scenario (S-10) at 27th April 2028.

As scenario S-10 has been chosen as the most extreme scenario for the whole study area, in this part of analysis it has been tried to visualize the depth of saturated zone below the existing ground surface. Depth of phreatic surface for this scenario is shown in Figure 5.18 in which the average depth is -10.03m. Negative values refer to water below the ground level. Positive values of depth to phreatic surface refers to water on the surface. This will be the case where we have upward flow from the saturated zone, or when the rainfall exceeds the infiltration capacity, and the overland flow component will not be able to move the water.

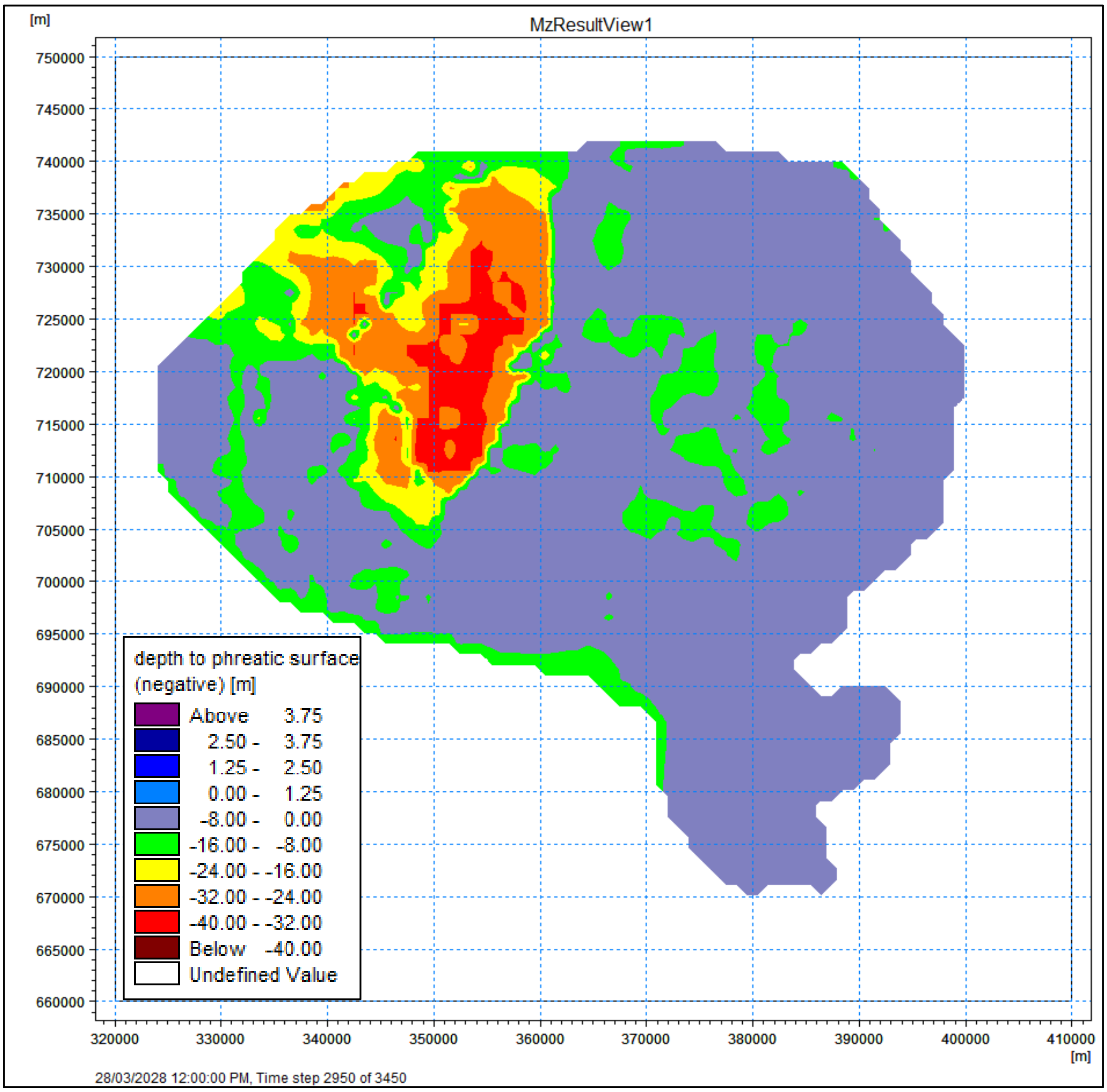


Figure 5.19: Depth of phreatic surface of less vulnerable scenario (S-02) at 27th April 2028.

Similarly, less vulnerable or suitable scenario of phreatic surface shows very large zone compared to worst scenario where depth of phreatic surface is less which indicates easiness of availability of GW resources. Depth of phreatic surface for less vulnerable is shown in Figure 5.19 in which average depth is -09.40m. Most of the study area has below 8m depth of saturated zone which indicates good availability of groundwater resources beneath the surface. This is why it has been chosen as suitable scenario for this study among other scenarios.

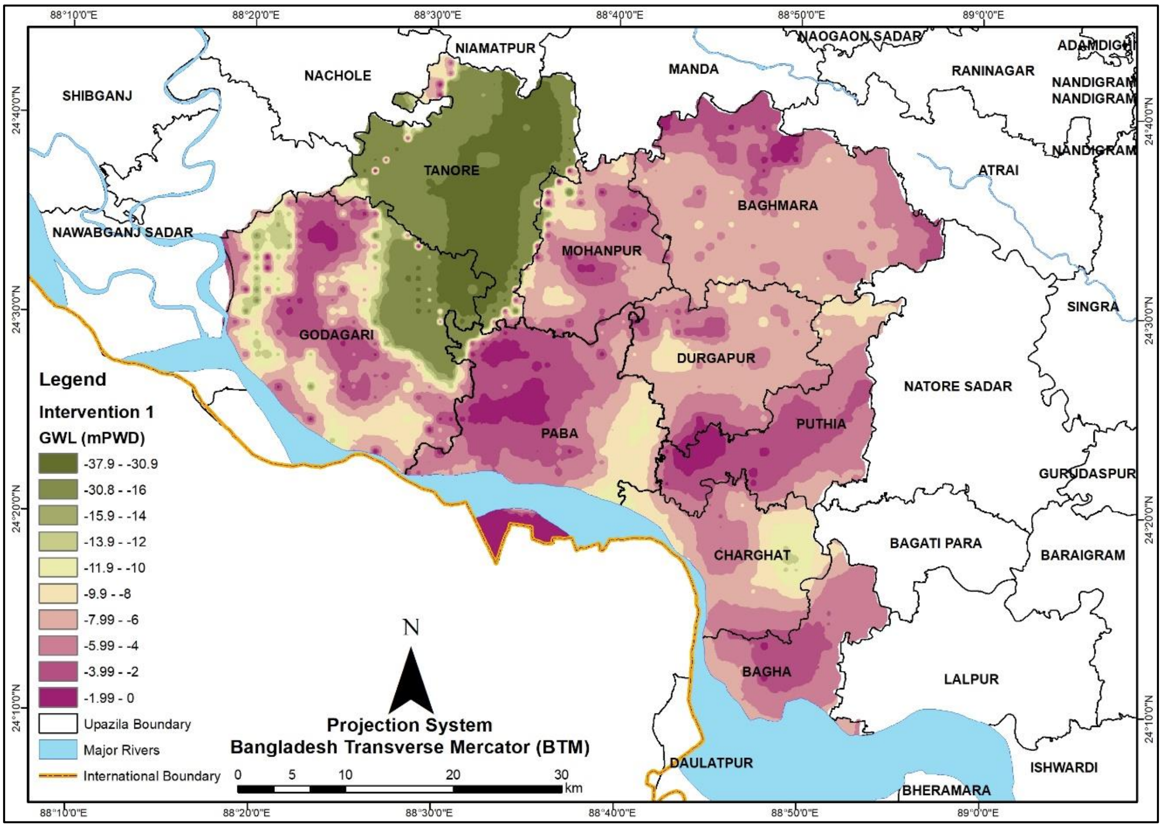


Figure 5.20: Depth of phreatic surface of Intervention 01 at 27th April 2028.

To counter extreme scenario S-10, three interventions have been applied. In intervention 1, high water consumed Boro rice has been replaced by low water consumed Wheat. And it makes a significant improvement of groundwater resources which can be seen in Figure 5.20. It is clear from this figure that this intervention can make the worst scenario (S-10) better than our suitable scenario (S-2). Depth of phreatic surface for intervention 01 is shown in Figure 5.18 in which average depth is -08.51m. Lowest average depth of saturated zone (-8.51m) indicates the overall situation of groundwater availability under this intervention.

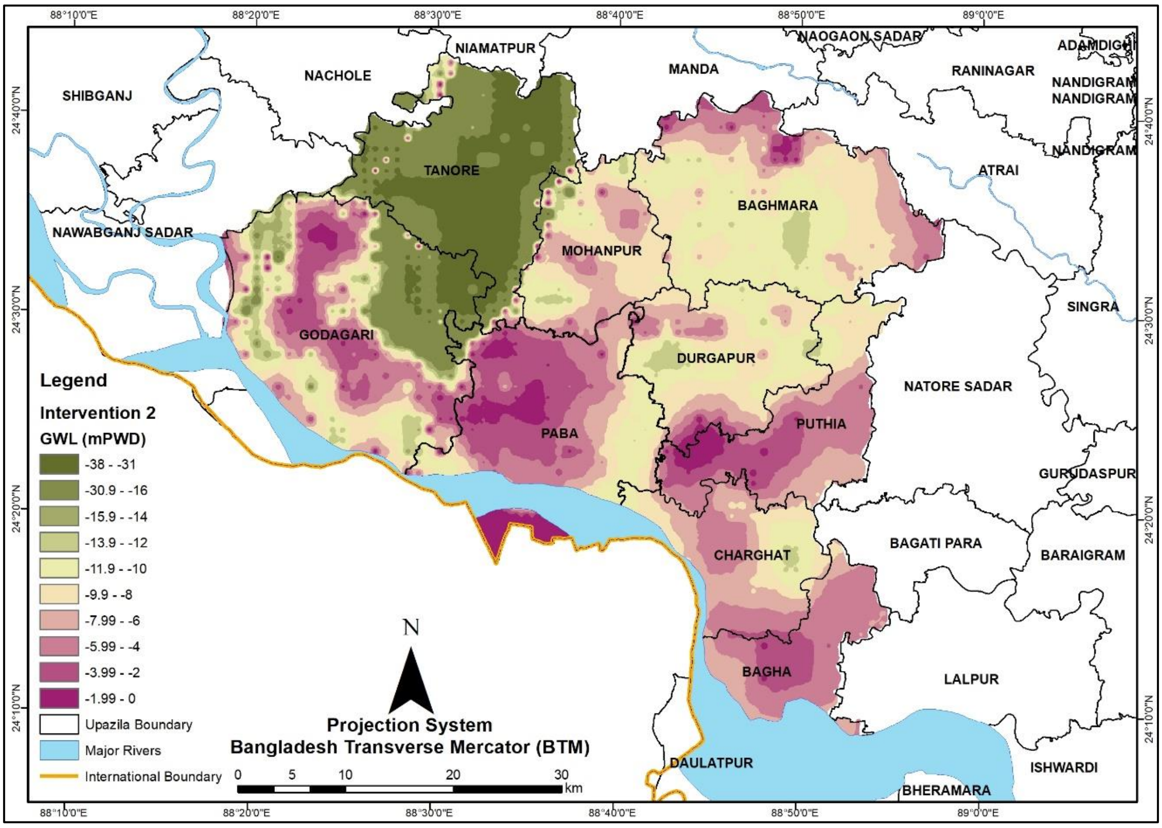


Figure 5.21: Depth of phreatic surface of Intervention 02 at 27th April 2028.

In intervention 2, instead of diversifying crops, regulatory water retaining structures have been introduced inn small canals/kharis to store water when needed. But this intervention is not as effective as previous one because stored water by this intervention is very low compared to high water stress. Depth of phreatic surface for intervention 02 is shown in Figure 5.21 in which average depth is -09.96m. This result shows positive improvement from worst scenario but not as good as suitable scenario.

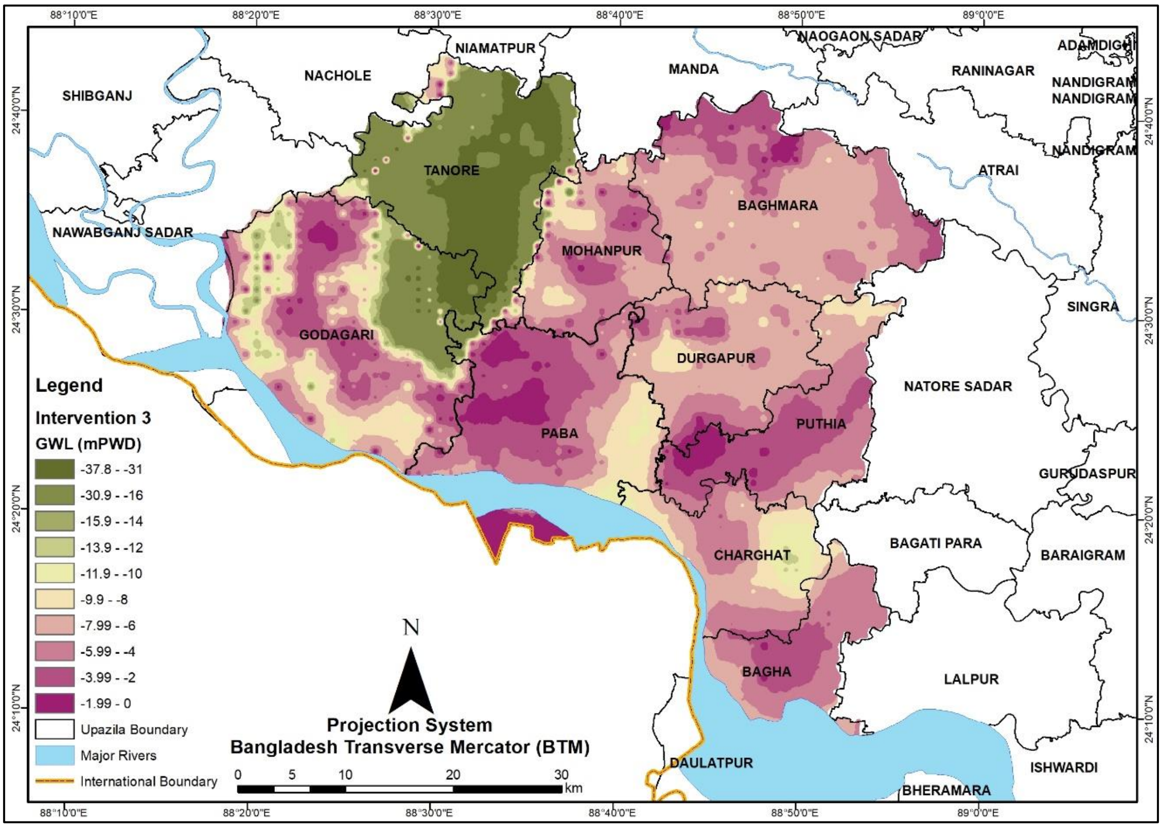


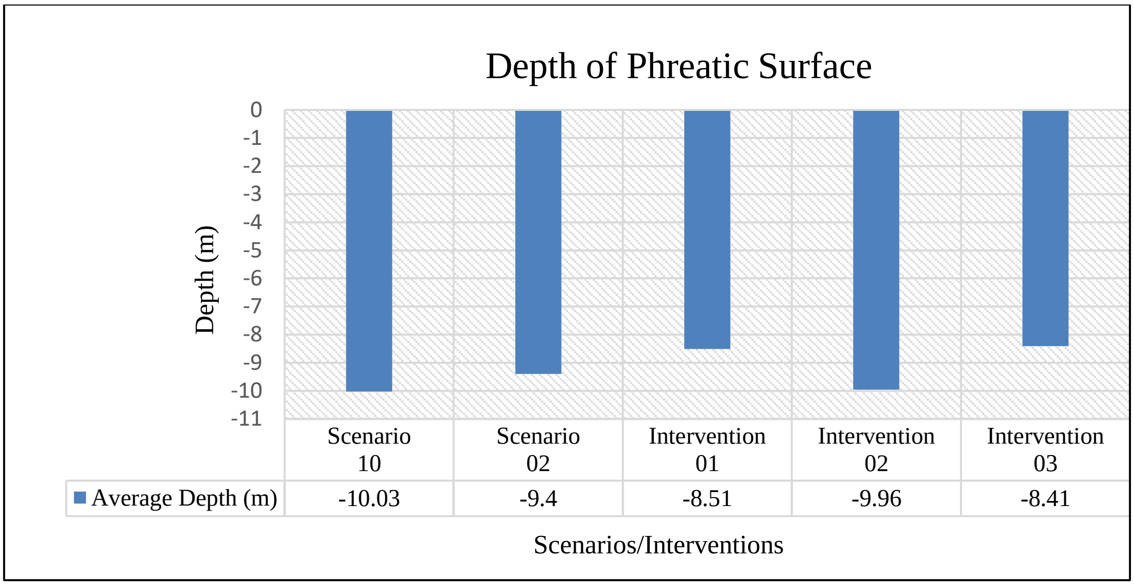
Figure 5.22: Depth of phreatic surface of Intervention 03 at 27th April 2028.

In intervention 3, combined effects of intervention 1 and intervention 2 has been analyzed. And it shows better than intervention 1 by a slight margin. Depth of phreatic surface for intervention 03 is shown in Figure 5.22 in which average depth is -08.41m.

Overall summary of these findings has been summarized below in Table 5.15 and Figure 5.23. To decide which intervention is most suitable for this area, we have to analyze more precisely in other ways as well.

Table 5.15: Zonal statistics of S-10, 02 and Intervention 01, 02 and 03

Scenario /Intervention	Mean Depth of GWT
Scenario 10	-10.03m
Scenario 02	-9.40m
Intervention 01	-8.51m
Intervention 02	-9.96m
Intervention 03	-8.41m



	Scenario 10	Scenario 02	Intervention 01	Intervention 02	Intervention 03
🟦 Average Depth (m)	-10.03	-9.4	-8.51	-9.96	-8.41

Figure 5.23: Average Depth of phreatic surface

5.8 Results from Analysis

From the above analysis it can be identified that intervention 03 has more suitable among these interventions. Compared to extreme scenario, intervention 03 has little more significant than intervention 01. But the difference of intervention 1 and intervention 3 is slight and by financial point of view intervention 3 is costlier. So another analysis needs to be carried to determine whether intervention 3 or intervention 1 is more suitable considering overall issues.

Another comparative analysis has been done against extreme Scenario (S-10) with Intervention 01, Intervention 02 and Intervention 03. To understand special variation of groundwater table within the study area and to visualize the improvement of groundwater table or Phreatic surface after application of different interventions, phreatic surface of extreme Scenario (S-10) has been deducted from phreatic surface of Intervention 01, Intervention 02 and Intervention 03. Deducted values have been specially distributed in the study area where positive values indicate improvement of groundwater level, negative values indicate further lowering of groundwater level. This analysis has been presented in figures 5.24 to figure 5.27 and summarized in Table 5.19. This analysis is helpful for mutual comparison for all interventions.

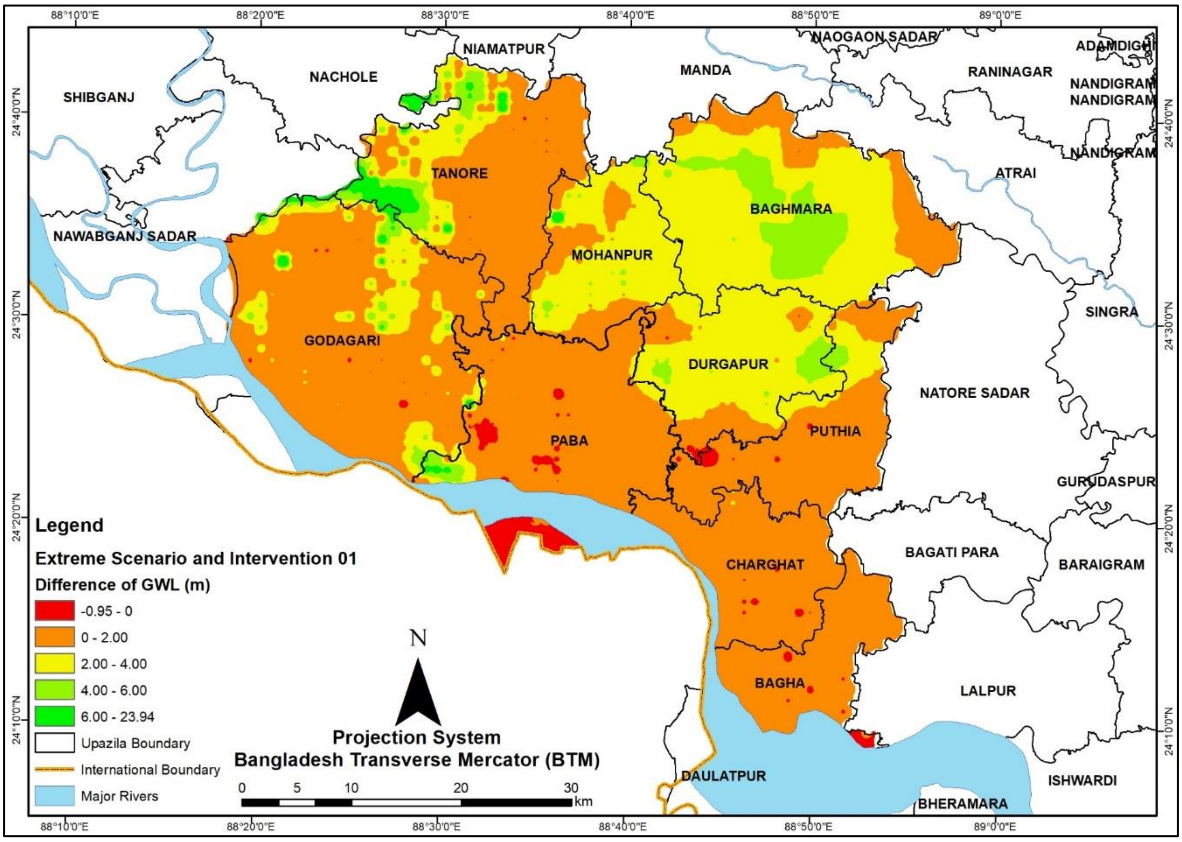


Figure 5.24: Comparison of depth of phreatic surface of Intervention 01 and Scenario 10

Comparison of extreme scenario vs intervention 01 is shown in Figure 5.24 where positive values indicates 96.55% improvement of groundwater level, negative values indicate 3.45% further lowering of groundwater level compared to extreme scenario. Details of this analysis have been tabulated in Table 5.16.

Table 5.16: Improved Area after application of intervention 01

Difference of GWL (m)	Percentage of Improved (+ve) /Deteriorated (-ve) Area
-0.98 to 0	-03.45
0 to 2	63.05
2 to 4	27
4 to 6	5.3
6 to 23.94	1.2

This result shows significant improvement of groundwater resources without any structural construction.

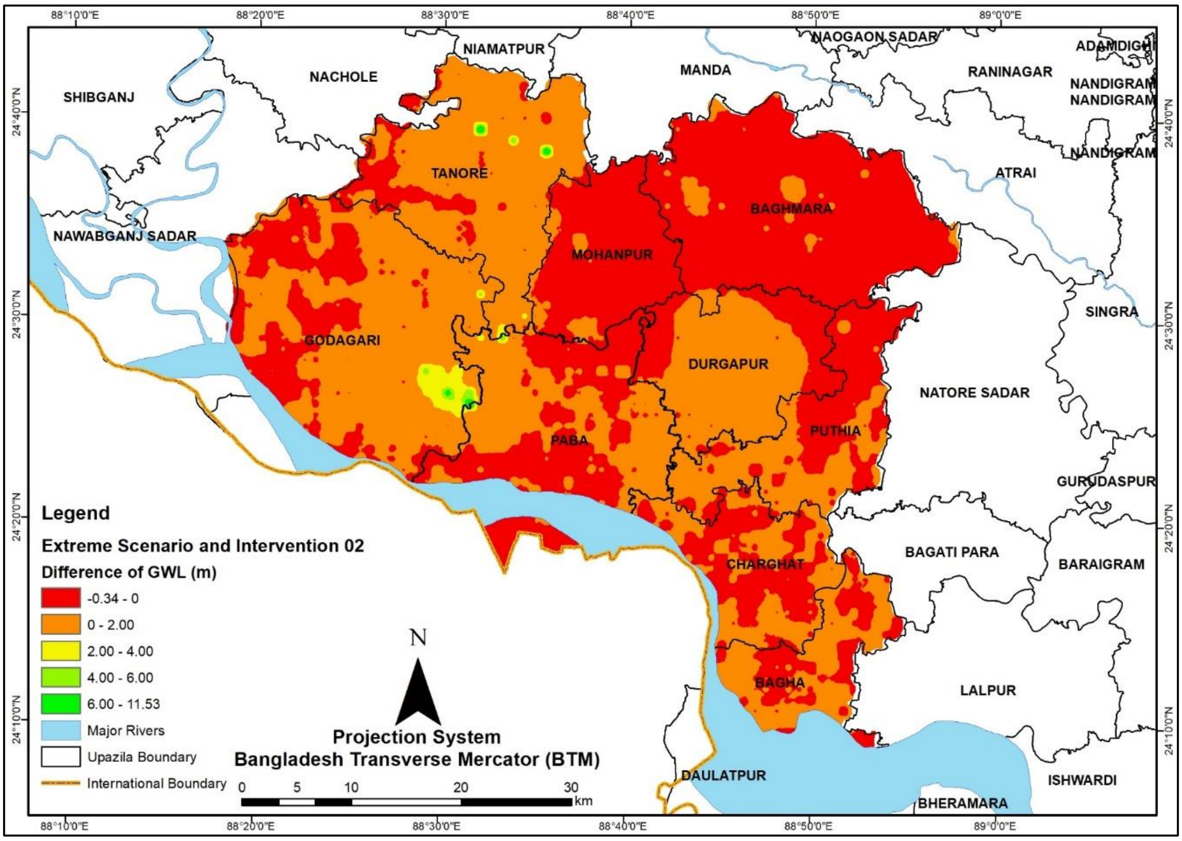


Figure 5.25: Comparison of depth of phreatic surface of Intervention 02 and Scenario 10

Comparison of extreme scenario vs intervention 02 is shown in Figure 5.25 where positive values indicates 51.44% improvement of groundwater level, negative values indicate 48.56% further lowering of groundwater level compared to extreme scenario. Details of this analysis have been tabulated in Table 5.17.

Table 5.17: Improved area after application of intervention 02

Difference of GWL (m)	Percentage of Improved (+ve)/Deteriorated (-ve) Area
-0.34 to 0	-48.56
0 to 2	50.44
2 to 4	0.8
4 to 6	0.1
6 to 11.53	0.1

This result shows insignificant and localized improvement of groundwater resources with structural construction which is shown in Figure 5.26.

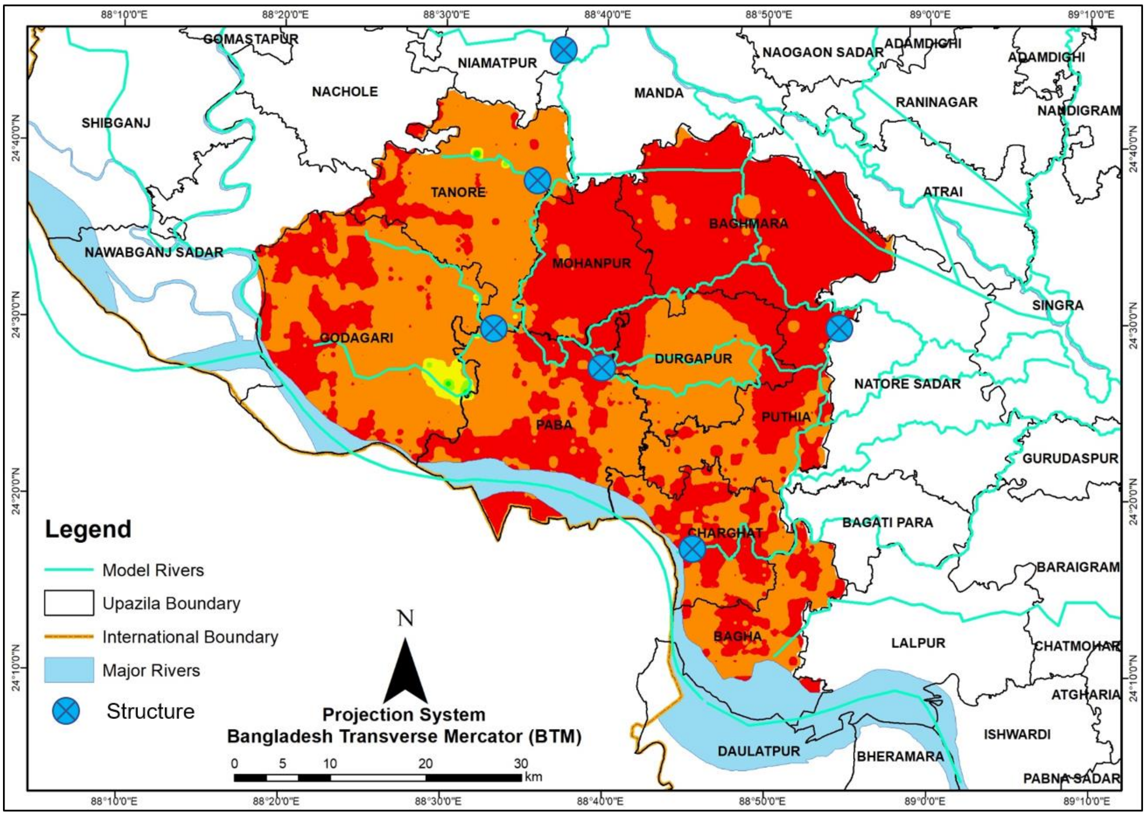


Figure 5.26: Localized improvement of groundwater resources

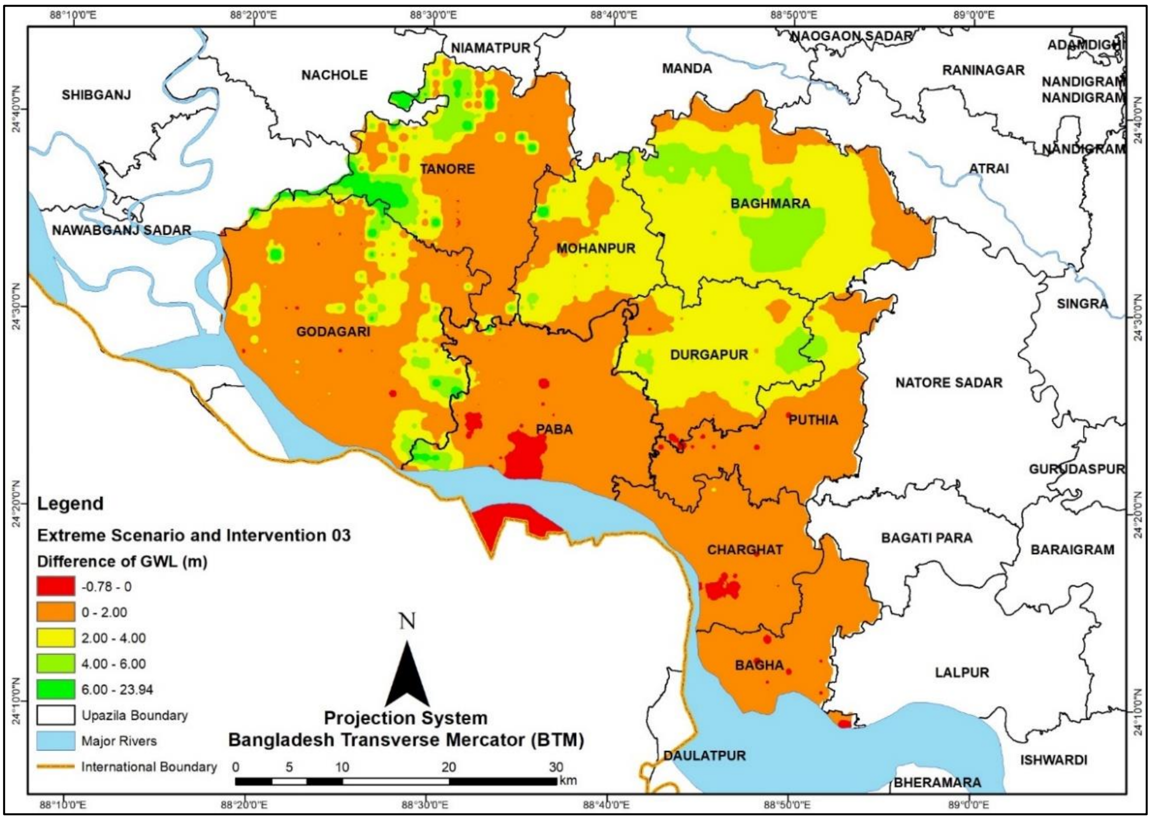


Figure 5.27: Comparison of depth of phreatic surface of Intervention 03 and Scenario 10

Comparison of extreme scenario vs intervention 03 is shown in Figure 5.27 where positive values indicates 95.73% improvement of groundwater level , negative values indicate 4.27% further lowering of groundwater level compared to extreme scenario. Details of this analysis have been tabulated in Table 5.18.

Table 5.18: Improved Area after application of intervention 03

Difference of GWL (m)	Percentage of Total Area
-0.78 to 0	4.27
0 to 2	60.7
2 to 4	27.2
4 to 6	6.55
6 to 23.94	1.28

This result shows that intervention 03 is not better than intervention 01 in spite of crop diversification and structural construction.

Figures 5.23 to figure 5.26 have been summarized in table 5.19 where it has been found that after application of intervention 01, 93.1% area of the study area has been improved with respect to extreme scenario.

Table 5.19: Improved Area after application of interventions

Interventions	Improved Study Area	Deteriorated Study Area	Overall Improvement
Intervention 01	96.55%	3.45%	93.1%
Intervention 02	51.44%	48.56%	02.88%
Intervention 03	95.73%	4.27%	91.46%

Volumetric analysis is carried out in which it is calculated that after application of intervention 01, 3620 million cubic meter saturated zone is increased in the study area compared to extreme scenario. According to water table fluctuation method, additional 253 million cubic meter water resources have been added in the study area as groundwater recharge.

5.8.1 River-Aquifer Interaction

The interaction between river and aquifer is an important phenomenon of nature. The interaction of Sib-Barnai River (within Rajshahi district) with adjacent aquifer has been analyzed for Intervention 01 for 2016 and 2030.

According to Figure 5.28, aquifer contributes to river from early mid of August to mid of February and river contributes to aquifer from mid of February to early mid of August for Intervention 01 for 2016. The figure also illustrates that, aquifer contributes to river from early mid of August to end of February and river contributes to aquifer from starting of March to early mid of August for Intervention 01 for 2030. River-aquifer interaction volume is given in Table 5.20.

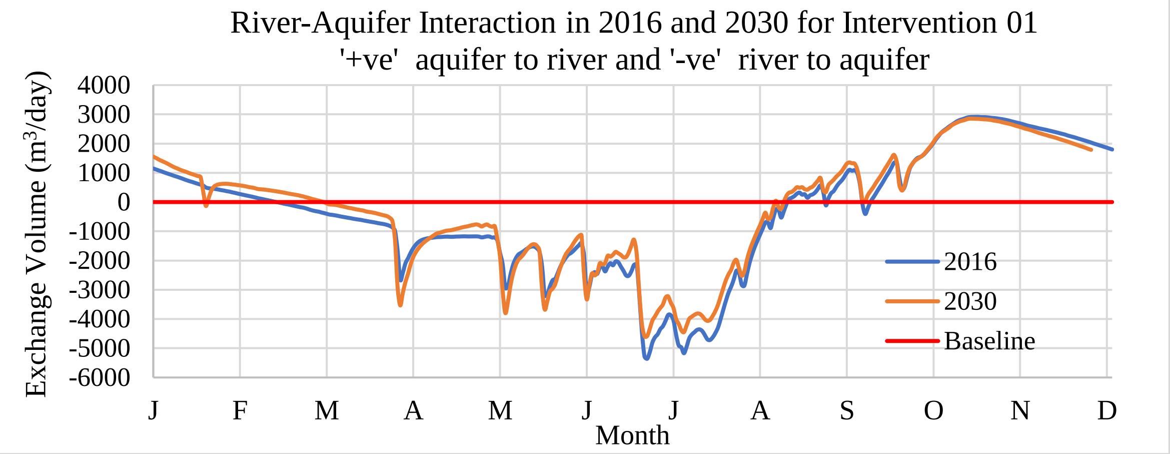


Figure 5.28: Comparison of River-Aquifer Interaction between 2016 and 2030

Table 5.20: River-Aquifer Interaction

Year	Intervention 01 (Total Volume, m^3)	
	River to Aquifer	Aquifer to River
2016	-374894.0	233768.5
2030	-329565.0	237636.8

From above graph and table, it is seen that flow from river to aquifer decreased and flow from aquifer to river increased for Intervention 01. This phenomenon testifies the long term improvement of groundwater resources after application of Intervention 01.

5.8.2 Positive Trend of GWL from 2017 to 2030

After application of Intervention 01, except Tanore Upazila, all of the wells within the model boundary have shown positive trend from 2012 to 2030 which are tabulated in Table 5.21. For trend analysis of GWL, annual maximum and annual minimum GWL of each station have been analysed. Locations of these GW stations are shown in Figure 4.8 and annual maximum and annual minimum GWL data required for these trend analysis are tabulated in Appendix E.

Table 5.21: Positive Trend of GWL within Model Area

Well ID	Max. (m/year)	Min. (m/year)	Well ID	Max. (m/year)	Min. (m/year)
GT8134016	0.42	0.72	GT8182042	0.05	0.3
GT8153031	0.26	0.35	GT8172040	0.04	0.17
GT8112001	0.16	0.27	GT6403002	0.03	0.18
GT8134028	0.14	0.26	GT8112002	0.02	0.31
GT6447023	0.13	0.2	GT8131015	0.02	0.31
GT8153030	0.12	0.37	GT8112003	0.02	0.43
GT8125011	0.11	0.01	GT8125009	0.02	0.12
GT8134027	0.09	0.13	GT8134021	0.01	0.02
GT8172037	0.08	0.11	GT8182041	0.01	0.16
GT8125010	0.06	0.03	GT8194046	-0.05	-0.06
GT8134018	0.06	0.27	GT8194044	-0.17	-0.17
GT8172036	0.06	0.24	GT8194047	-0.82	-0.51
GT8182043	0.05	0.07	GT8194048	-0.86	-0.74
GT8125006	0.05	0.08			

Considering overall analysis, it can be said that (intervention 01) will be a suitable solution to sustain groundwater resources for future.

5.9 Meeting Goals of SDGs 2030

Groundwater is an important resource for achievement of the UN Sustainable Development Goals SDGs. Groundwater could be important to ensuring access to water and sanitation for all (Goal 6) as well as contributing to a number of other goals: poverty eradication (Goal 1), food security (Goal 2), and combating climate change (Goal 13). Study findings of this research will be helpful in achieving particular goals of SDGs in the following ways:

Goal 1 & 2: (Poverty Eradication & Food Security)

Agriculture is the largest employment sector in Bangladesh. The performance of this sector has an overwhelming impact on employment generation, poverty alleviation, human resources development, food security, etc. In this study area, almost all of the required water demand is agricultural. Because of being one of the most severe water stressed area of the country, agriculture of this area has been facing threat of challenging adverse climate effects. It could hamper poverty eradication and food security in this area where agriculture is the largest source of livelihood. For achieving poverty eradication & food security, sustainable agriculture is necessary. This study findings have paved ways to sustain agriculture in this area up to 2030 which will be helped to achieve Goal 1 and Goal 2 of SDGs 2030.

Goal 6: (Water and Sanitation for All)

Though agricultural water demand is the most prominent in the study area, people relay complete on groundwater for domestic purposes such as drinking and sanitation. Over extraction to meet agricultural demand, groundwater level in this area has been falling continuously posing threat to right of water and sanitation for all. This study has proposed a probable solution to sustain groundwater resources for sustainable supply of water and sanitation for all and this measure will be helpful to access to clean drinking water and adequate sanitation and thus achieve Goal 6 of SDGs 2030.

Goal 13: (Combating Climate Change)

Water resources an essential part of the solution to climate change. Climate change will affect the availability, quality and quantity of water needed for basic human needs, thus undermining enjoyment of the basic rights to safe drinking water and sanitation of people. By sustaining water resources in the study area up to 2030, this study has found a solution to combat adverse impact of climate change and will be helpful to achieve Goal 13 of SDGs 2030.

5.10 Summary

Overall findings of the study can be summarized as follows:

This study is very challenging because the chosen study area is the driest area of the country. And most extreme dry event of 10 years return period has been chosen to simulate future worst scenario. Moreover all analysis have been done to counter the driest event (27 April, 2028) of worst scenario so that reaming events could be could be countered.

Lots of difficulties have been faced to counter this extreme future scenario because of adverse climatic condition and geographic location of this area. Low rainfall, high evaporation, huge extraction of groundwater, low recharge, thick clay layer, steep slope, high elevation, lack of water bodies, reduction of surface water flow from prominent transboundary rivers etc. are associated with the existing water stressed condition of this study area. Groundwater levels of almost all Upazilas show negative trend and rate of depletion of minimum groundwater level is higher than rate of depletion of maximum groundwater level. Since agricultural water demand is the most dominant among all other water demands in this area, therefore increasing trend of production of Boro rice in dry period is mainly responsible for decreasing trend of groundwater level. Lack of rainfall and surface water, people are bound to use groundwater for almost all purses including agriculture. This dependency on groundwater leads to lowering GWL beyond reach day by day at an alarming rate. To simulate future scenario of groundwater there are ten scenarios have been formulated. Optional runs have been carried out in base model (2012-2016) to understand the most extreme and suitable future situations considering climate change impacts for 2017 to 2030. After finding these scenarios, there are three interventions have been formulated to counter the most extreme scenario. Replacement of Boro rice fields by Wheat has shown a significant relief from water stressed situation in the long run within the study area. Storing of surface water in small khals/kharies has insignificant influence over the study area under extreme dry scenario. Replacement of Boro rice by Wheat along with controlling structures has shown almost similar result with replacement of Boro rice by Wheat only. Therefore from above analysis, considering driving forces, it can be said that to sustain groundwater resources up to 2030, replacement of Boro rice by Wheat will be a good solution.

CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

6.1 General

The objective of the study is to assess the current and future situation of groundwater levels of the underlying aquifer system of the Rajshahi district using MIKE SHE hydrologic model. To understand future scenarios from 2017 to 2030 there are 10 probable options have been studied and worst option has been chosen compared to other options. For the sustainability of groundwater resources up to 2030 there are three interventions have been applied in the worst condition and most suitable intervention has been identified for this study area.

6.2 Conclusions of the Study

1. Almost all of the GW Stations within the study area have shown permanent depletion of GWL for the duration of 30 years period (1986 to 2016). Maximum depletion rate of maximum and minimum GWL has been found around 0.85m/year and of 0.67m/year respectively.
2. Out of 10 assumed scenarios, “Scenario 10” has been found the most extreme scenario up to 2030. In this above mentioned scenario, agricultural water demand of base year 2016 has been increased by 2.5% up to year 2030, meteorological data have been generated from GCM up to 2030, boundary GWL of extreme dry event of 1994 has been assumed constant from 2016 to 2030 and municipal demand has been calculated based on BBS growth rate prediction.
3. There are three interventions including “Structural”, “Non-Structural” and “Combined” interventions have been applied to counter worst scenario where only Non-Structural intervention has been found effective for sustainability of groundwater resources.
4. Non-Structural intervention has been found significantly effective to reduce water stress in this heavily water stressed study area. Replacement of Boro rice fields by Wheat has shown a significant relief from water stressed situation in the long run

within the study area. Except Tanore Upazila, all of the GWL observation wells within the model boundary have shown positive trend of GWL.

5. 27th April 2028 has been as found most dry event within 2016 to 2030 time period. After application of Non-Structural intervention on this particular date, 95.66% of the study area has shown improvement of groundwater resources by increasing volume of saturated zone of 3619 million cubic meter.
6. Structural intervention in which storing of surface water in small khals/kharies has insignificant influence over the study area under extreme dry scenario and Combined intervention has almost similar impact as Non-Structural intervention.

6.3 Recommendations for Further Study

The recommendations for the future research are as follows:

1. In this study three interventions have been applied and these are change of crop pattern, application of control structures to store surface water and their combination. Other interventions such as rainwater harvesting, artificial recharge of aquifer etc. are highly recommended to study in this study area.
2. In this study Boro rice has been replaced by Wheat as an intervention. Crop diversification by introducing other crops or cropping systems are recommended to observe their influence on groundwater resource improvement.
3. In this study grid size has been taken as 1000m X 1000m. As a result, fluctuation of groundwater level of small zones less than 1 square km has not been visualized clearly. It is recommended to use grid size lower than 100mX100m for future study to get more precise result.
4. In this study small amount of water has been stored by applying control structures on small kharis that is why improvement of groundwater was insignificant and localized. It is recommended to explore large storage capacity in major rivers to see the improvement of groundwater resources in the study area.

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Appendix A: Double Mass Curve

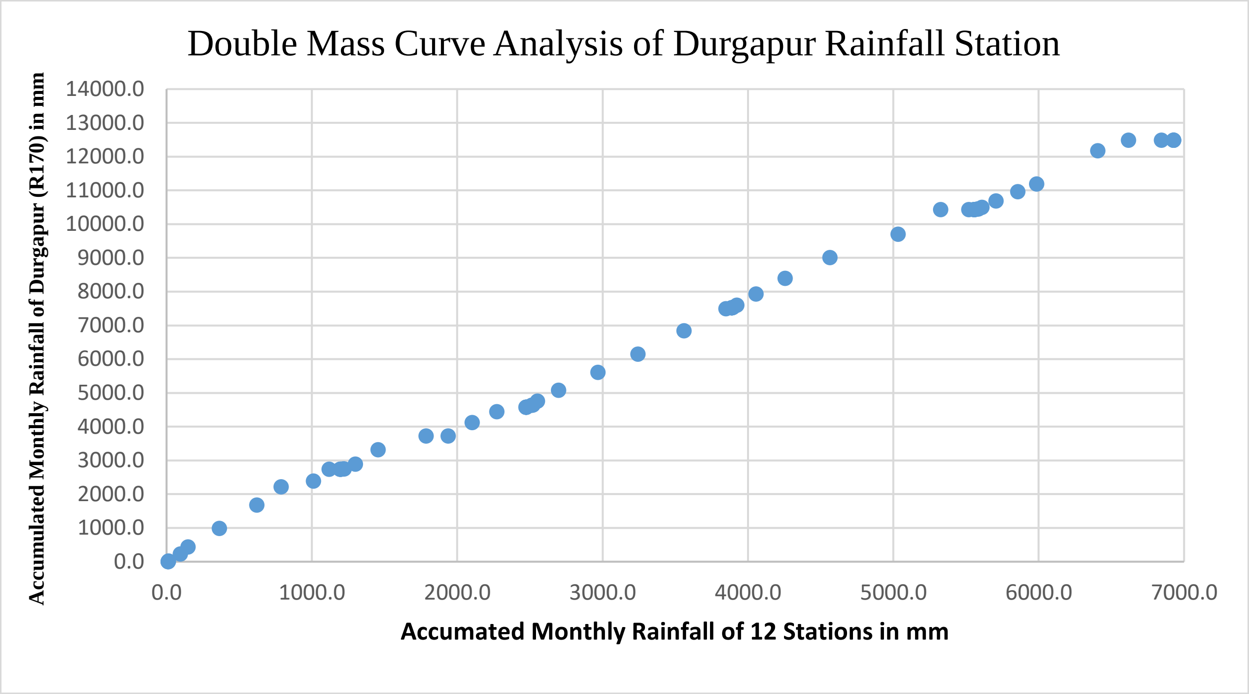

Figure A1: Double mass curve of Rainfall at R170

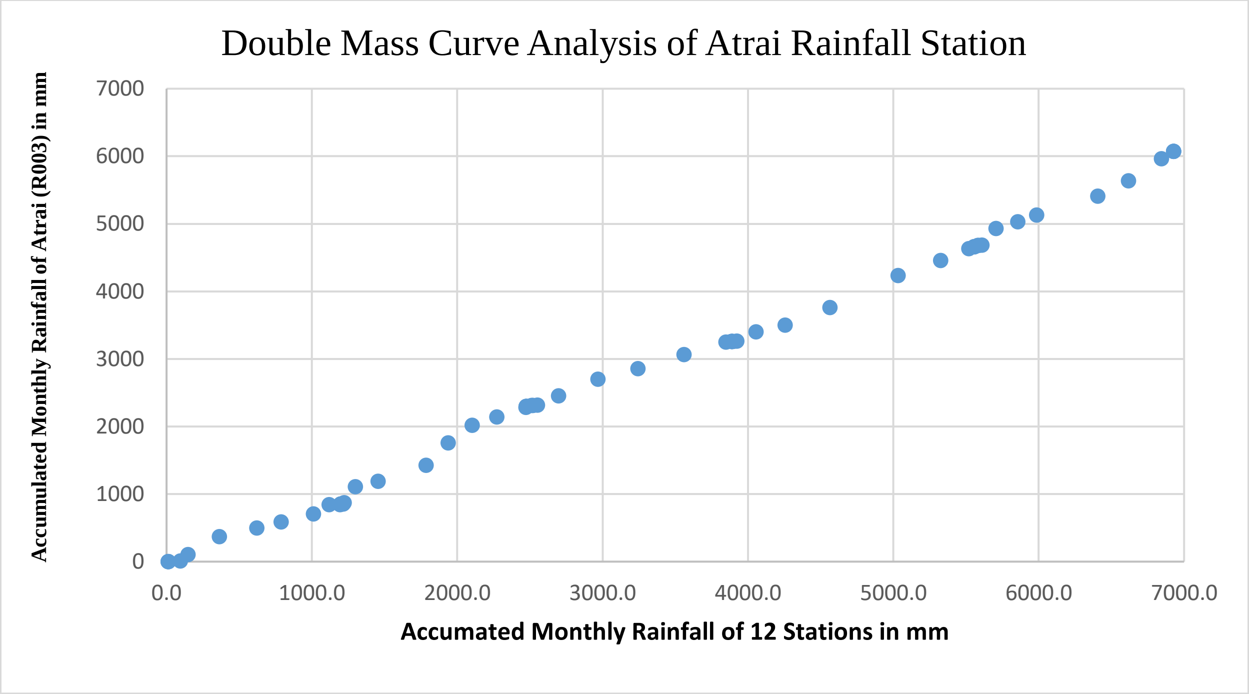

Figure A2: Double mass curve of Rainfall at R003

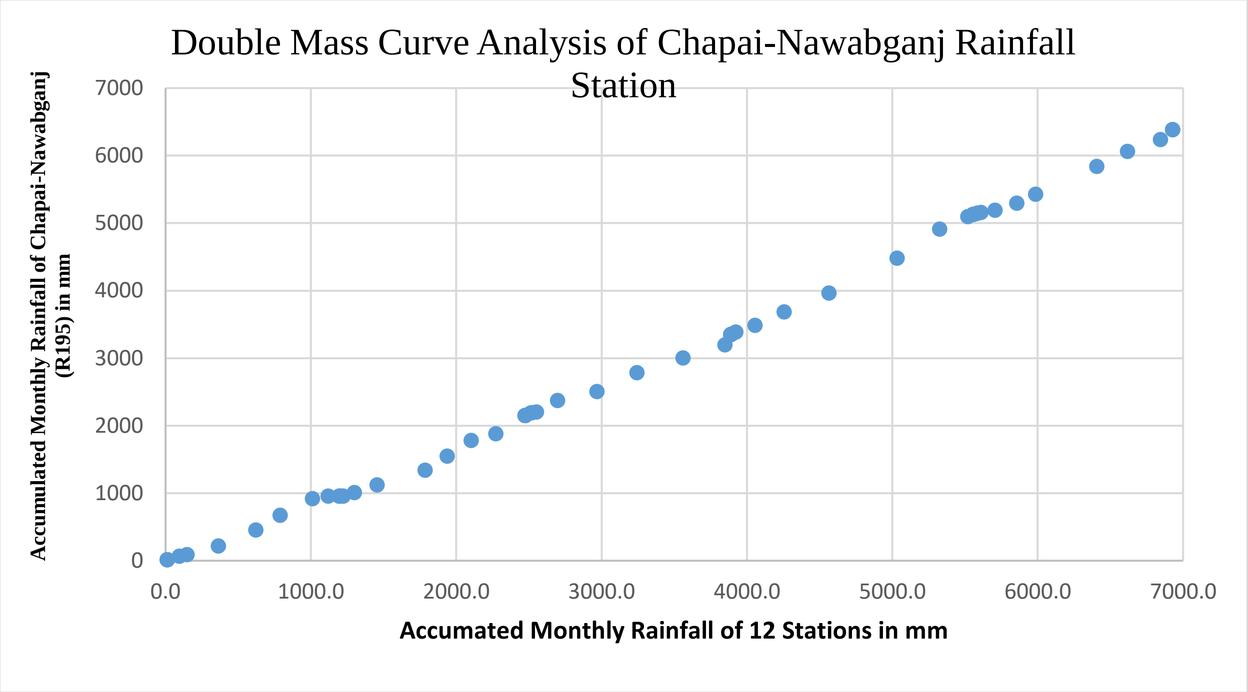

Figure A3: Double mass curve of Rainfall at R195

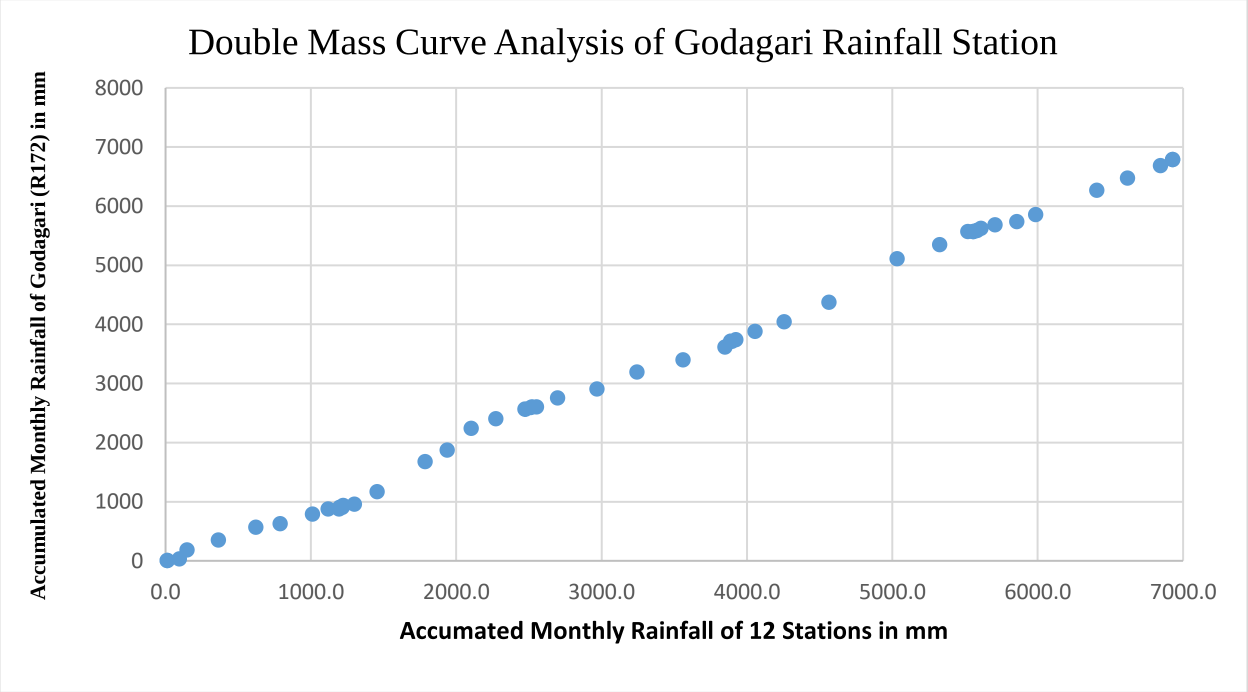

Figure A4: Double mass curve of Rainfall at R172

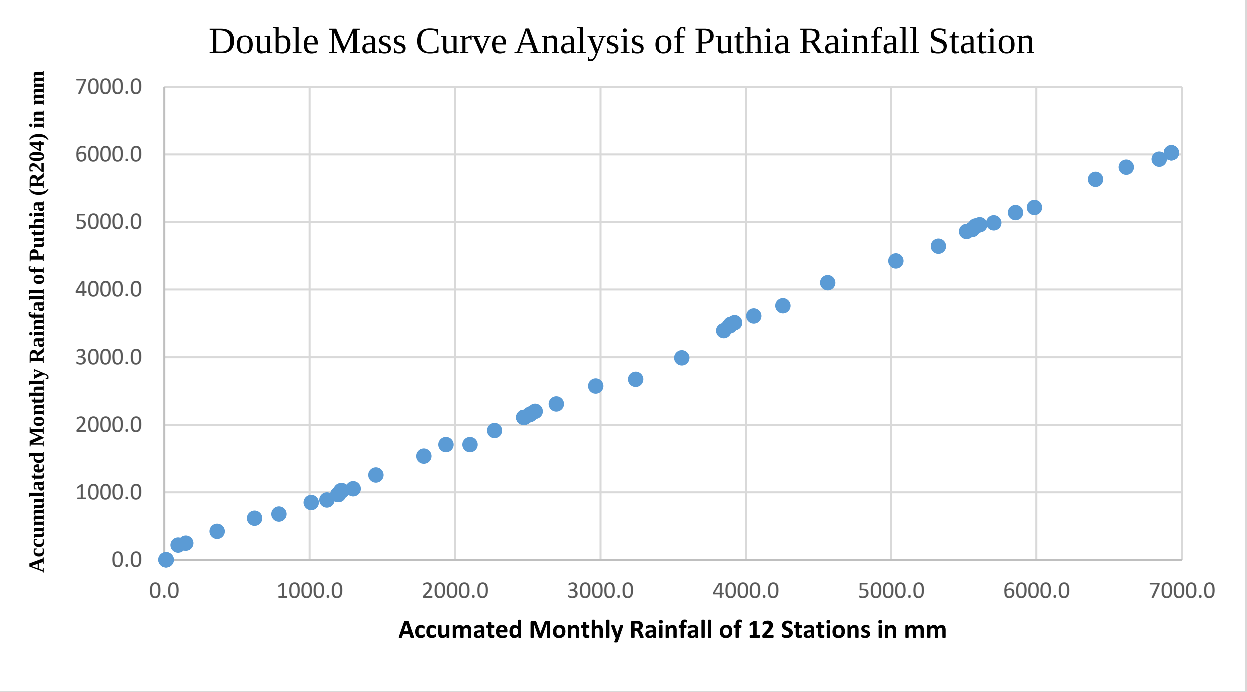

Figure A5: Double mass curve of Rainfall at R204

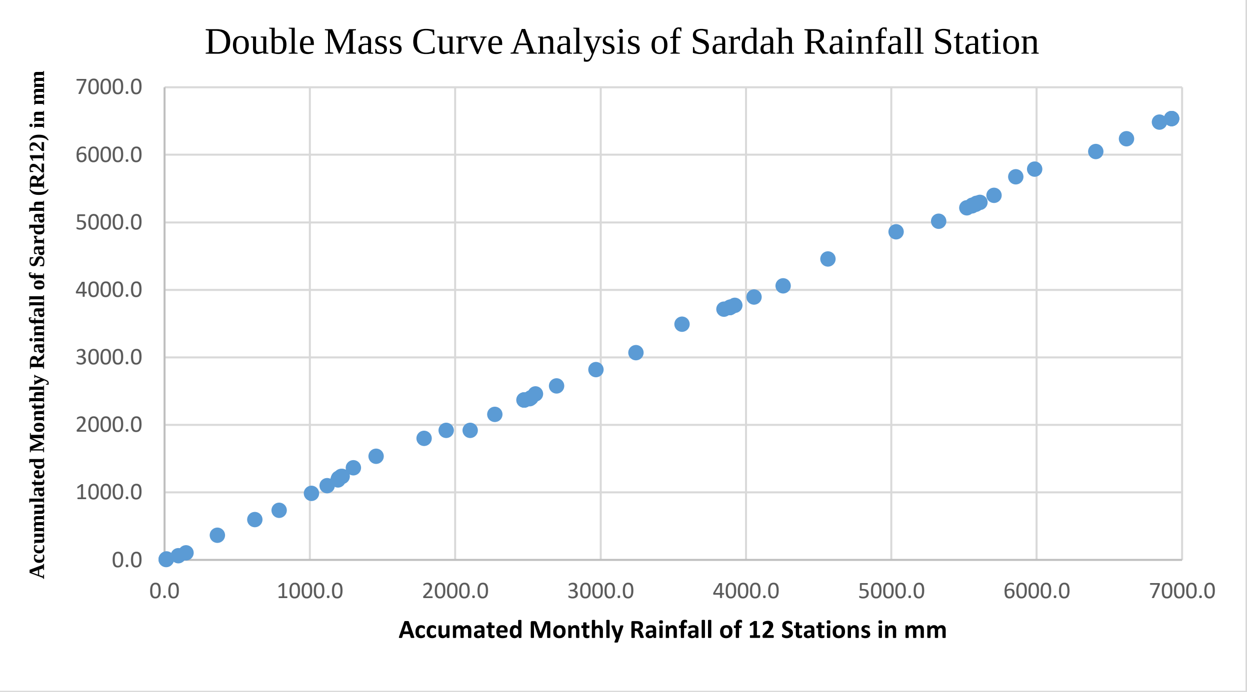

Figure A6: Double mass curve of Rainfall at R212

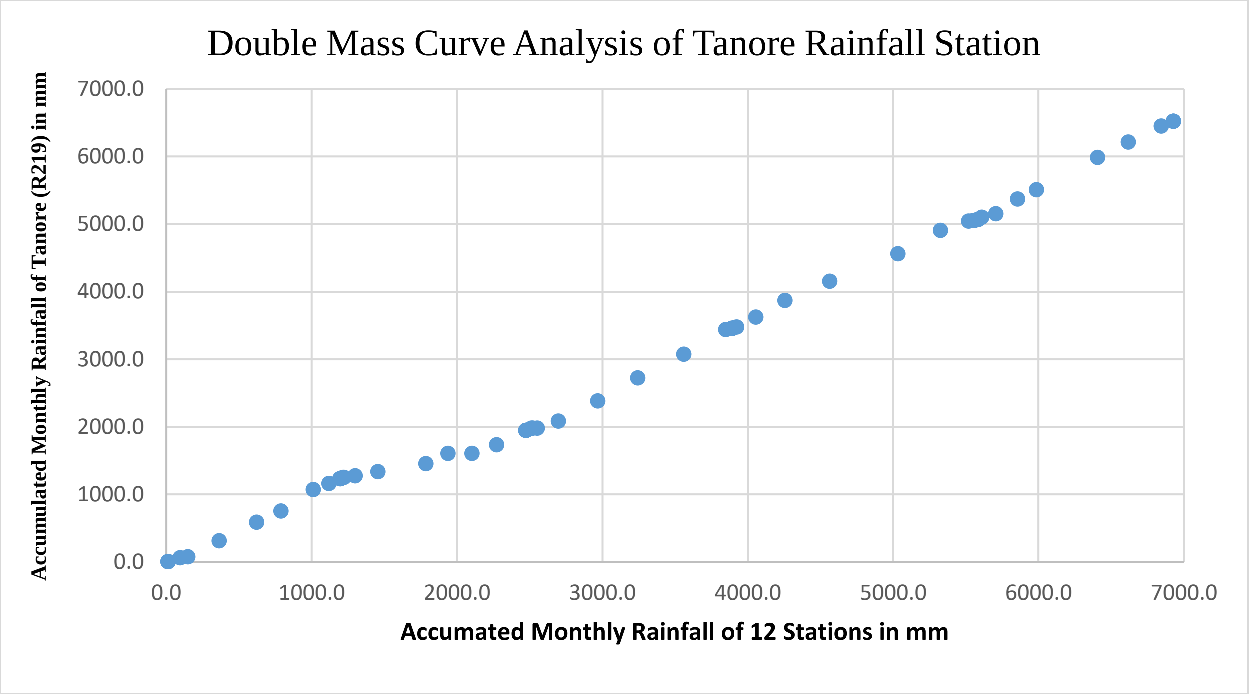

Figure A7: Double mass curve of Rainfall at R219

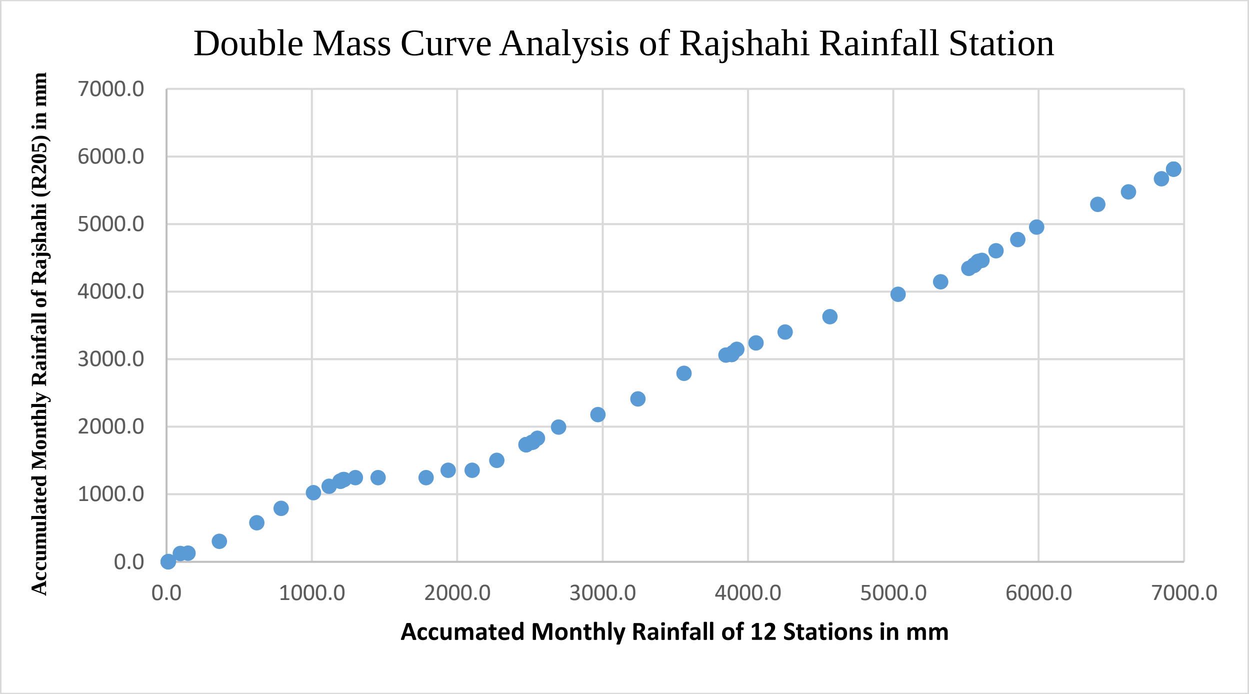

Figure A8: Double mass curve of Rainfall at R205

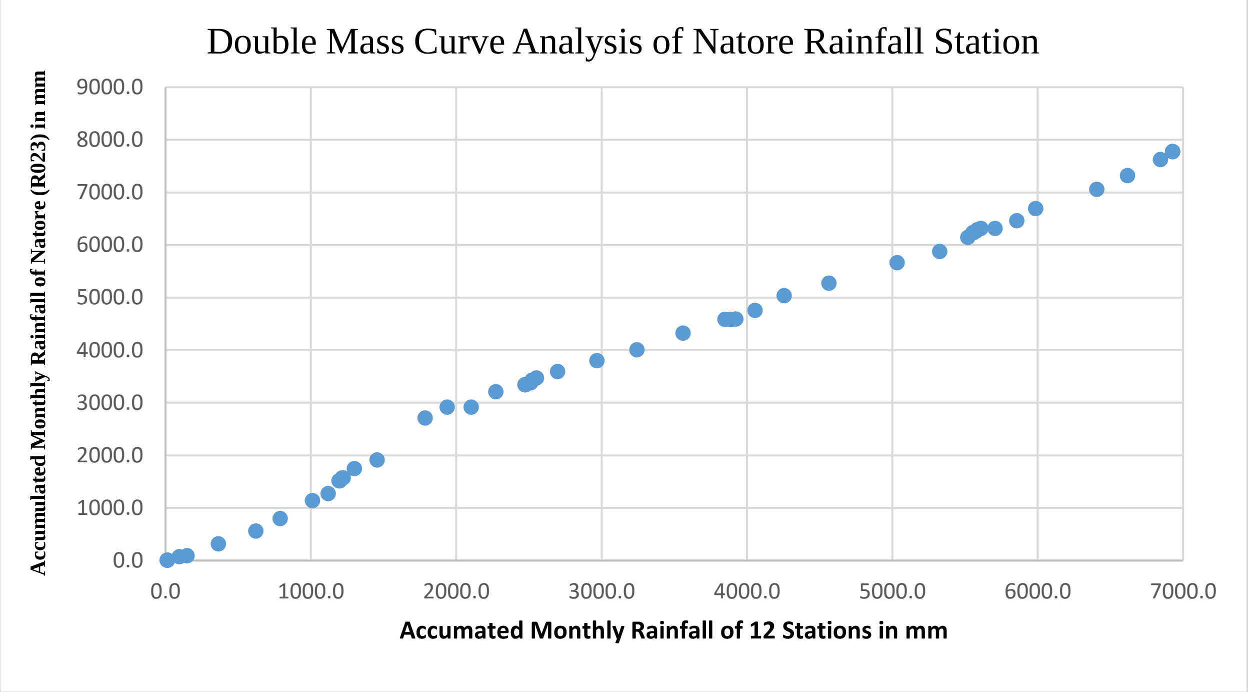

Figure A9: Double mass curve of Rainfall at R023

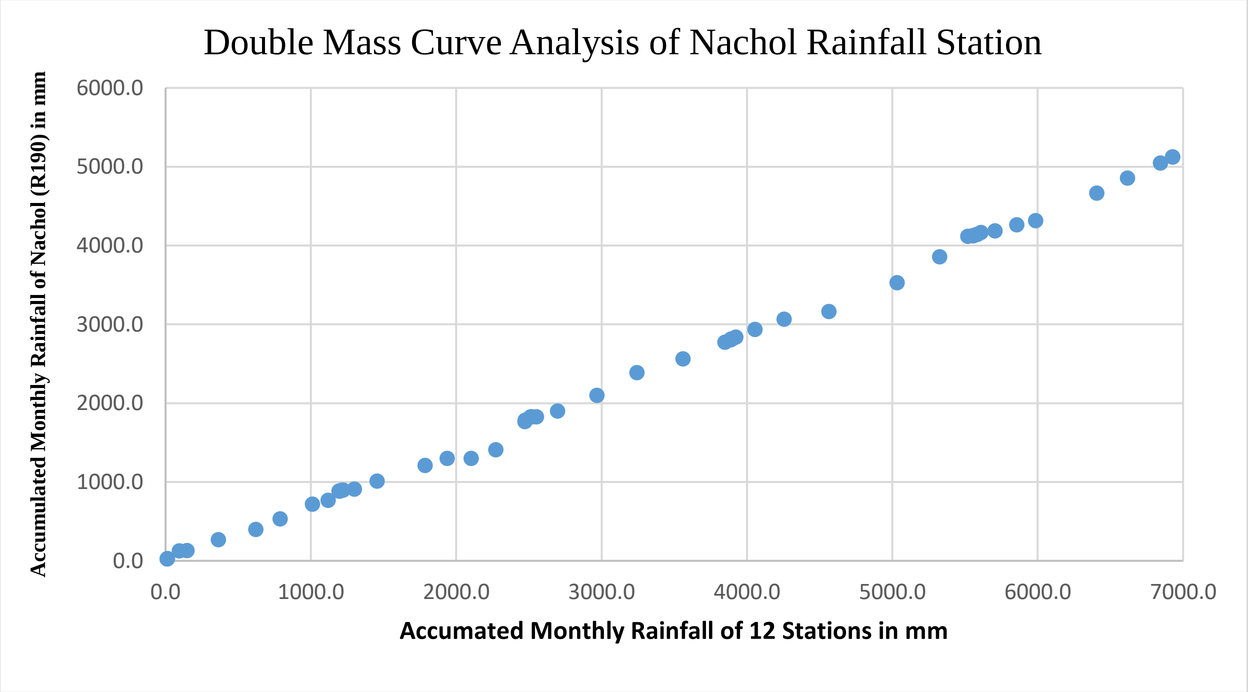

Figure A10: Double mass curve of Rainfall at R190

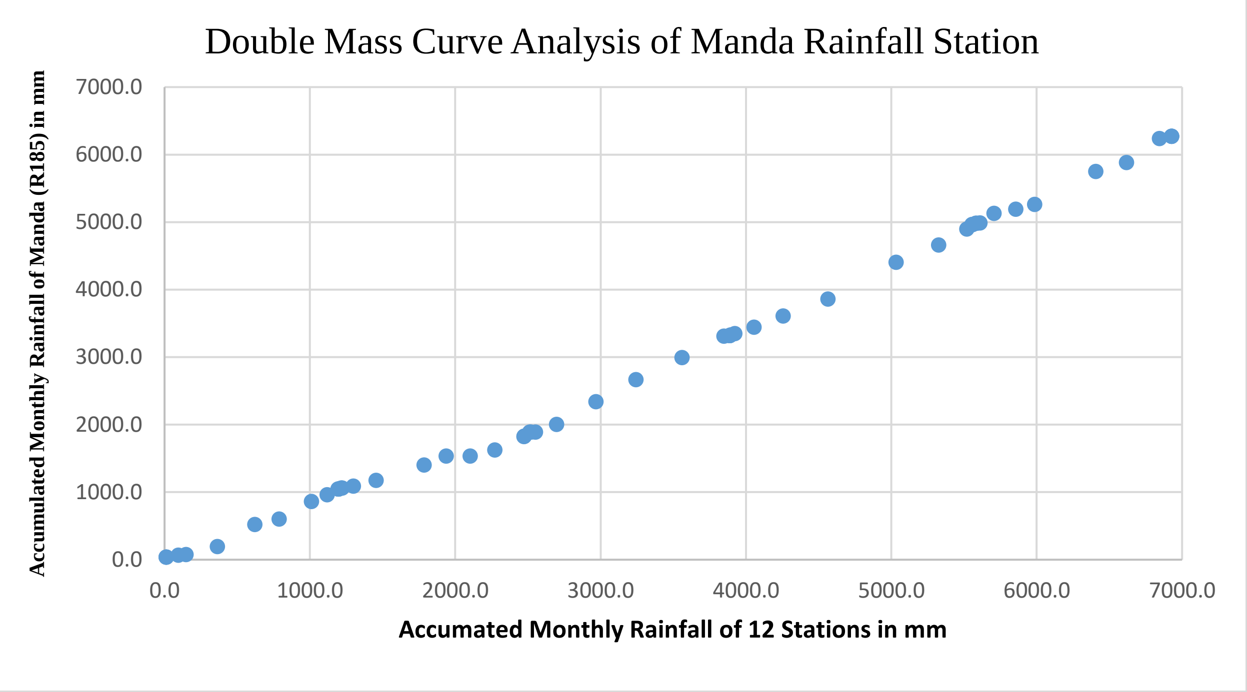

Figure A11: Double mass curve of Rainfall at R185

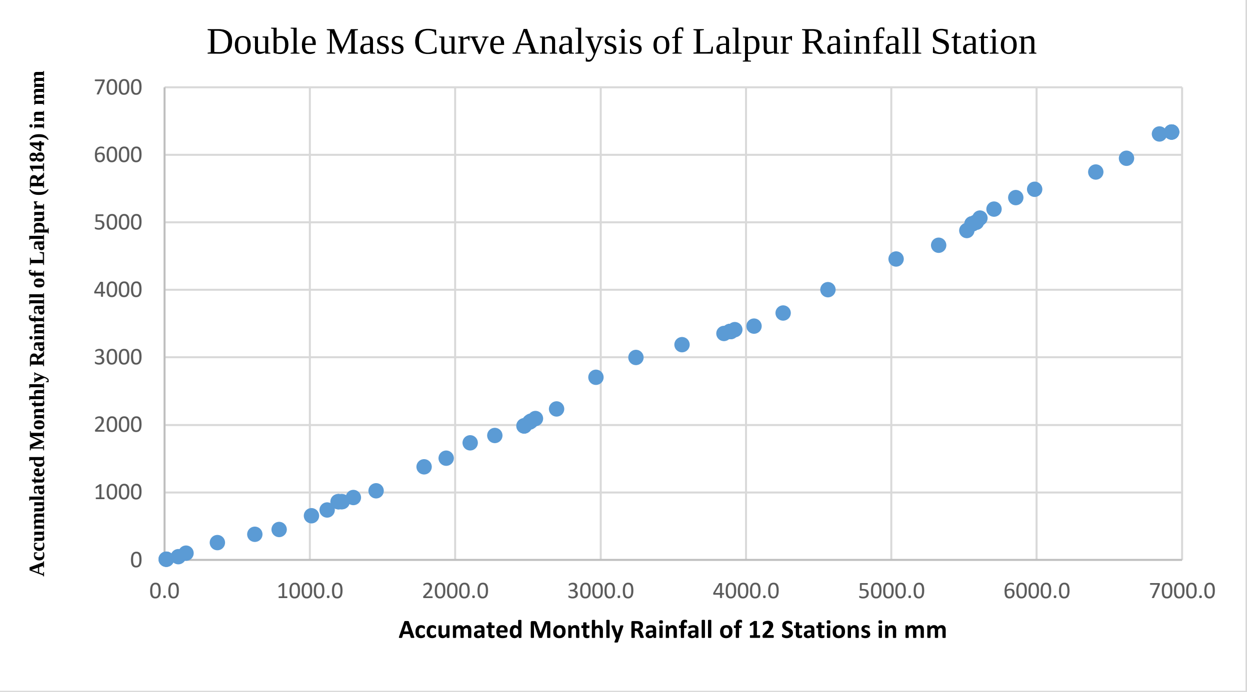

Figure A12: Double mass curve of Rainfall at R184

Appendix B: Trend Analysis of GWL for Rajshahi District

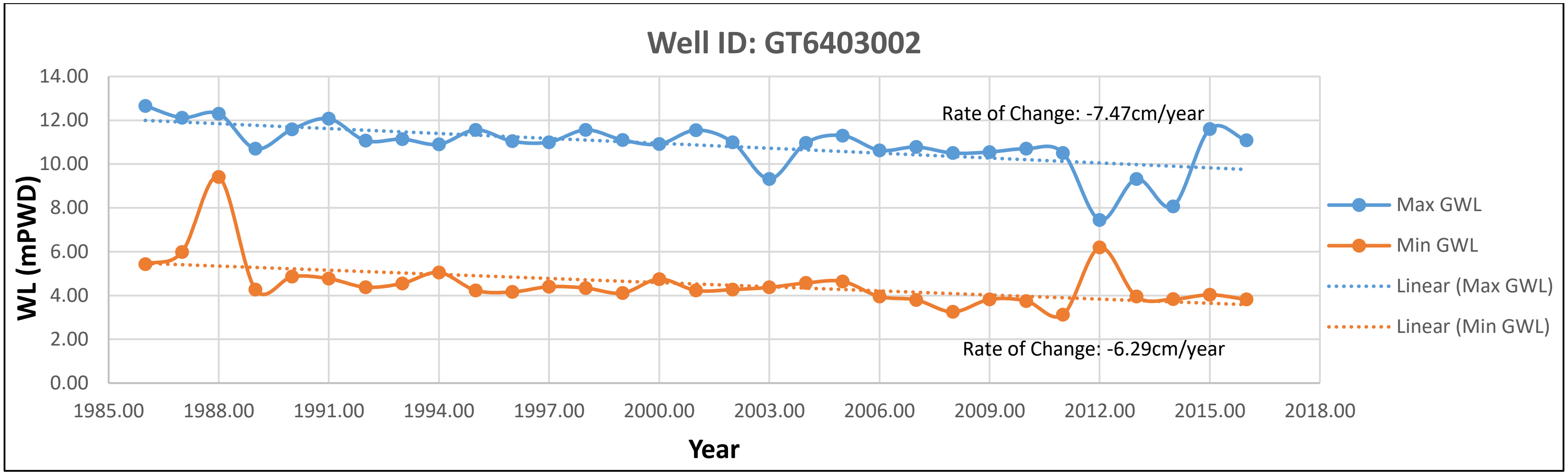

Figure B1: Rate of change of Maximum and Minimum GWL at GT6403002

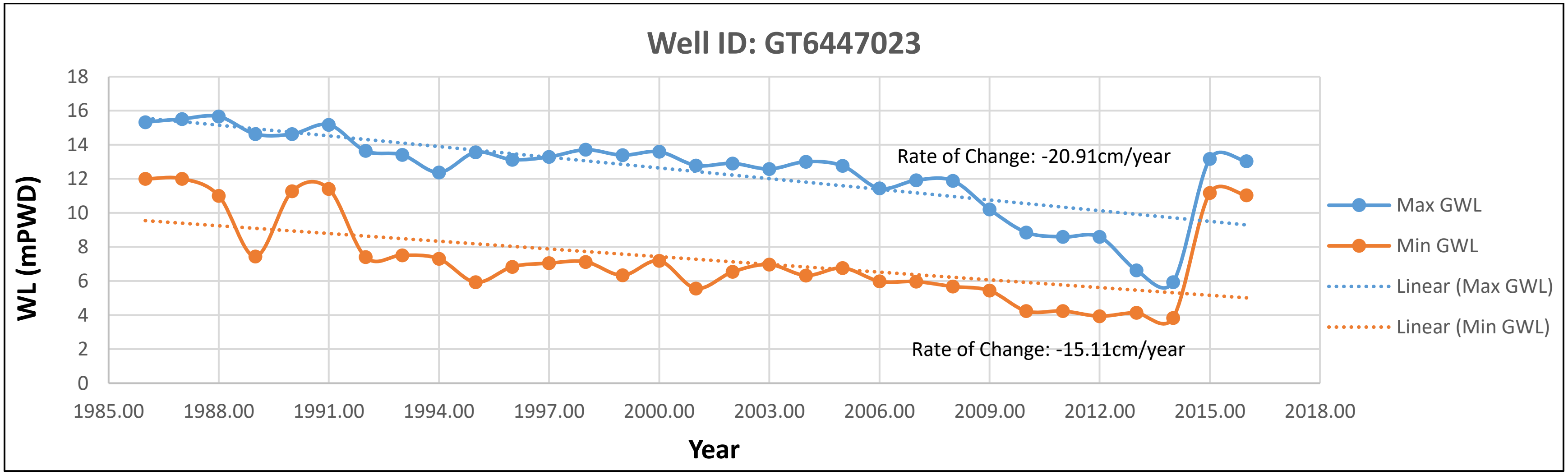

Figure B2: Rate of change of Maximum and Minimum GWL at GT6447023

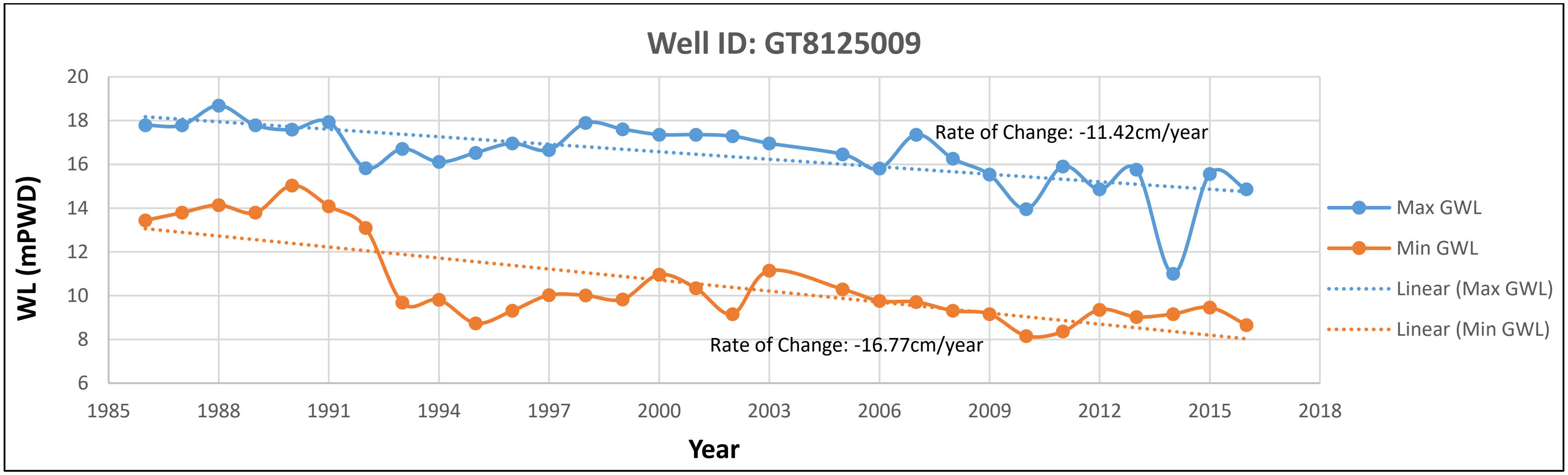

Figure B3: Rate of change of Maximum and Minimum GWL at GT8125009

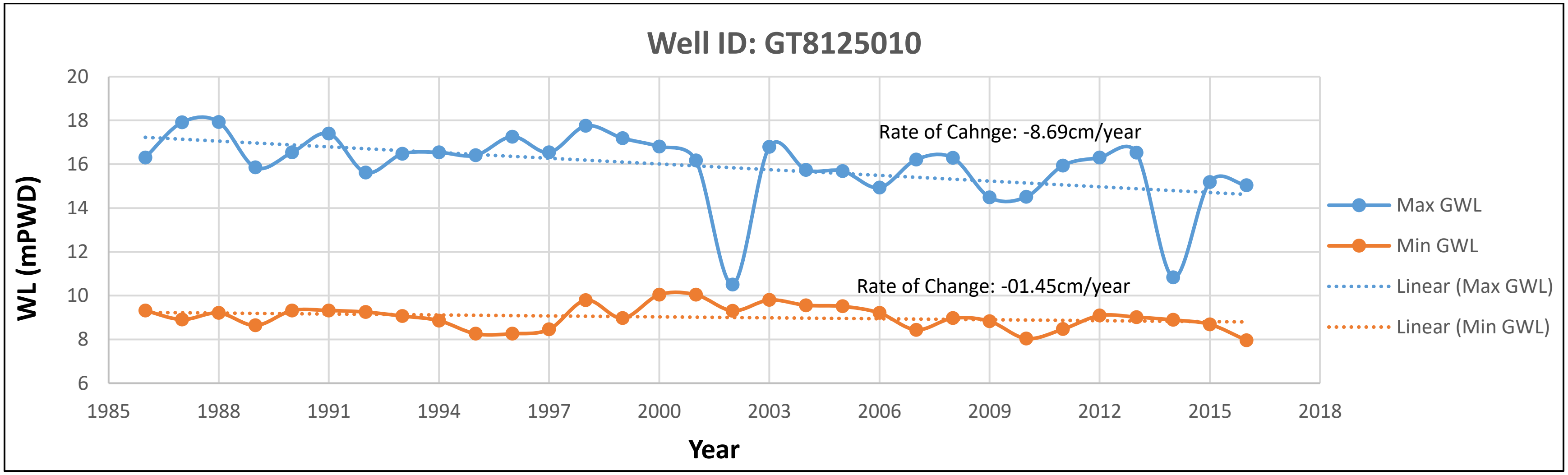

Figure B4: Rate of change of Maximum and Minimum GWL at GT8125010

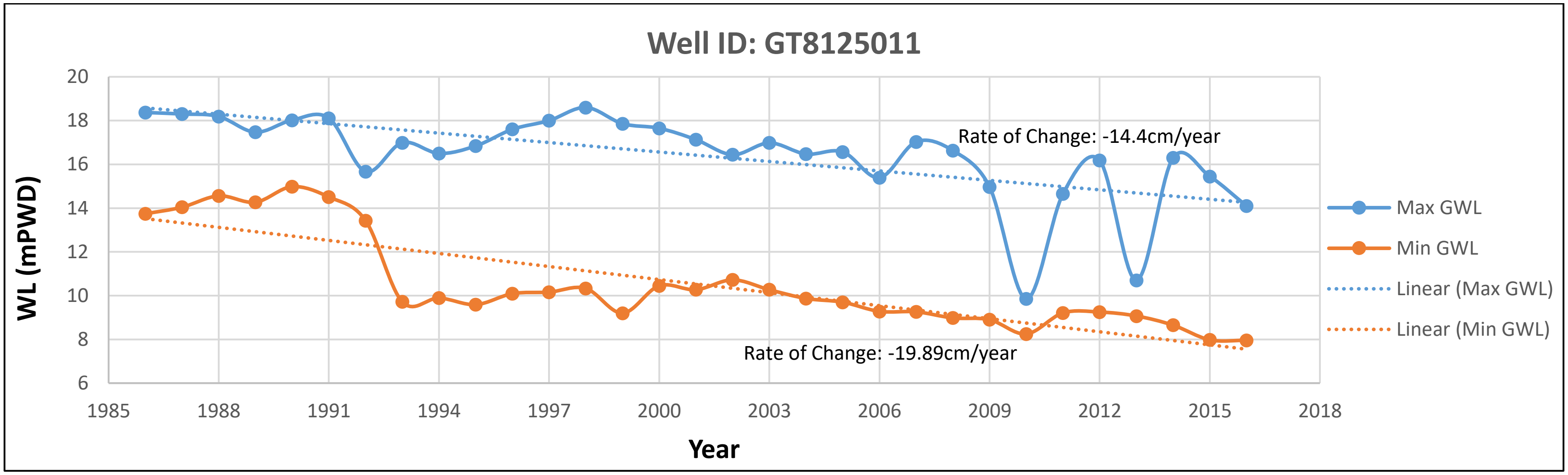

Figure B5: Rate of change of Maximum and Minimum GWL at GT8125011

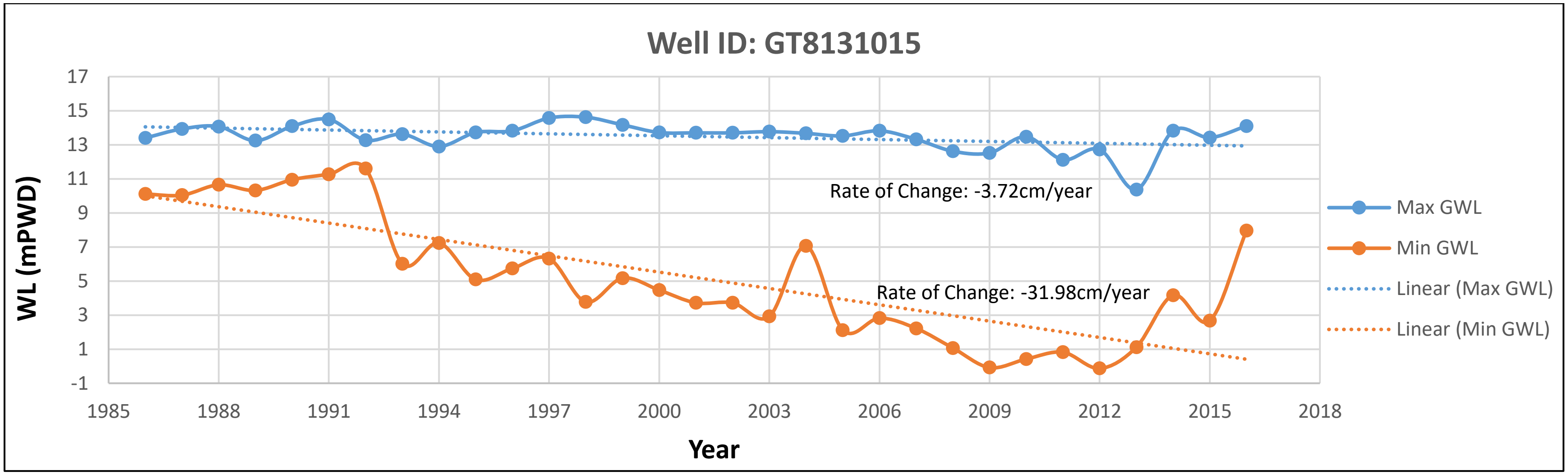

Figure B6: Rate of change of Maximum and Minimum GWL at GT8131015

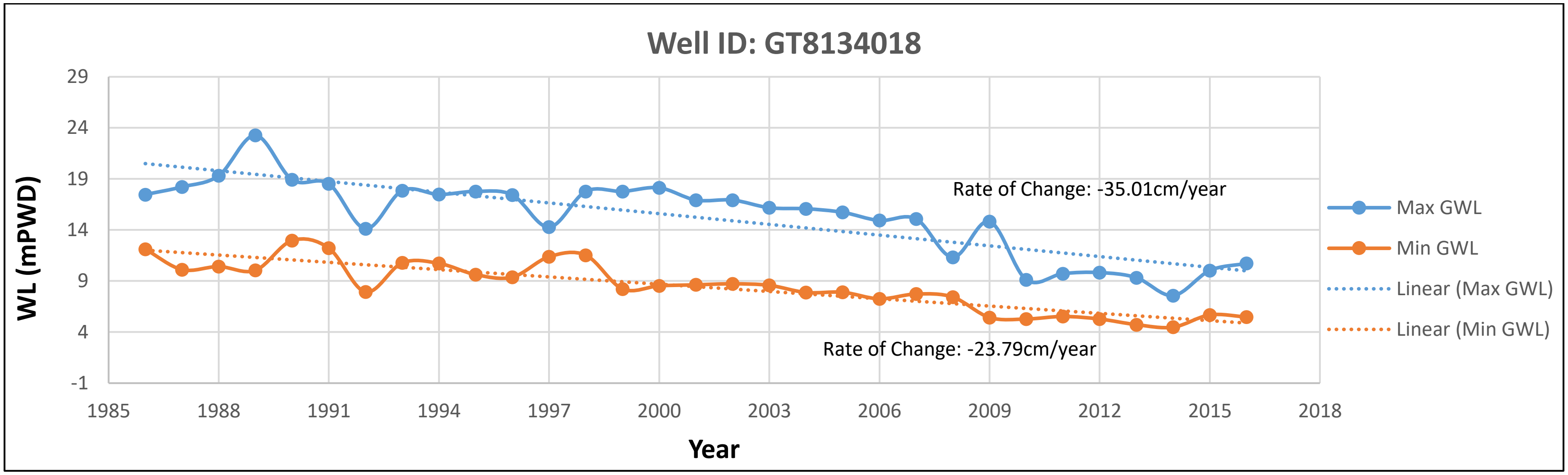

Figure B7: Rate of change of Maximum and Minimum GWL at GT8134018

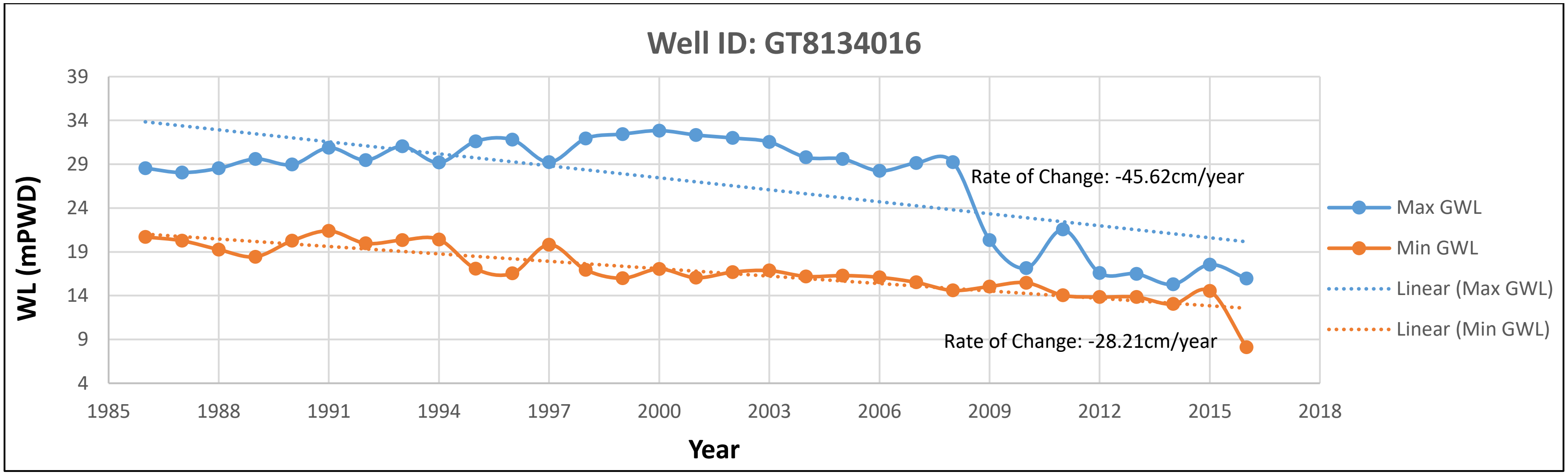

Figure B8: Rate of change of Maximum and Minimum GWL at GT8134016

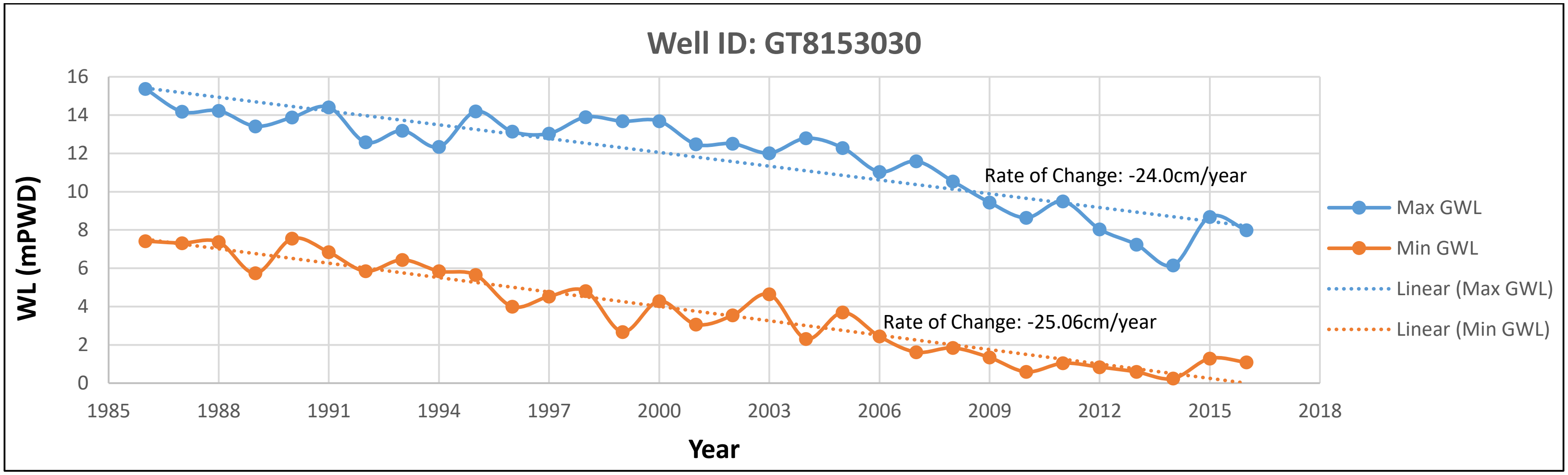

Figure B9: Rate of change of Maximum and Minimum GWL at GT8153030

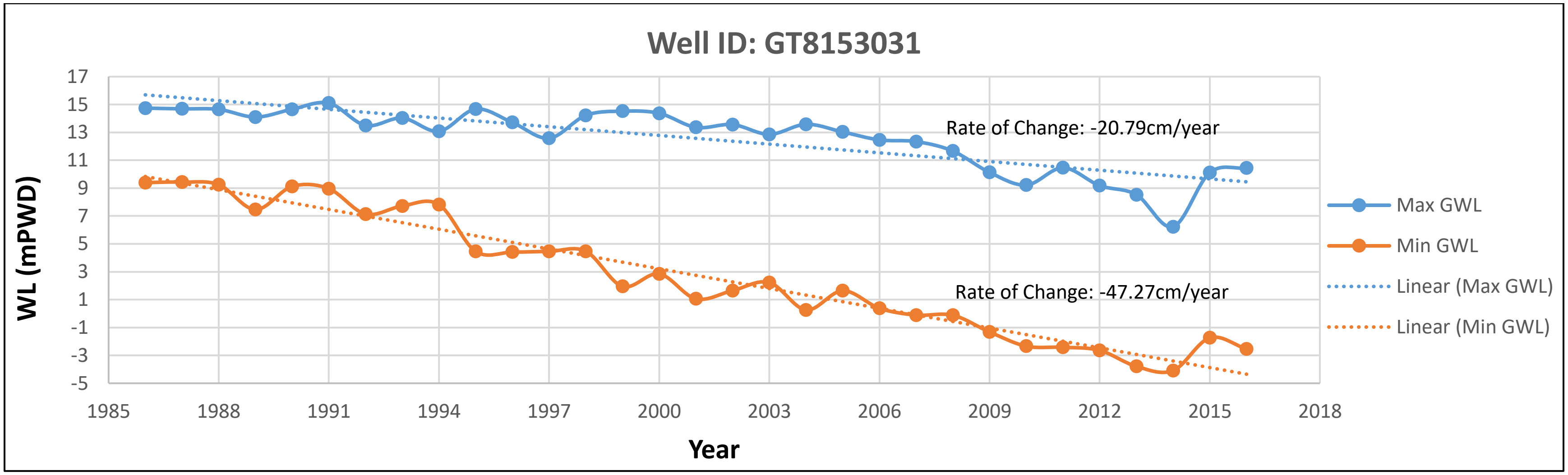

Figure B10: Rate of change of Maximum and Minimum GWL at GT8153031

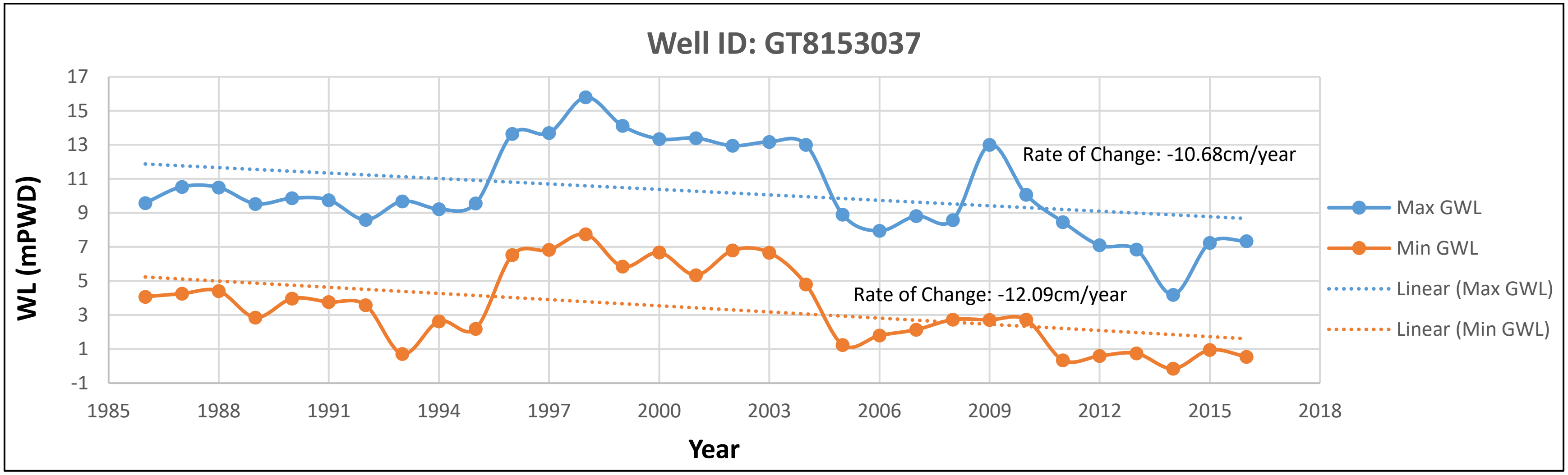

Figure B11: Rate of change of Maximum and Minimum GWL at GT8153037

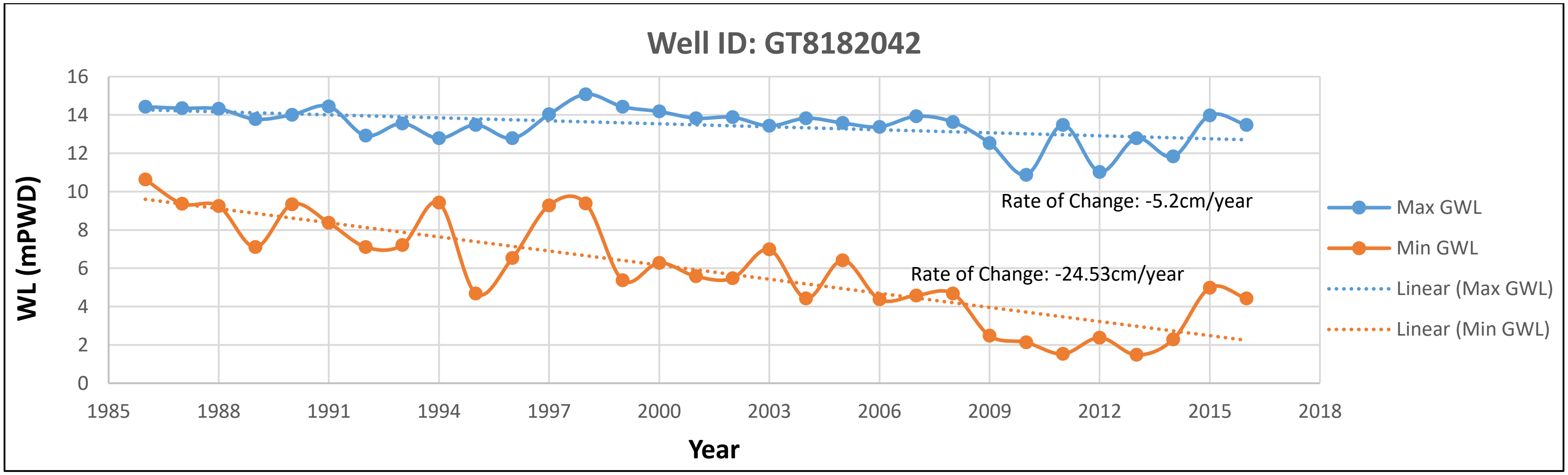

Figure B12: Rate of change of Maximum and Minimum GWL at GT8182042

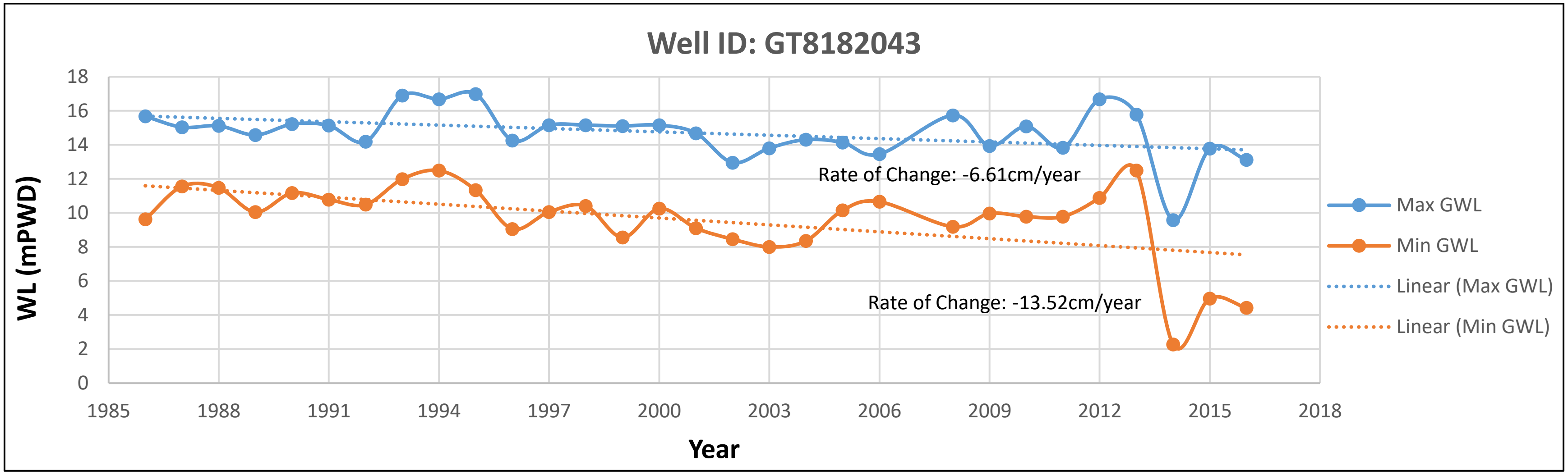

Figure B13: Rate of change of Maximum and Minimum GWL at GT8182043

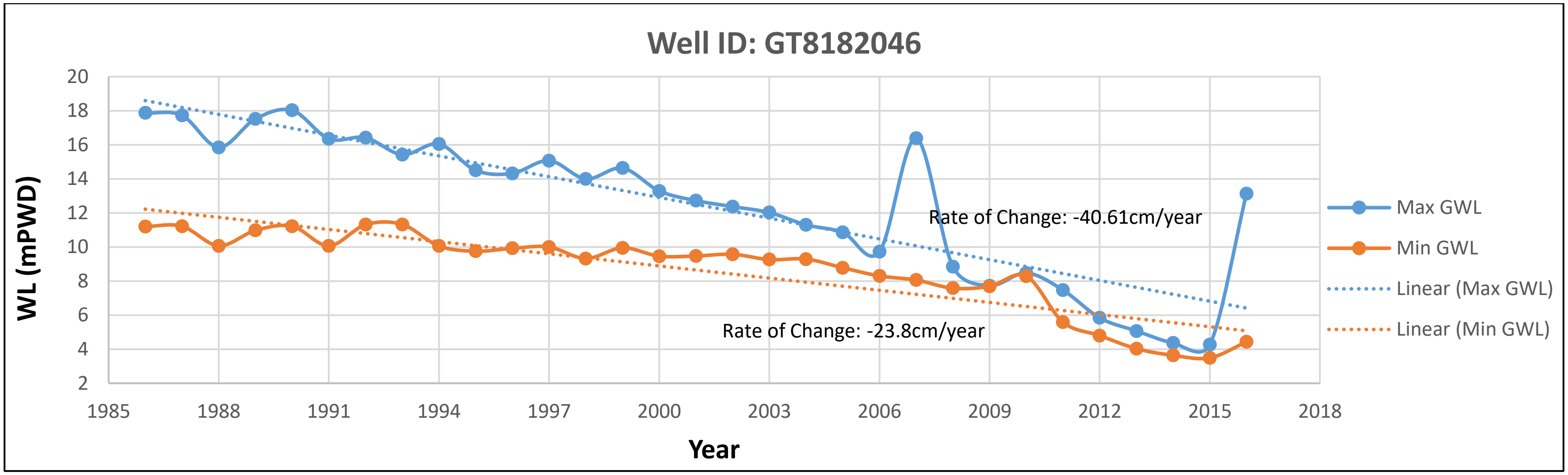

Figure B14: Rate of change of Maximum and Minimum GWL at GT8182046

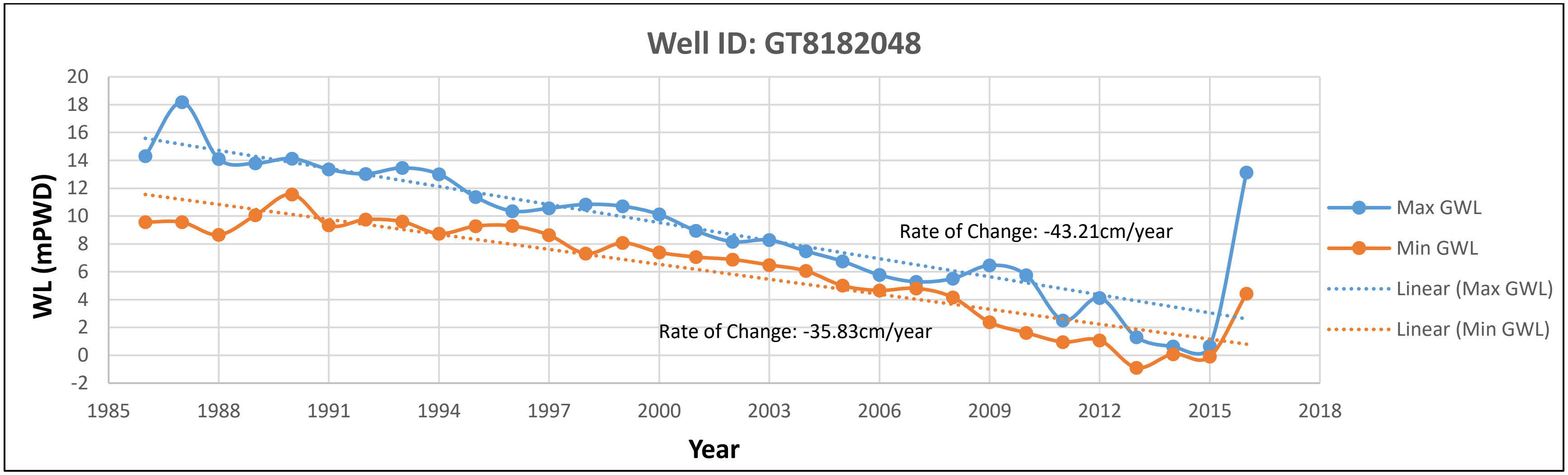

Figure B15: Rate of change of Maximum and Minimum GWL at GT8182048

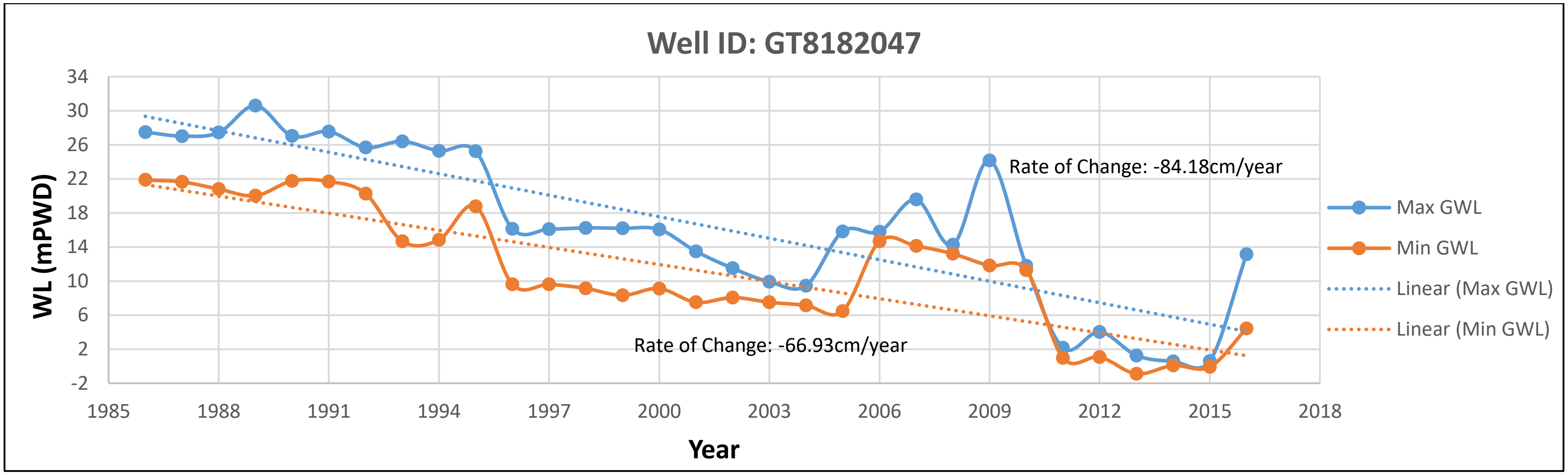

Figure B16: Rate of change of Maximum and Minimum GWL at GT8182047

Appendix C: Hydro-Stratigraphic Cross Sections

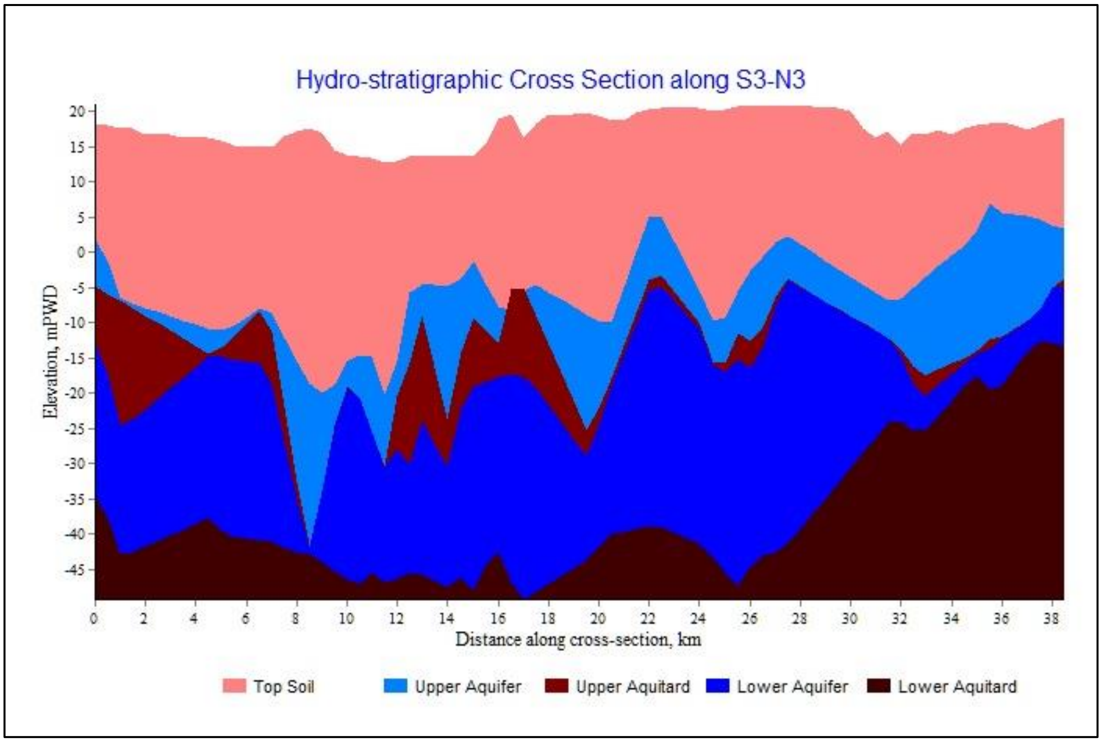

Figure C1: Hydro-stratigraphic Cross Section along S3-N3

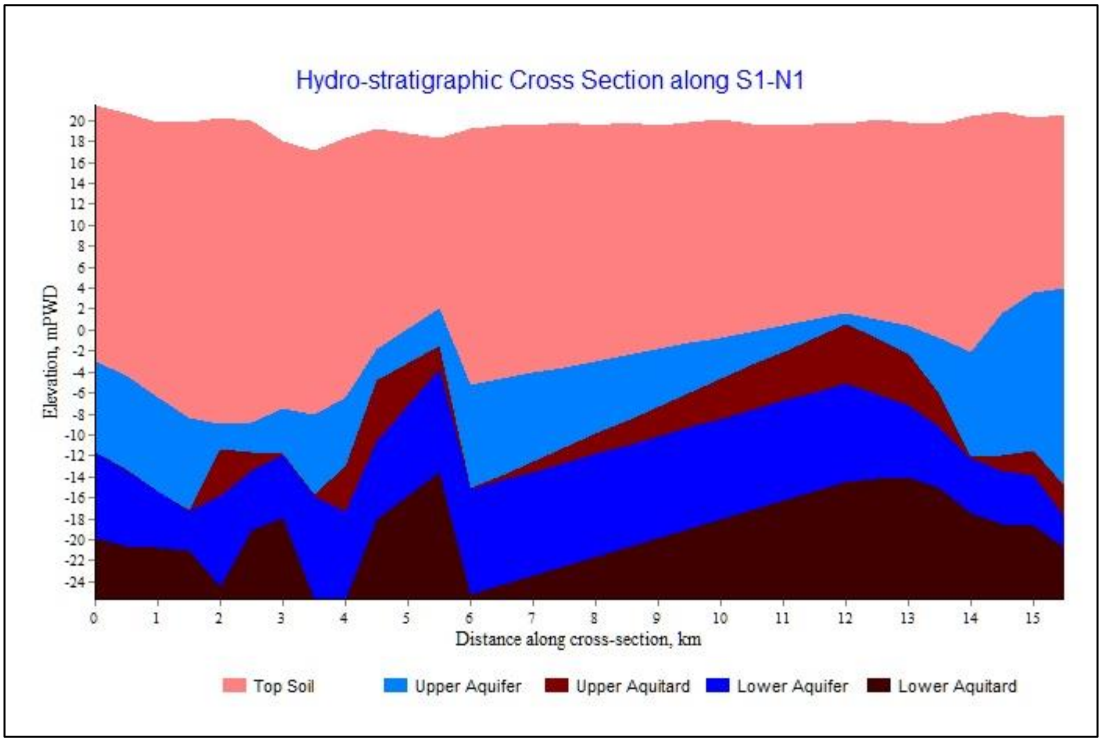

Figure C2: Hydro-stratigraphic Cross Section along S1-N1

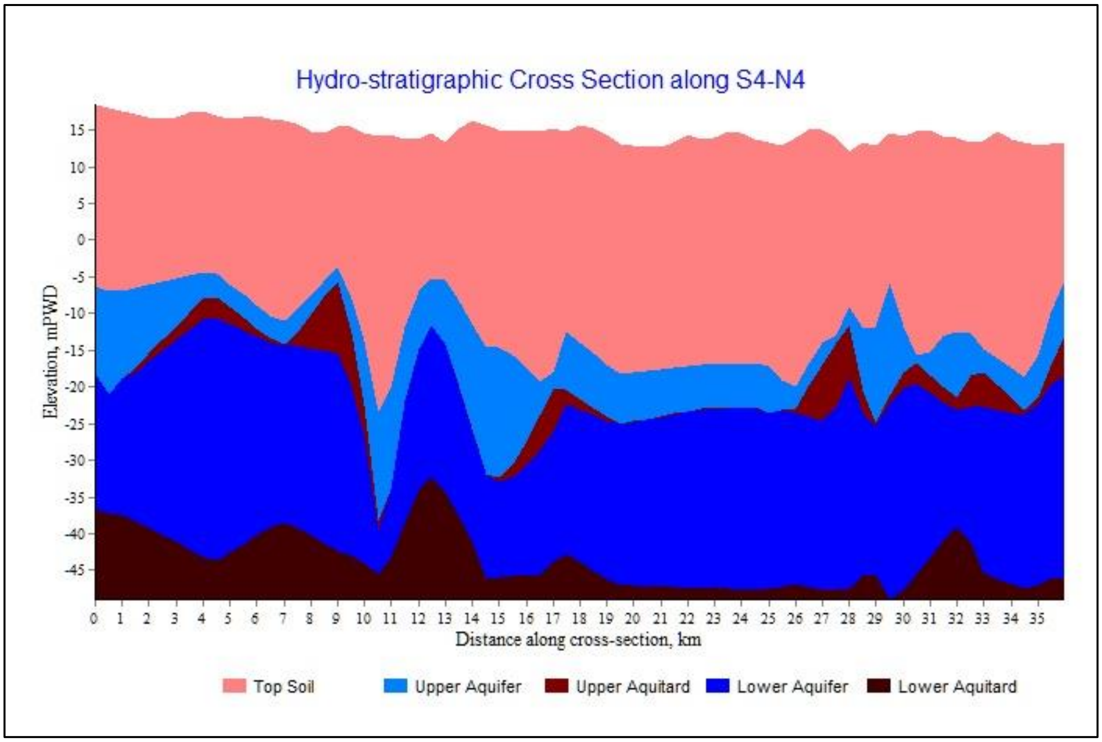

Figure C3: Hydro-stratigraphic Cross Section along S4-N4

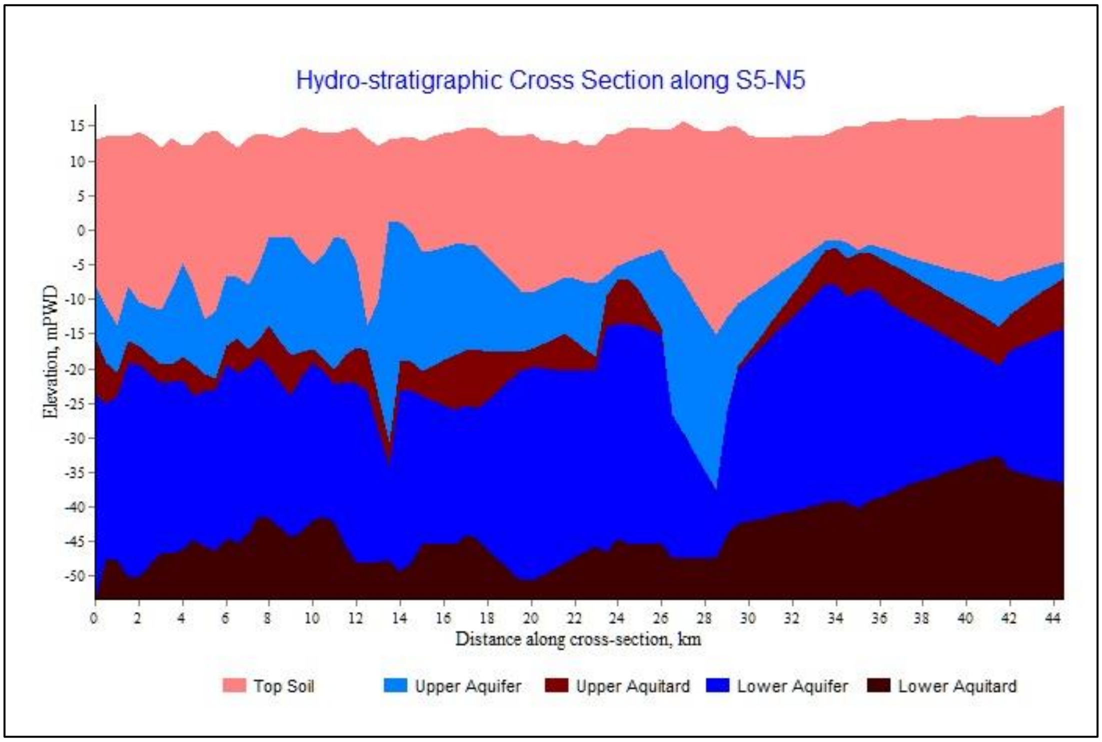

Figure C4: Hydro-stratigraphic Cross Section along S5-N5

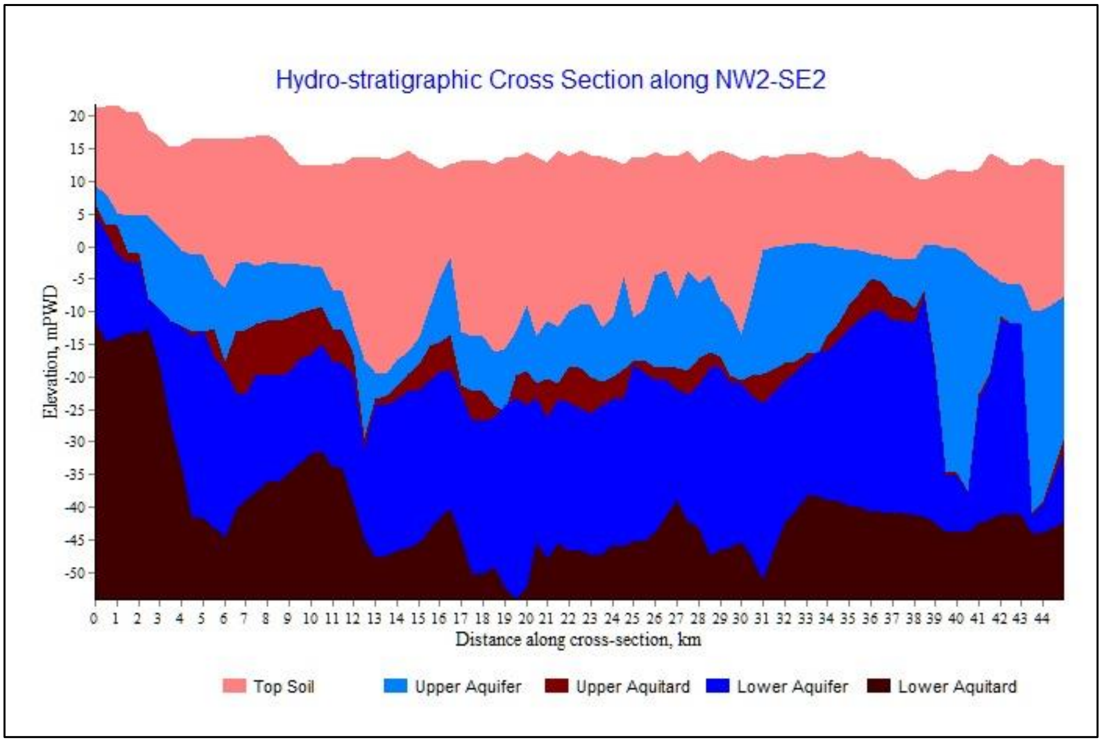

Figure C5: Hydro-stratigraphic Cross Section along NW2-SE2

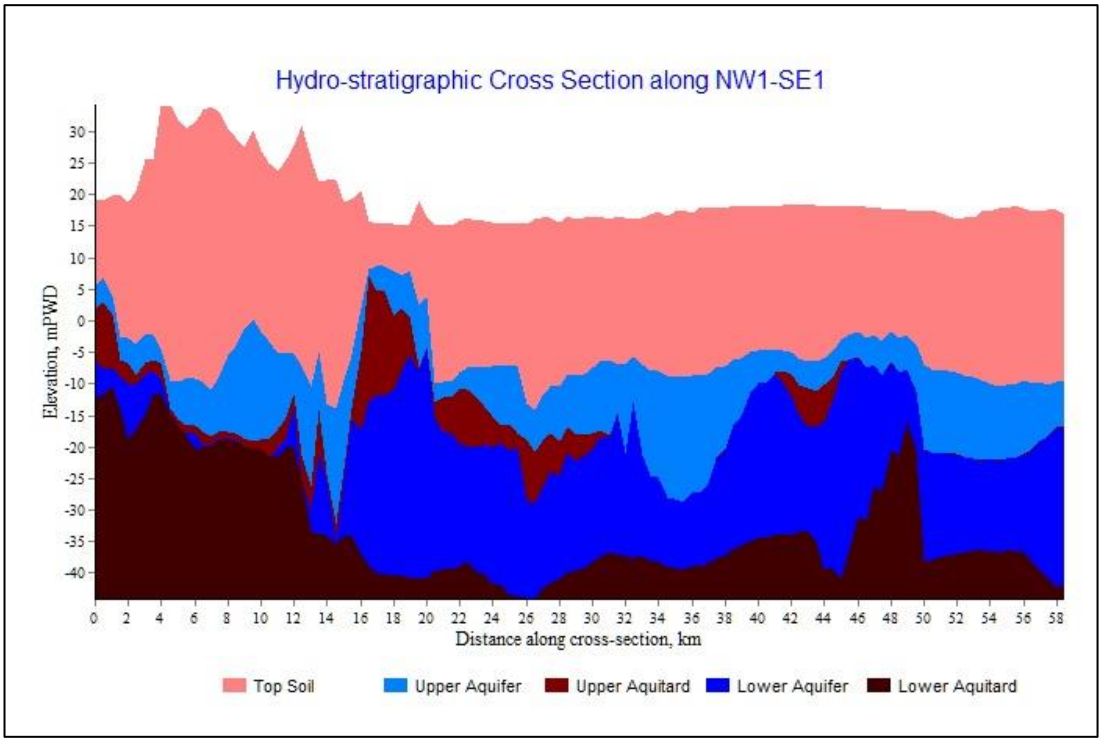

Figure C6: Hydro-stratigraphic Cross Section along NW1-SE1

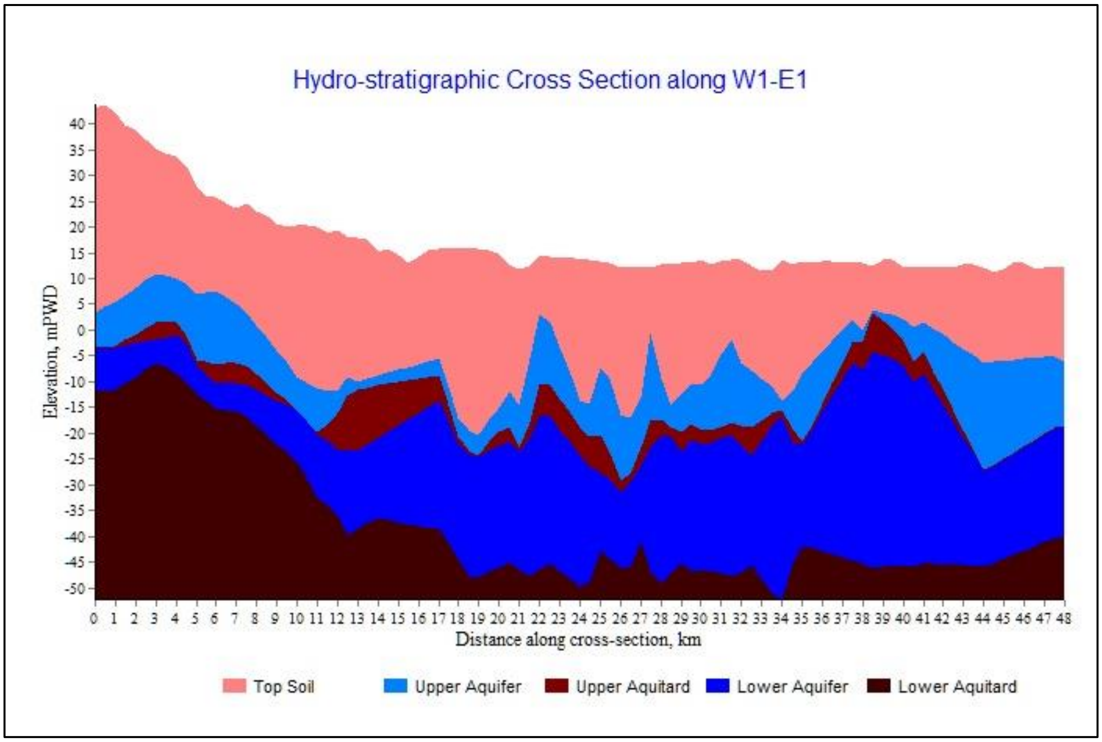

Figure C7: Hydro-stratigraphic Cross Section along W1-E1

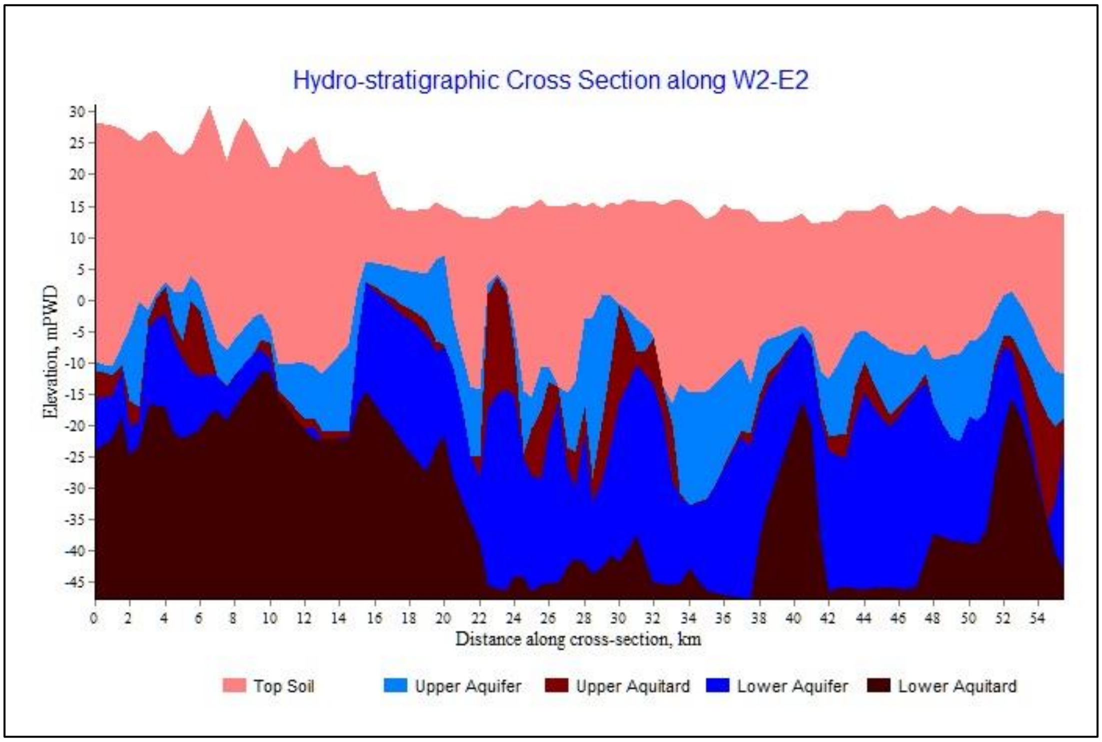

Figure C8: Hydro-stratigraphic Cross Section along W2-E2

Appendix D: Calibration and Validation of SW & GW Models

Calibration and Validation of GW model

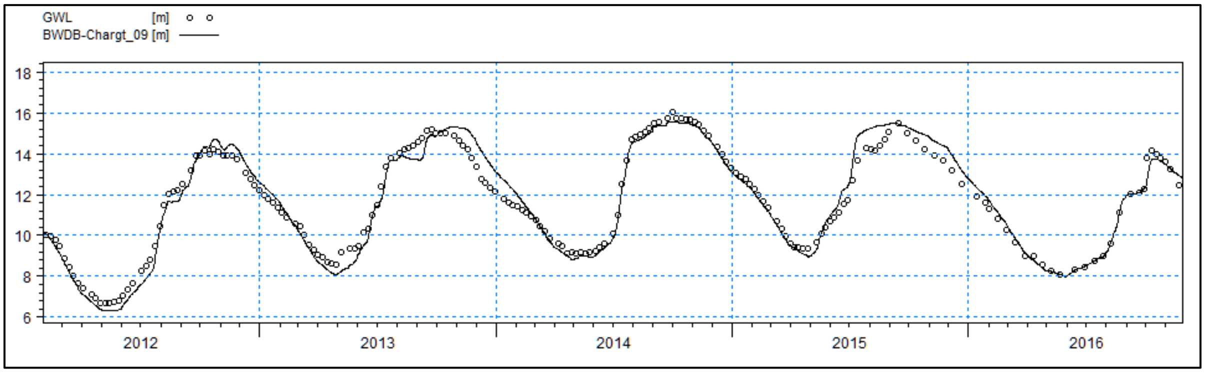

Figure D1: Calibration and Validation of GW model for GWL of Station ID GT 8125009

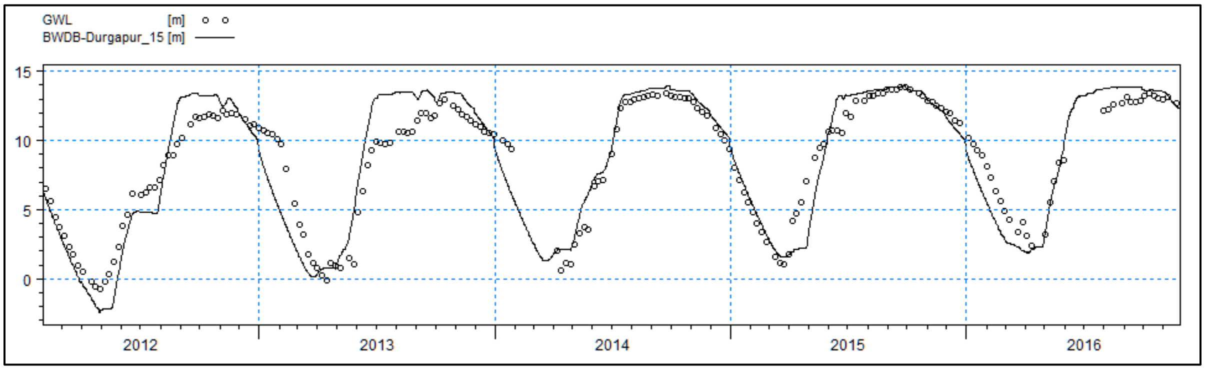

Figure D2: Calibration and Validation of GW model for GWL of Station ID GT 8131015

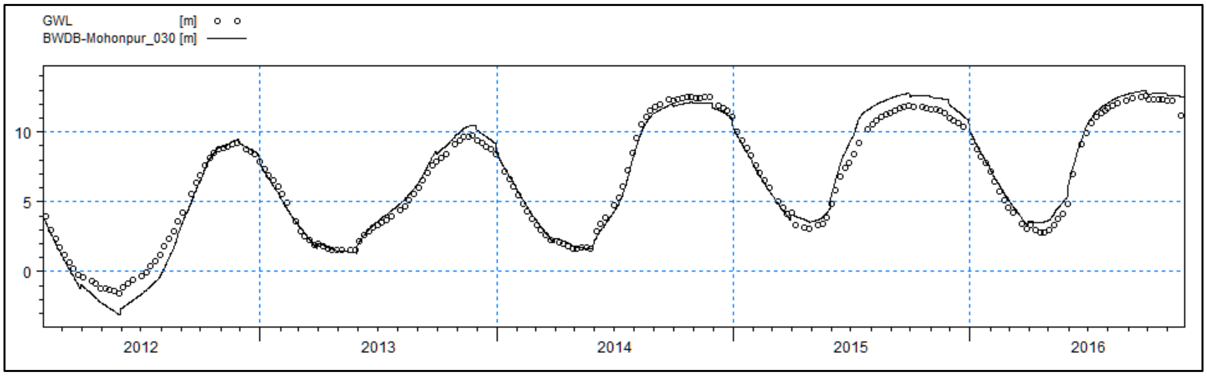

Figure D3: Calibration and Validation of GW model for GWL of Station ID GT 8153030

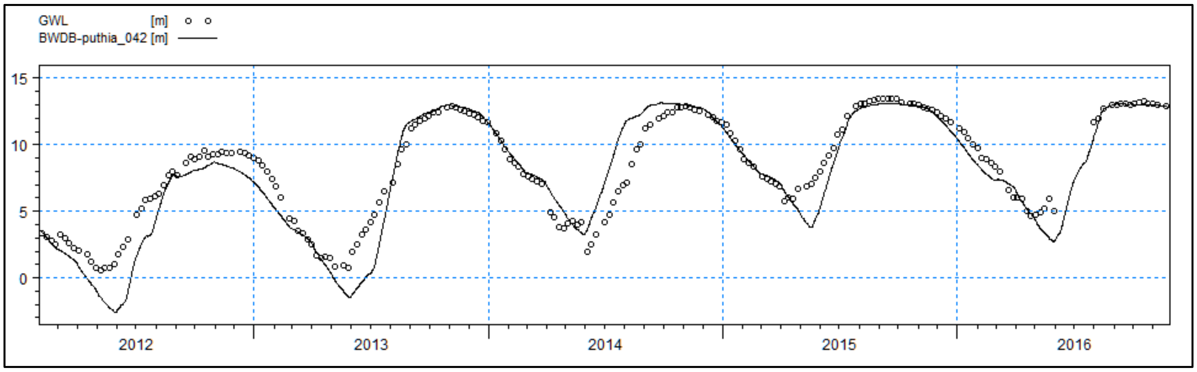

Figure D4: Calibration and Validation of GW model for GWL of Station ID GT 8182042

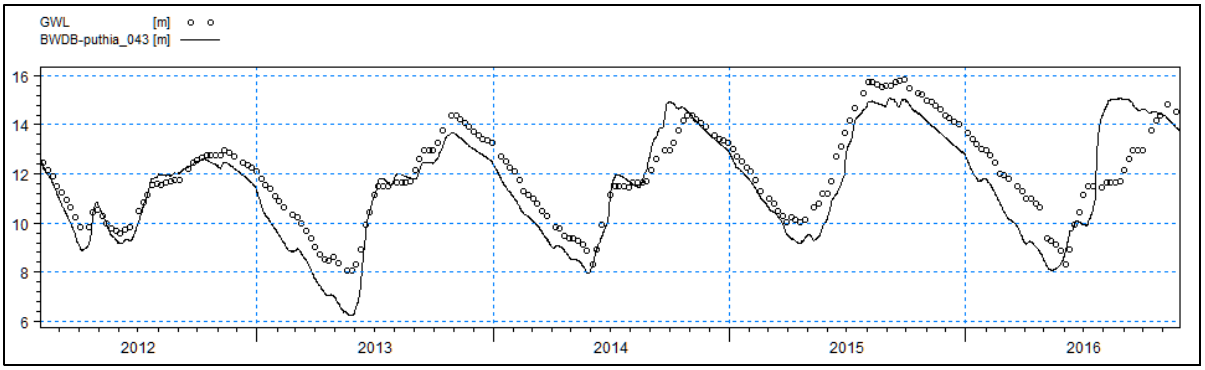

Figure D5: Calibration and Validation of GW model for GWL of Station ID GT 8182043

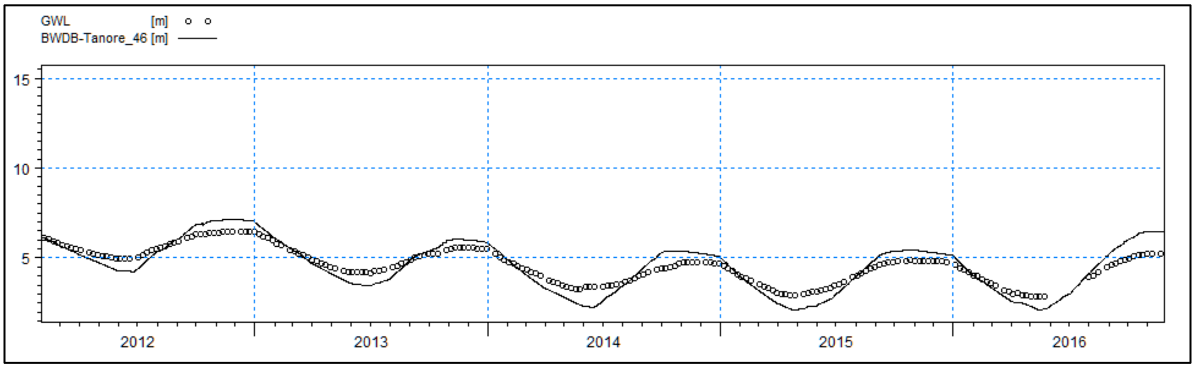

Figure D6: Calibration and Validation of GW model for GWL of Station ID GT 8194046

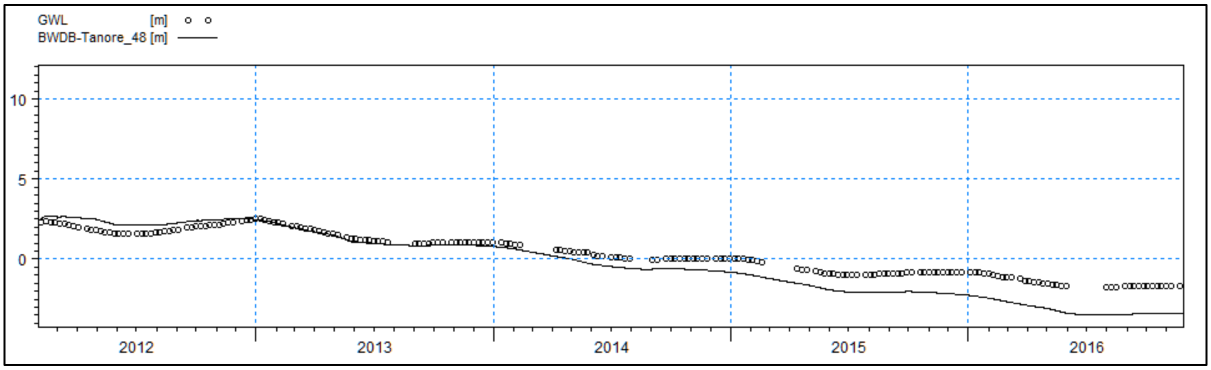

Figure D7: Calibration and Validation of GW model for GWL of Station ID GT 8194048

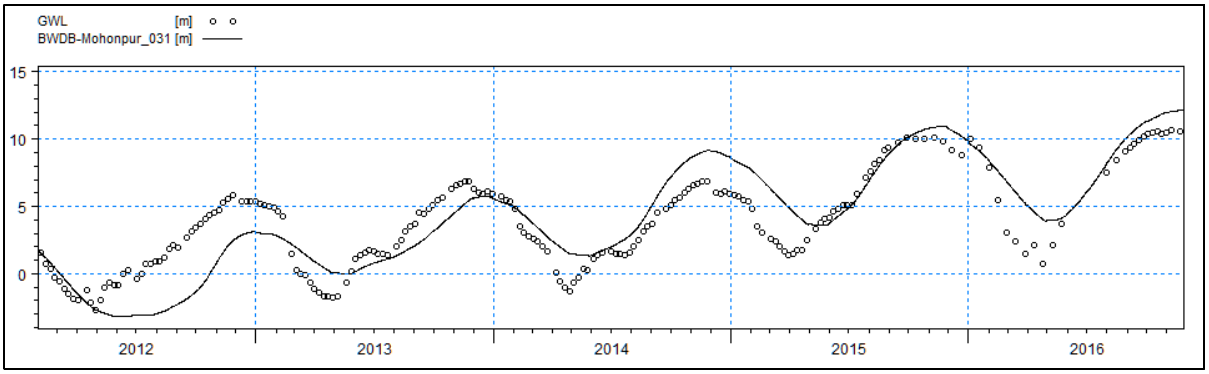

Figure D8: Calibration and Validation of GW model for GWL of Station ID GT 8153031

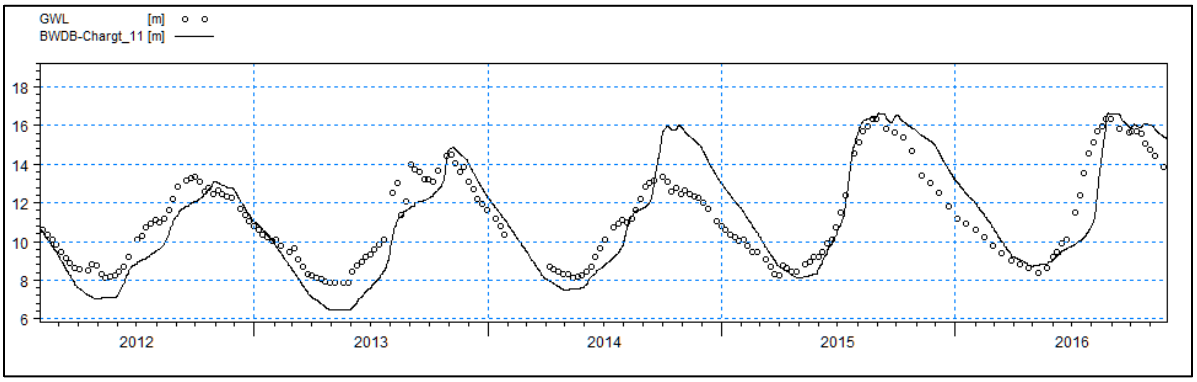

Figure D9: Calibration and Validation of GW model for GWL of Station ID GT 8125011

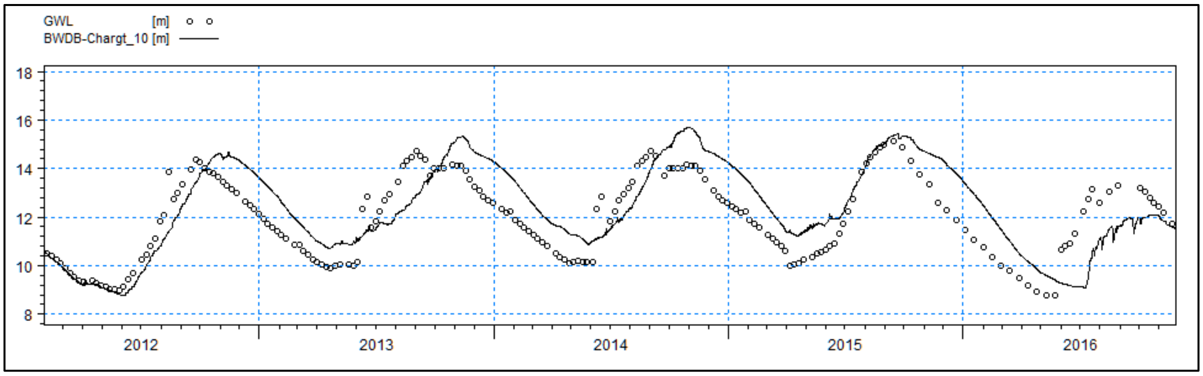

Figure D10: Calibration and Validation of GW model for GWL of Station ID GT 8125010

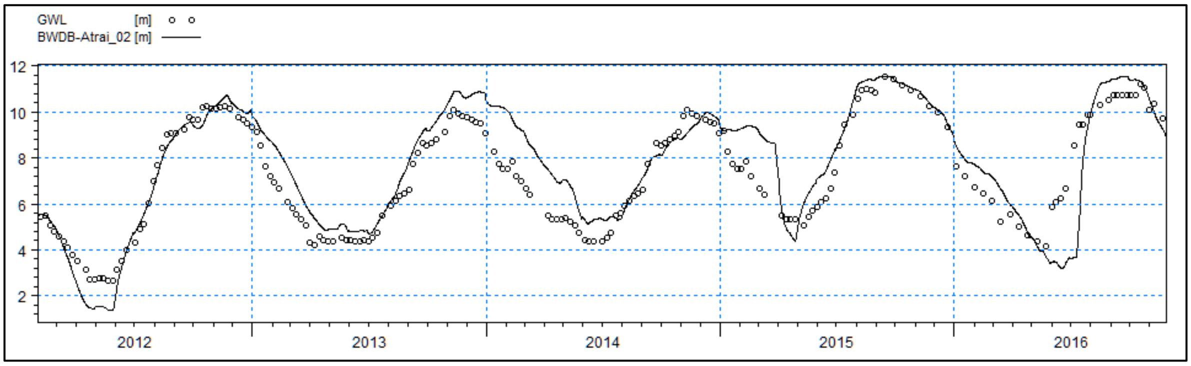

Figure D11: Calibration and Validation of GW model for GWL of Station ID GT 6403002

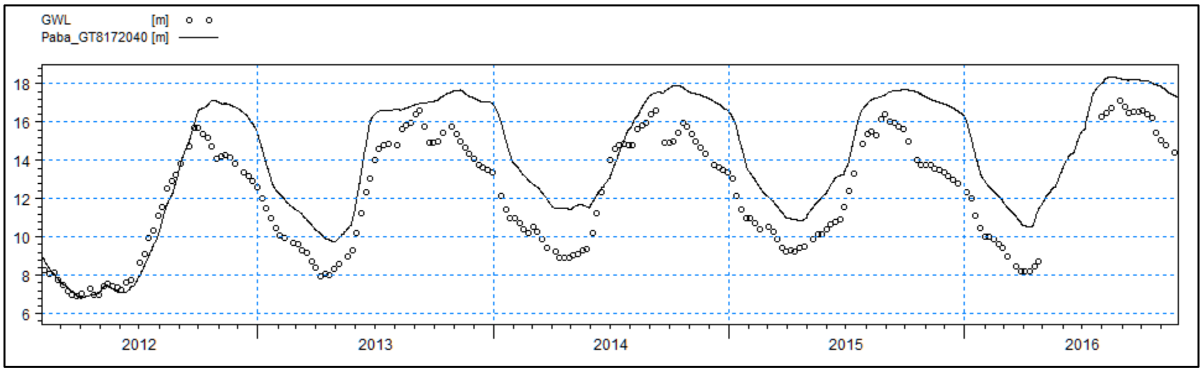

Figure D12: Calibration and Validation of GW model for GWL of Station ID GT 8172040

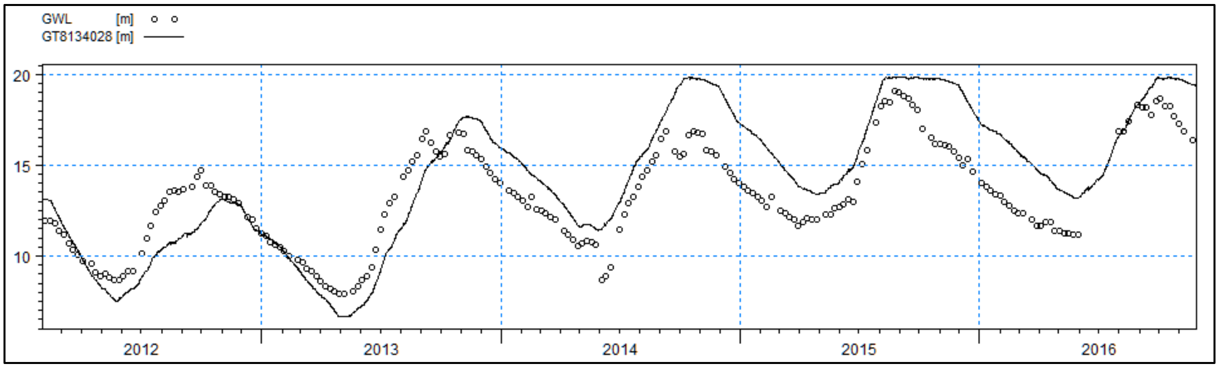

Figure D13: Calibration and Validation of GW model for GWL of Station ID GT 8134028

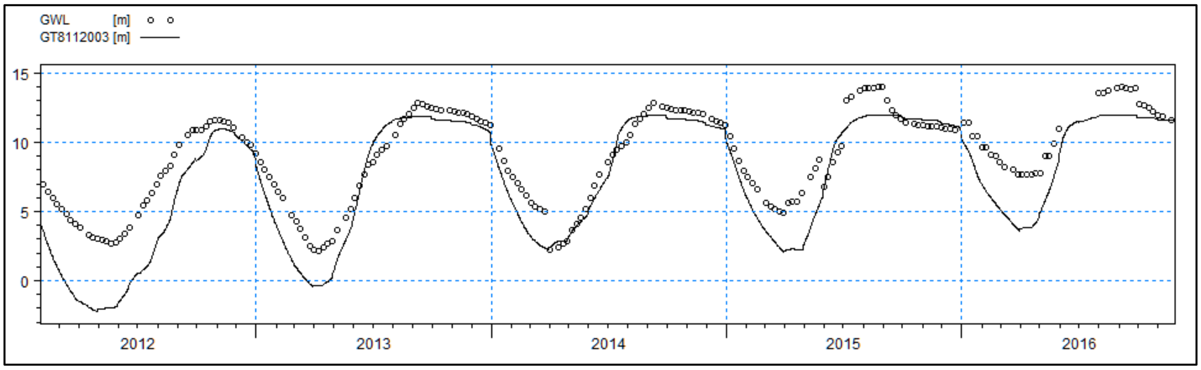

Figure D14: Calibration and Validation of GW model for GWL of Station ID GT 8134028

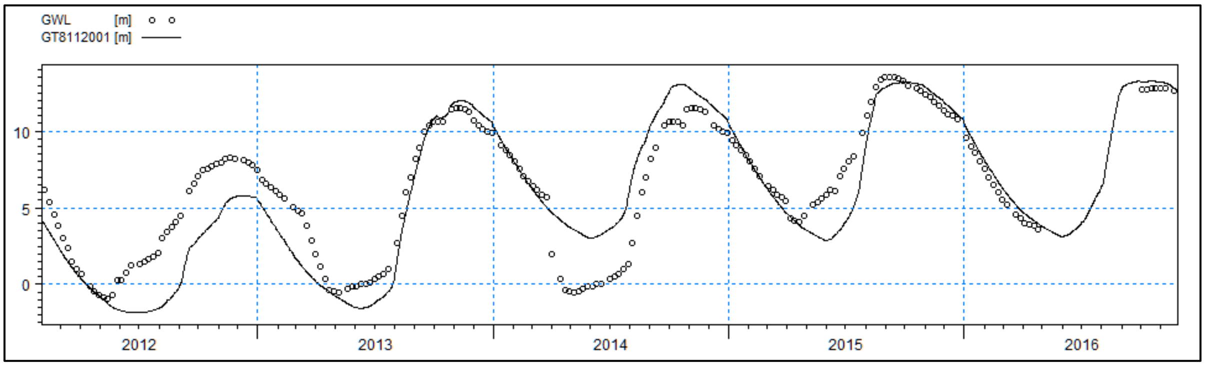

Figure D15: Calibration and Validation of GW model for GWL of Station ID GT 8112001

Calibration and Validation of SW model

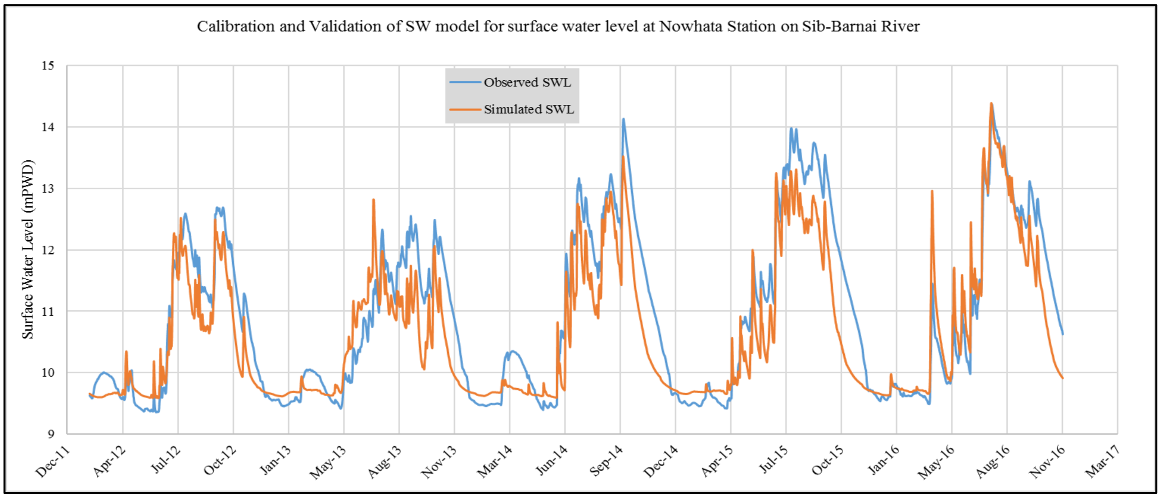

Figure D16: Calibration and Validation of SW model for SWL of Nowhata Station

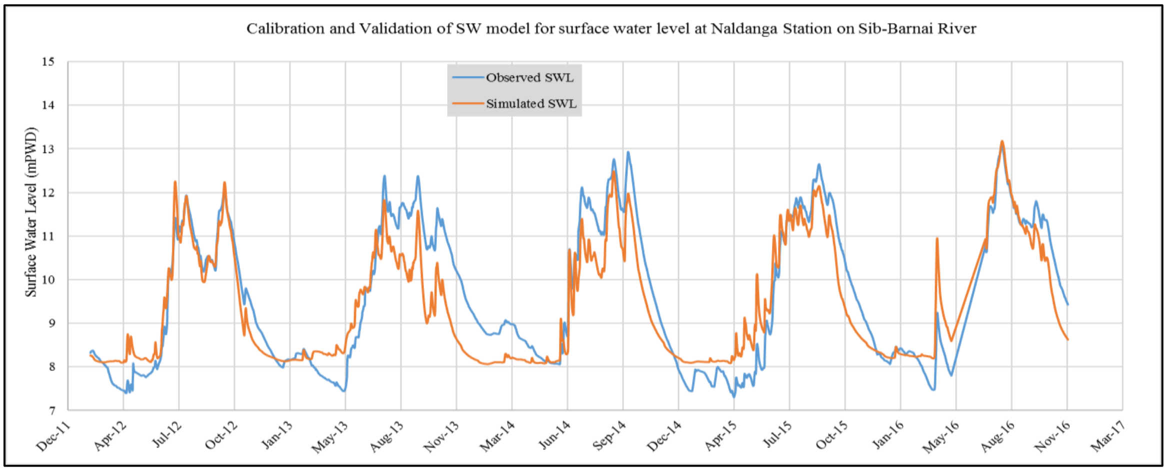

Figure D17: Calibration and Validation of SW model for SWL of Naldanga Station

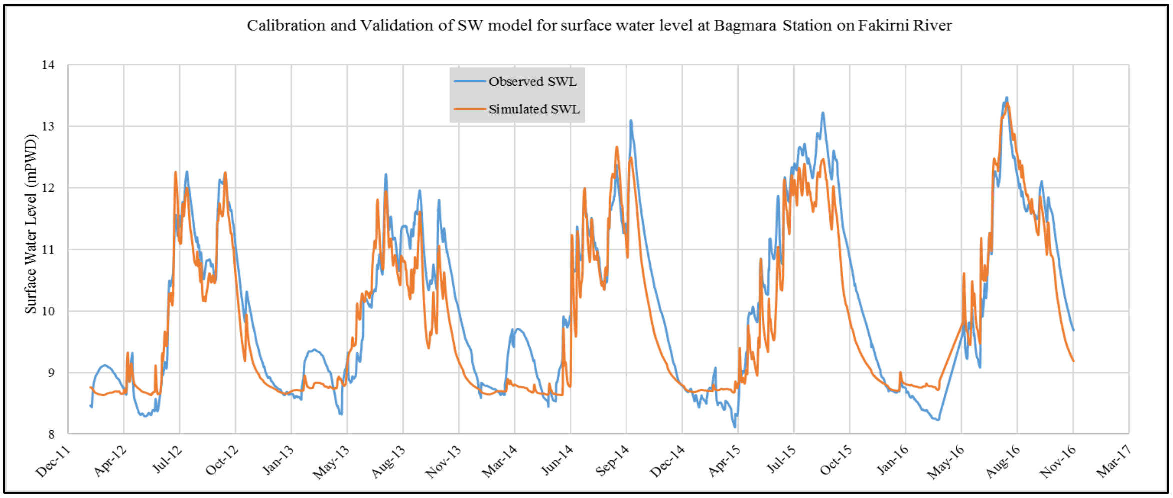

Figure D18: Calibration and Validation of SW model for SWL of Bagmara Station

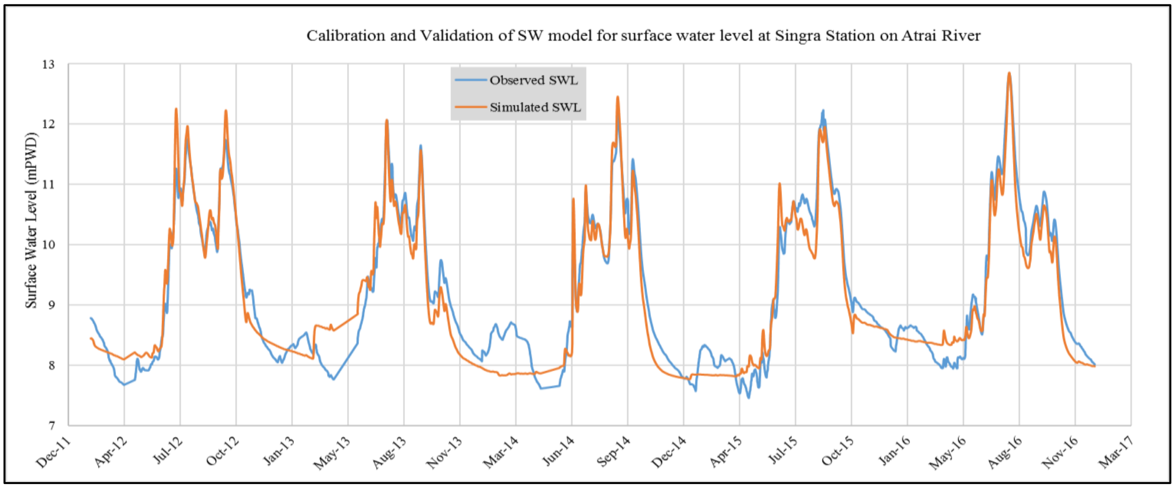

Figure D19: Calibration and Validation of SW model for SWL of Singra Station

Appendix E: Annual Maximum and Minimum GWL for Rajshahi District for the Period of 2012 to 2030

Table E-1: Annual Maximum and Minimum GWL for the Study Period (2012-2030) for GW Stations of BWDB within the Model Area

	Max. GWL (mPWD)	Min. GWL (mPWD)	Max. GWL (mPWD)	Min. GWL (mPWD)
Year	GT6403002		GT8125011	
2012	10.779	1.277	12.581	5.617
2013	11.133	4.251	14.431	4.566
2014	10.648	4.444	15.950	5.704
2015	11.302	4.825	16.589	6.514
2016	11.292	2.825	15.990	6.636
2017	11.431	6.800	16.588	7.061
2018	11.455	6.661	16.589	7.219
2019	11.376	6.553	16.589	7.108
2020	11.385	6.600	16.589	6.936
2021	11.405	6.453	16.589	6.715
2022	11.459	6.637	16.589	6.558
2023	11.470	6.613	16.589	6.441
2024	11.475	6.505	16.589	6.171
2025	11.497	6.418	16.589	6.077
2026	11.527	6.349	16.589	6.061
2027	11.529	6.343	16.587	6.057
2028	11.525	6.349	16.589	6.031
2029	11.511	6.345	16.589	6.054
2030	11.346	6.356	16.589	6.064
Year	GT8125010		GT8125006	
2012	14.344	8.629	12.104	4.452
2013	14.932	10.289	13.801	7.037
2014	15.099	10.261	14.549	7.666
2015	14.920	10.698	14.678	8.294
2016	14.419	10.247	14.579	9.026
2017	14.963	11.503	14.660	9.598
2018	15.156	11.619	14.666	9.603
2019	15.178	11.449	14.659	9.502
2020	15.179	11.269	14.641	9.350
2021	15.243	11.079	14.631	9.251
2022	15.293	10.917	14.626	9.111
2023	15.419	10.842	14.626	8.991
2024	15.458	10.834	14.618	8.809
2025	15.523	10.762	14.615	8.748
2026	15.445	10.626	14.616	8.668
2027	15.508	10.547	14.608	8.632
2028	15.596	10.519	14.605	8.544
2029	15.667	10.539	14.605	8.526
2030	15.712	10.563	14.603	8.425
Year	GT8125009		GT8131015	
2012	14.501	4.975	13.354	-3.524
2013	15.279	6.664	13.525	-1.328

	Max. GWL (mPWD)	Min. GWL (mPWD)	Max. GWL (mPWD)	Min. GWL (mPWD)
2014	15.555	7.576	13.859	0.089
2015	15.530	7.796	13.869	0.387
2016	15.449	8.497	13.834	4.706
2017	15.426	9.531	14.026	5.649
2018	15.486	9.537	14.028	6.090
2019	15.429	9.451	14.021	5.887
2020	15.430	9.383	14.027	5.795
2021	15.429	9.267	14.023	5.740
2022	15.419	9.197	14.029	5.566
2023	15.476	9.097	14.027	5.503
2024	15.419	8.962	14.013	5.353
2025	15.419	8.940	14.008	5.188
2026	15.471	8.917	13.992	4.985
2027	15.420	8.909	13.989	4.802
2028	15.477	8.879	13.987	4.745
2029	15.477	8.886	13.880	4.530
2030	15.421	8.874	13.875	4.434
Year	GT8134016		GT8134018	
2012	15.510	6.803	13.831	3.146
2013	23.381	9.019	16.299	7.933
2014	29.042	14.296	16.621	9.443
2015	32.083	18.043	16.489	9.387
2016	32.039	26.110	16.612	11.557
2017	32.069	26.873	16.916	12.797
2018	32.067	26.728	16.916	12.969
2019	32.075	26.618	16.902	12.932
2020	32.068	26.516	16.863	12.843
2021	32.069	26.431	16.901	12.798
2022	32.066	26.356	16.873	12.772
2023	32.061	26.235	16.854	12.731
2024	32.070	26.082	16.865	12.619
2025	32.068	25.936	16.825	12.542
2026	32.063	25.833	16.792	12.482
2027	32.066	25.618	16.736	12.421
2028	32.066	25.505	16.765	12.276
2029	32.058	25.368	16.746	12.222
2030	32.056	25.166	16.724	12.087
Year	GT6447023		GT8153030	
2012	9.611	4.799	8.536	-4.106
2013	9.382	5.848	9.932	0.820
2014	10.726	5.339	12.116	1.530
2015	11.880	6.625	12.745	3.198
2016	12.338	8.524	12.748	6.870
2017	12.765	9.208	12.882	7.722
2018	12.854	9.816	12.899	8.341

	Max. GWL (mPWD)	Min. GWL (mPWD)	Max. GWL (mPWD)	Min. GWL (mPWD)
2019	12.864	9.893	12.890	7.922
2020	12.847	9.879	12.888	8.065
2021	12.828	9.844	12.882	7.902
2022	12.806	9.770	12.885	7.943
2023	12.772	9.634	12.877	7.758
2024	12.743	9.608	12.872	7.862
2025	12.723	9.525	12.866	7.708
2026	12.709	9.445	12.852	7.280
2027	12.674	9.368	12.849	7.449
2028	12.679	9.287	12.834	7.085
2029	12.662	9.144	12.824	6.734
2030	12.629	9.106	12.818	6.913
Year	GT8153031		GT8172037	
2012	2.749	-3.886	7.803	1.106
2013	5.341	-0.441	9.336	3.330
2014	8.262	0.877	10.328	4.023
2015	9.933	2.937	11.091	4.784
2016	10.343	5.559	11.352	6.330
2017	10.926	5.968	12.099	6.956
2018	11.109	6.898	12.394	7.402
2019	11.164	6.773	12.388	7.395
2020	11.189	6.808	12.231	7.208
2021	11.195	6.684	12.122	7.029
2022	11.184	6.678	11.999	6.843
2023	11.141	6.536	11.914	6.649
2024	11.127	6.540	11.722	6.431
2025	11.062	6.353	11.614	6.239
2026	11.018	6.266	11.467	6.030
2027	11.000	6.269	11.332	5.831
2028	10.917	6.063	11.154	5.583
2029	10.880	6.064	10.986	5.397
2030	10.813	5.874	10.875	5.154
Year	GT8182042		GT8182043	
2012	10.155	-4.266	12.745	9.209
2013	12.848	-2.587	13.997	6.674
2014	13.110	2.301	14.953	7.787
2015	13.091	2.681	14.971	9.395
2016	13.023	3.839	14.700	9.346
2017	13.069	4.873	14.909	10.682
2018	13.068	4.796	14.917	10.635
2019	13.066	4.661	14.924	10.520
2020	13.064	4.506	14.932	10.361
2021	13.060	4.460	14.943	10.232
2022	13.058	4.352	14.946	10.094
2023	13.057	4.370	14.963	9.976

	Max. GWL (mPWD)	Min. GWL (mPWD)	Max. GWL (mPWD)	Min. GWL (mPWD)
2024	13.055	4.241	14.968	9.846
2025	13.053	4.382	14.971	9.777
2026	13.049	4.649	14.977	9.722
2027	13.042	4.662	14.984	9.695
2028	13.038	4.619	14.986	9.699
2029	13.036	4.799	14.975	9.709
2030	13.030	4.817	14.976	9.724
Year	GT8194047		GT8194048	
2012	11.206	1.032	3.138	1.769
2013	3.028	-2.645	1.782	-0.319
2014	-1.661	-5.014	-0.322	-2.356
2015	-4.543	-7.392	-2.358	-4.251
2016	-6.699	-8.546	-4.253	-5.787
2017	-8.154	-9.261	-5.789	-7.073
2018	-8.816	-9.941	-7.075	-8.271
2019	-9.458	-10.531	-8.273	-9.322
2020	-10.003	-11.020	-9.324	-10.286
2021	-10.444	-11.385	-10.287	-11.195
2022	-10.780	-11.577	-11.197	-11.936
2023	-10.991	-11.577	-11.870	-12.124
2024	-11.050	-11.577	-12.062	-12.265
2025	-11.073	-11.577	-12.185	-12.384
2026	-11.099	-11.577	-12.299	-12.461
2027	-11.122	-11.577	-12.370	-12.511
2028	-11.147	-11.577	-12.412	-12.548
2029	-11.168	-11.577	-12.444	-12.581
2030	-11.189	-11.577	-12.480	-12.617
Year	GT8194046		GT8172036	
2012	7.379	4.548	13.014	5.281
2013	7.057	3.781	14.398	8.591
2014	5.759	2.480	15.377	10.200
2015	5.000	2.181	15.414	11.766
2016	5.316	1.695	15.468	12.543
2017	5.832	2.193	15.502	13.219
2018	6.155	2.749	15.501	13.251
2019	6.343	3.083	15.497	13.239
2020	6.453	3.218	15.492	13.215
2021	6.441	3.243	15.493	13.212
2022	6.383	3.200	15.497	13.181
2023	6.245	3.110	15.489	13.171
2024	6.120	2.970	15.485	13.153
2025	5.990	2.817	15.490	13.126
2026	5.880	2.625	15.486	13.107
2027	5.667	2.422	15.484	13.088
2028	5.463	2.188	15.477	13.061

	Max. GWL (mPWD)	Min. GWL (mPWD)	Max. GWL (mPWD)	Min. GWL (mPWD)
2029	5.326	1.943	15.477	13.041
2030	5.074	1.689	15.478	13.019
Year	GT8134027		GT8134021	
2012	9.737	7.669	9.769	4.350
2013	8.612	6.899	11.420	3.146
2014	8.198	6.529	12.586	4.349
2015	7.830	5.900	14.871	4.349
2016	7.551	6.517	13.660	6.430
2017	7.877	6.731	14.116	6.821
2018	8.208	7.056	14.536	7.168
2019	8.543	7.372	14.727	7.243
2020	8.863	7.680	14.716	7.132
2021	9.145	7.972	14.561	7.002
2022	9.384	8.213	14.423	6.738
2023	9.571	8.410	14.216	6.461
2024	9.696	8.555	13.913	6.027
2025	9.764	8.652	13.564	5.681
2026	9.778	8.692	13.253	5.249
2027	9.739	8.685	12.878	4.763
2028	9.652	8.624	12.549	4.295
2029	9.531	8.527	12.274	4.005
2030	9.365	8.399	11.898	3.602
Year	GT8134028		GT8172040	
2012	13.231	7.229	17.158	6.047
2013	17.174	6.193	18.038	9.574
2014	19.812	10.715	17.838	11.007
2015	19.873	13.119	17.356	10.741
2016	19.844	14.195	17.330	12.259
2017	19.858	14.696	17.773	14.256
2018	19.856	14.723	17.832	14.100
2019	19.848	14.711	17.884	13.657
2020	19.860	14.664	17.907	13.329
2021	19.856	14.594	18.057	13.092
2022	19.856	14.478	18.087	12.831
2023	19.855	14.410	18.109	12.690
2024	19.853	14.365	18.160	12.688
2025	19.857	14.214	18.170	12.688
2026	19.857	14.188	18.179	12.675
2027	19.859	14.169	18.182	12.667
2028	19.857	13.954	18.181	12.674
2029	19.858	13.913	18.190	12.737
2030	19.857	13.769	18.225	12.732
Year	GT8182041		GT8194044	
2012	12.514	7.482	12.630	8.157
2013	12.764	6.304	10.397	8.958

	Max. GWL (mPWD)	Min. GWL (mPWD)	Max. GWL (mPWD)	Min. GWL (mPWD)
2014	13.079	8.716	9.375	8.286
2015	13.122	10.646	10.278	7.235
2016	12.942	10.406	10.146	7.321
2017	12.999	11.119	10.164	7.732
2018	13.013	11.169	10.319	7.996
2019	13.013	11.170	10.327	8.019
2020	13.002	11.147	10.294	7.887
2021	13.010	11.152	10.211	7.744
2022	13.001	11.123	10.006	7.541
2023	13.009	11.127	9.812	7.272
2024	13.006	11.107	9.547	6.978
2025	12.999	11.123	9.281	6.681
2026	12.996	11.104	8.953	6.310
2027	12.994	11.120	8.645	6.035
2028	12.996	11.104	8.319	5.633
2029	12.996	11.095	7.912	5.395
2030	12.998	11.103	7.520	5.246
Year	GT8112003		GT8112002	
2012	11.042	-3.272	12.436	-2.886
2013	11.949	1.576	12.993	2.982
2014	11.966	4.121	13.277	4.764
2015	11.981	3.666	13.278	3.915
2016	11.981	7.647	13.276	7.892
2017	11.985	9.163	13.277	8.738
2018	11.985	9.028	13.277	9.050
2019	11.984	9.110	13.276	8.732
2020	11.984	9.080	13.276	8.921
2021	11.984	8.598	13.277	8.222
2022	11.980	8.874	13.277	8.515
2023	11.983	9.427	13.278	8.594
2024	11.983	8.894	13.278	8.305
2025	11.982	8.971	13.277	8.187
2026	11.982	8.563	13.277	7.898
2027	11.979	9.163	13.278	8.169
2028	11.978	9.286	13.277	7.961
2029	11.978	9.303	13.277	7.939
2030	11.977	9.110	13.278	7.734