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EXECUTIVE SUMMARY

E1. Background

Water Resources Planning Organization (WARPO) is an apex body under the Ministry of Water Resources (MoWR) dealing with nationwide water resources planning and as designated by the Bangladesh Water Act 2013, is mandated as the lead agency for providing administrative and secretariate support to the Executive Committee of National Water Resources Council (ECNWRC) for the implementation of the Bangladesh Water Act 2013 and the Bangladesh Water Rules, 2018 and the regulation of water resources development. Also, as per the National Water Policy (NWPo) 1999, WARPO is to routinely update the water resources assessment of the country and monitor the state of water resources system so that the implementation, performance, and the impacts of the National Water Management Plan (NWMP)/the National Water Resources Plan (NWRP) can be adequately addressed.

Against this backdrop, WARPO conceived a project, titled “Operationalizing Integrated Water Resources Management (IWRM) in Compliance with the Bangladesh Water Rules, 2018”, partnered with the Swiss Agency for Development and Cooperation (SDC). Under this project, WARPO engaged IWM to conduct a study on “Hydrological investigation and Modelling of the State of Surface and Groundwater Resources in the High Barind Region”.

E2. Objectives and Scope of Works

The study area is located in twenty-five upazilas covering 215 unions of three districts namely, Rajshahi, Chapainawabganj and Naogaon Districts. The study aims at (i) developing numerical models to assess the state of surface and groundwater resources through field investigation and mathematical modelling, (ii) aquifer mapping of the study area, (iii) assessing the safe yield level of the aquifer, and (iv) demarcation of Water Stress Area (WSA) based on different parameters. During this study a comprehensive field data collection program has been conducted which includes:

- Exploratory drilling at 53 selected locations (40 nos. up to 200m depth, 10 nos. up to 300m depth and 03 nos. up to 500m depth).
- Construction of production tubewells at 06 locations.
- Long term (3 days) aquifer pump tests at 24 selected locations using existing deep tubewells.
- Long term (3 days) aquifer pump tests at 06 selected locations in newly installed production wells.
- Installation and monitoring of 50 groundwater observation wells including BM connection.
- Water quality sampling and analysis at 50 locations.
- Seepage and percolation measurements at 30 selected locations.
- Geophysical resistivity survey at 30 locations.
- Cross section survey of rivers and their tributaries/distributaries (2000 nos.).
- River Water Level Gauge installation and monitoring at 12 locations.

- River Discharge measurement, riverbed material sampling and analysis at 12 locations.

E3. Methodology

A set of activities were carried out to assess the state of surface and groundwater resources. For assessment of groundwater resources, bore logs data available in secondary sources and exploratory drilling under this study have been used to define the lithological formation of the study area. A coupled surface water-groundwater water model was set up using MIKE11-MIKESHE modeling tools, where MIKE11 represents one-dimensional hydrodynamic model for the rivers, while MIKE SHE represents groundwater model. The developed model uses an explicit representation of SW-GW interaction to help achieve the study objectives. Data required to develop the models have been collected from field survey, secondary sources, and PRA study. The models have been calibrated for the period of 2012-2017 and validated for the periods of 2018-2022. The calibrated models have been applied for various development scenarios.

Groundwater level trend analysis was performed to have a better understanding of water stressed areas in the study area. The annual maximum and minimum water table depths of groundwater readings have been extracted from the database at different parts of the study area, and linear regression has been performed on the data set for each location.

Groundwater quality has been tested for 18 physio-chemical parameters at 50 locations in the project area. Some of the physical parameters have been measured in-situ in the field, while most of the hydro-chemical parameters have been examined in DPHE laboratory and Department of Geology, University of Dhaka.

IWM also conducted a study on “Participatory Rural Appraisal (PRA) / Baseline Study of the State of Water Resources in the High Barind region” under the same project. This PRA study provided useful information for the current study. For the PRA study, IWM has divided the study area comprising 5070 mouzas into 126 clusters having +/- 40 (forty) mouzas in each of the clusters, where one representative from each mouza participated in the FGD. For each cluster, FGD were organized in two sessions, where maximum 20 representatives participated among which one-third participants are women. A total 25 numbers of PRA validation workshops have been conducted at upazila level to disseminate the PRA study findings.

E4. Findings

E4.1. Geological Settings

Rajshahi district mostly falls under the two physiographic units: Barind Tract and Ganges Flood plain. Tanore and Godagari upazilas fall under the unit of Barind Tract where a thin aquifer exists in the shallow depth except some eastern part of Tanore and Godagari upazila, with thickness of the aquifer varies from 3 to 6 m and depth to groundwater table varies from 23 to 34 m. A thick aquifer is present in Soranjai, Pachandor, Talando and Kamargaon unions in the eastern part of Tanore and Godagari upazila where the aquifer thickness varies from 27

to 72 m. In the area depth to groundwater table has declined down to a depth of 25-27 m. Rajshahi City Corporation, Puthia, Bagha, Paba, Charghat and Bagmara and part of Mohonpur upazilas fall under the unit of Ganges River Floodplain where multi-aquifers exist. The depth to groundwater table ranges from 3 to 21 m except some parts of Rajshahi City Corporation, Mohonpur and Bagmara upazilas. In Mohonpur, Tanore and Godagari area, the declining trend of water level is very alarming, suggesting no further abstraction of groundwater. Mundumala pourashava and Badhair union falls under critical conditions in terms of subsurface lithology and declining trend of groundwater level, suggesting that special attention will be required before further development.

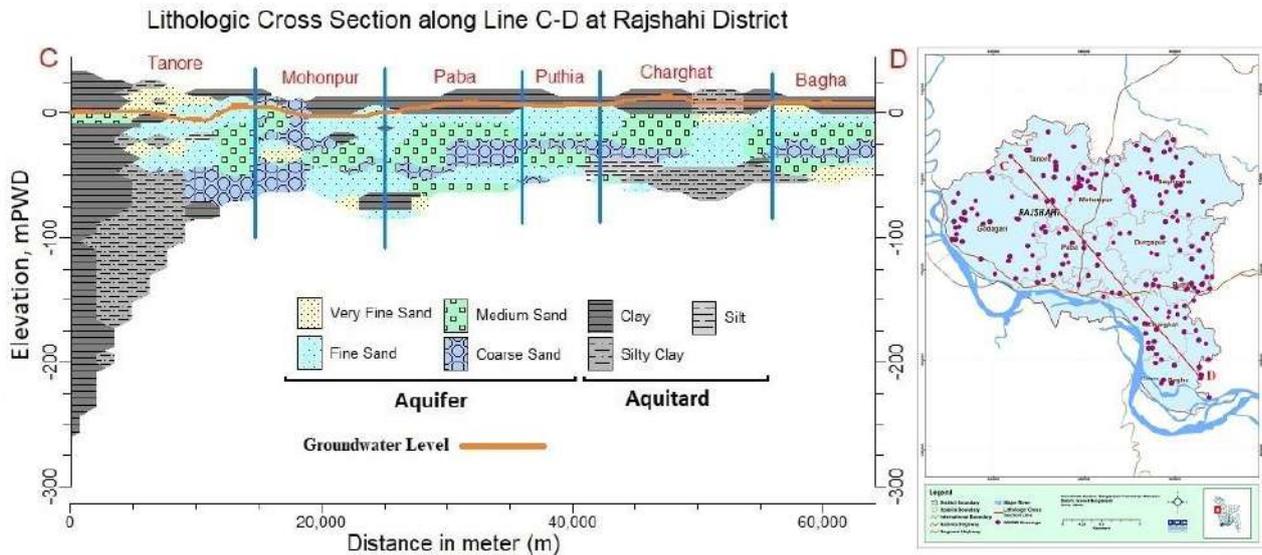


Figure E1: Lithologic Cross Sections with Groundwater Table along Line C-D at Rajshahi District

The Chapainawabganj district mostly falls under three physiographic units: Ganges River Floodplain, Teesta Floodplain and Barind Tract. Nachol, eastern part of Chapainawabganj Sadar and Gomostapur upazilas fall under the unit of Barind Tract where a thin aquifer exists in the shallow depth throughout the area except a part of Nachol pourashava. The thickness of that aquifer varies from 6 to 18 m which is the only drinking water source for these areas up to the drilling depth of 432 m. The depth to groundwater table varies from 30 to 32 m which has already dropped down beyond the suction limit (7 m) may create a very alarming situation for the area. Due to existence of thin aquifer, the groundwater table condition of Nachol, Kosba, Fatehpur, Jhilim, Parbatipur, Rohanpur and Radhanagar unions are very alarming where the depth to groundwater table varies from 27 to 35 m which has dropped down beyond the suction limit. On the other hand, Bholahat, western part of Gomostapur, western part of Chapainawabganj Sadar and Shibganj upazila falls under the unit of Ganges River Floodplain and Teesta Floodplain where a thick aquifer exists except the Shibganj pourashava area, where thickness of aquifer varies from 18 to 60 m. At Shibganj pourashava area, the existence of two aquifers have been found upto the drilling depth of 265 m. The depth to groundwater table condition of Shibganj, Monakasha, Chakkirti, Mobarakpur, Ranihati, Bholahat and Shahabajpur unions are relatively good where groundwater table ranges from 4 to 12 m.

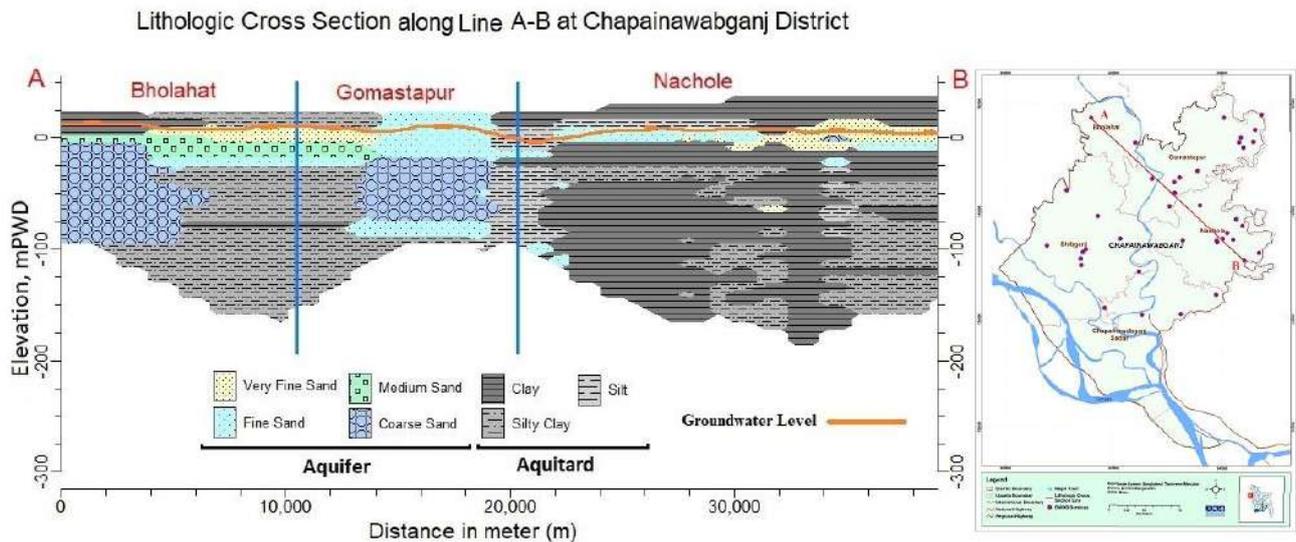


Figure E2: Lithologic Cross Sections with Groundwater Table along Line A-B at Chapainawabganj District

The Naogaon district mostly falls under three physiographic units: Teesta Floodplain, Lower Atrai Basin and Barind Tract. Naogaon Sadar, Atrai, Raninagar, Mohadevpur, Manda, Badalgachi and some Part of Patnitala and Dhamoirhat fall under the unit of Teesta Floodplain and Lower Atrai Basin where a thick aquifer exists. On the other hand, Porsha, Sapahar, Niamatpur and some parts of Patnitala and Dhamoirhat upazilas fall under the unit of Barind Tract where there is only one aquifer exists. Even in some areas of Porsha and Sapahar upazilas such as Chaor, Ganguria and Tetulia union, no suitable aquifer is found upto the drilling depth of 300 m. The depth to groundwater table of Porsha, Niamatpur, part of Sapahar, Patnitala and part of Dhamoirhat upazilas has dropped down beyond the suction limit which creates a very alarming situation for those areas.

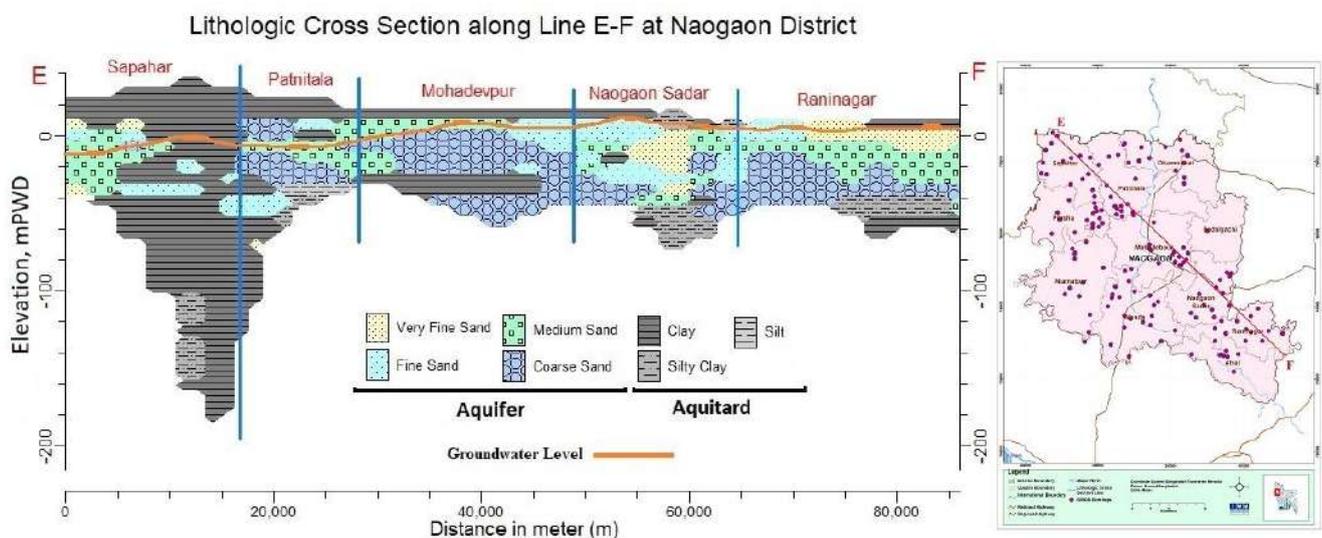


Figure E3: Lithologic Cross Sections with Groundwater Table along Line E-F at Naogaon District

E4.2 Water Quality

Groundwater samples have been collected from 50 wells where the depth of wells was 23 m to 95 m. A total of 18 physio-chemical parameters have been measured and analyzed for the collected samples. Overall quality of groundwater in the study area for drinking and irrigation purposes is generally good, except certain chemical elements such as bicarbonate, iron, and manganese, which exceed the permissible standard limits set by Bangladesh. The majority of collected groundwater samples (the depth range of the collected samples from the wells were 23 to 95m) exhibit elevated levels of bicarbonate (98% of samples), iron (80% of samples), and manganese (76% of samples).

According to the data collected under this study and the report of BGS 2001, the arsenic concentration has been found as beyond the drinking water limit (BD standard) at Durlabpur, Monakasha unions of Shibganj upazila and Ranihati union of Chapainawabganj sadar upazila in Chapainawabganj district, Jewpara union of Puthia upazila, Baksimoilunion of Mohonpur upazila, Haripur and Hujuripara unions of Paba upazila in Rajshahi district and Nurullabad and Manda unions of Manda upazila in Naogaon district.

E4.3. Groundwater Level Trend Analysis

To perform the trend analysis the annual maximum and minimum water table depth of groundwater readings have been extracted from the database and a linear regression performed on each set. The rate of variation (slope) of each set has been extracted and classified into the trend types according to the definitions as shown below.

TYPES	DESCRIPTION
Type-1	Strongly declining levels in both minimum groundwater depths and maximum groundwater depths; little or no wet season recovery.
Type-2	Dry season minimum groundwater depth is declining, and the wet season induced recharge top-up appears insufficient to fully restore groundwater levels; strong declines in the maximum depth of the water table and some decline in the minimum depth.
Type-3	Maximum depth is declining (i.e., increasing abstractions and losses), but there is no decline in the minimum depth; wet season recharge is currently sufficient to make up the dry season deficit.
Type-4	Both minimum depth and maximum depth show no trend; wet season recharge is sufficient to account for dry season losses and abstractions

From the trend analysis of groundwater level data at 122 locations, it has been found that 46 nos. fall under Type 1 (these wells have strongly declining levels in both minimum groundwater depths and maximum groundwater depths), 48 nos. fall under Type 2 (groundwater trends where the dry season minimum groundwater depth is declining and the wet season induced recharge top-up appears insufficient to fully restore groundwater levels), 24 nos. fall under Type 3 (groundwater trends where the maximum depth is declining but there

is no decline in the minimum depth) and only 4 nos. fall under Type 4 (both minimum depth and maximum depth show no trend) indicating occurrence of insufficient recharge to compensate abstractions in most part of the study areas which is very alarming.

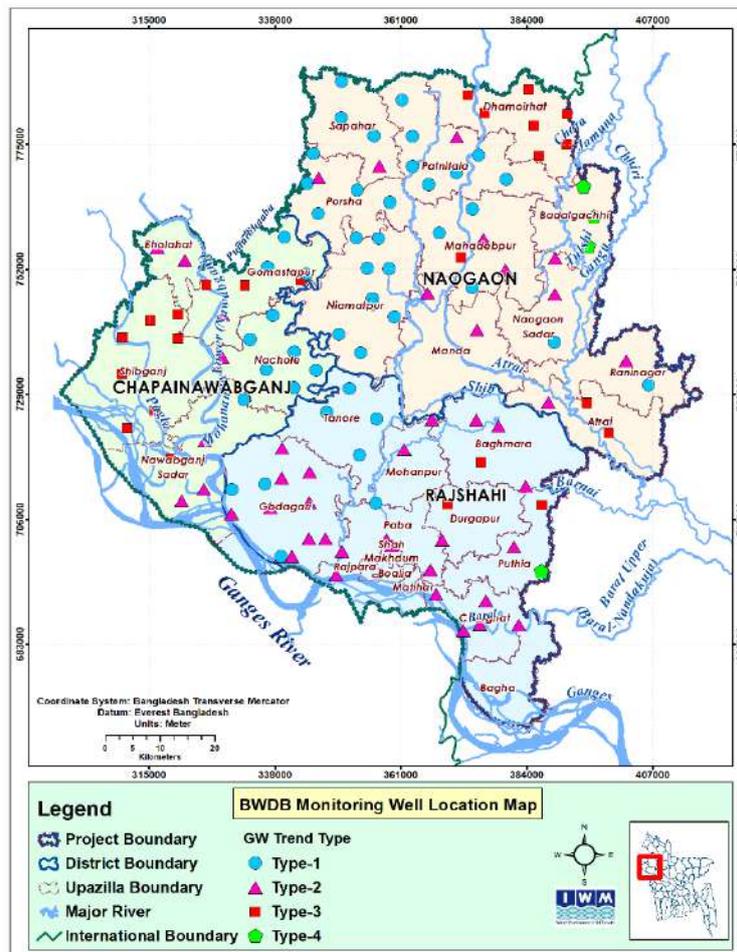


Figure E4: Trend Types and Location of Observation Wells in the Study Area

E4.4. Safe Yield Assessment

The union wise safe yield level of groundwater resources has been calculated based on actual recharges using mathematical modelling techniques. A method named Successive Simulation Method has been conducted for model simulation (in average hydrological condition) to visualize whether the groundwater table regains to its original position for a number of pre-defined locations. As groundwater tables in most of the area are declining (falls under Type 1, 2 or 3), yearly actual recharge (instead of potential recharge) has been estimated to find out safe yield level for the study area. According to the NWMP guideline and other literature review, 75% of actual recharge has been taken as safe yield level for the study areas.

The estimated union wise actual recharge has been found ranges from 160-708 mm for Rajshahi District, 193-727 mm for Chapainawabganj district and 116-780 mm for Naogaon District. Union wise safe yield computations, along with other relevant parameters and data, can be found in Chapter-10.

E4.5. Water Stress Area (WSA) Identification

Water stress area has been identified using an index-based groundwater vulnerability method, DRAHQEL, specifically developed for this particular study, following similar methodology and justifications as have been used in the very popular groundwater vulnerability method named DRASTIC. The method has been introduced by the Panel of Expert (PoE) committee of the project, with Water Stress Index (WSI) estimated from ratings and weightages for the 8 parameters (D: Depth to Water Table; R: Recharge; A: Aquifer Thickness; U: Media of Unsaturated Zone; H: Hydraulic conductivity of the Aquifer; Q: Groundwater Quality; E: Environmental Issues; L: Trend of Groundwater Level), assigned based on expert judgment.

According to WSI values, the study area has been classified into five zones- Very high-water stress area (WSI >160), high water stress area (WSI 140-160), Moderate water stress area (WSI 120-140), Low water stress area (WSI 100-120), and very low water stress area (WSI <100). In the high-water stress area, no additional abstraction should be allowed so that it would limit the groundwater table not exceeding the safe yield level and would keep the static water level in present condition. In the low stress area, some abstraction exceeding the present limit might be allowable.

From the identification of water stress area, it has been found that 3 unions of Godagari upazila, 1 union of Mohonpur upazila, 3 unions of Paba upazila and 6 unions of Tanore upazila under Rajshahi district; 1 union of Chapainawabganj Sadar upazila, 5 unions of Gomostapur upazila, 4 unions of Nachol upazila under Chapainawabganj district and 6 unions of Niamatpur upazila, 7 unions of Patnitala upazila, 6 unions of Porsha upazila, 5 unions of Sapahar upazila under Naogaon district falls in the very high water stress area.

It also has been found that 2 unions of Bagha upazila, 1 union of Bagmara upazila, 1 union of Charchhat upazila, 3 unions of Durgapur upazila, 3 unions of Godagari upazila, 4 unions of Mohonpur upazila, 1 union of Paba upazila, 1 union of Tanore upazila under Rajshahi district falls in the high water stress area. In Chapainawabganj district, 3 unions of Chapainawabganj Sadar upazila, 3 unions of Gomostapur upazila, 4 unions of Shibganj upazila lies with high water stress area. In Naogaon district, 1 union of Atrai, 3 unions of Manda upazila, 1 union of Mohadevpur upazila, 2 unions of Naogaon Sadar upazila, 1 union of Niamatpur upazila, 2 unions of Patnitala upazila, 3 unions of Raninagar upazila, 1 union of Sapahar upazila falls in the high water stress area. Identified district wise number of water stressed unions is shown below.

District	Number of Unions				
	Very High Stress	High Stress	Moderate Stress	Low Stress	Very Low Stress
Rajshahi	13	16	30	8	4
Chapainawabganj	10	10	14	-	11
Naogaon	24	14	22	22	17
Total	47	40	66	30	32

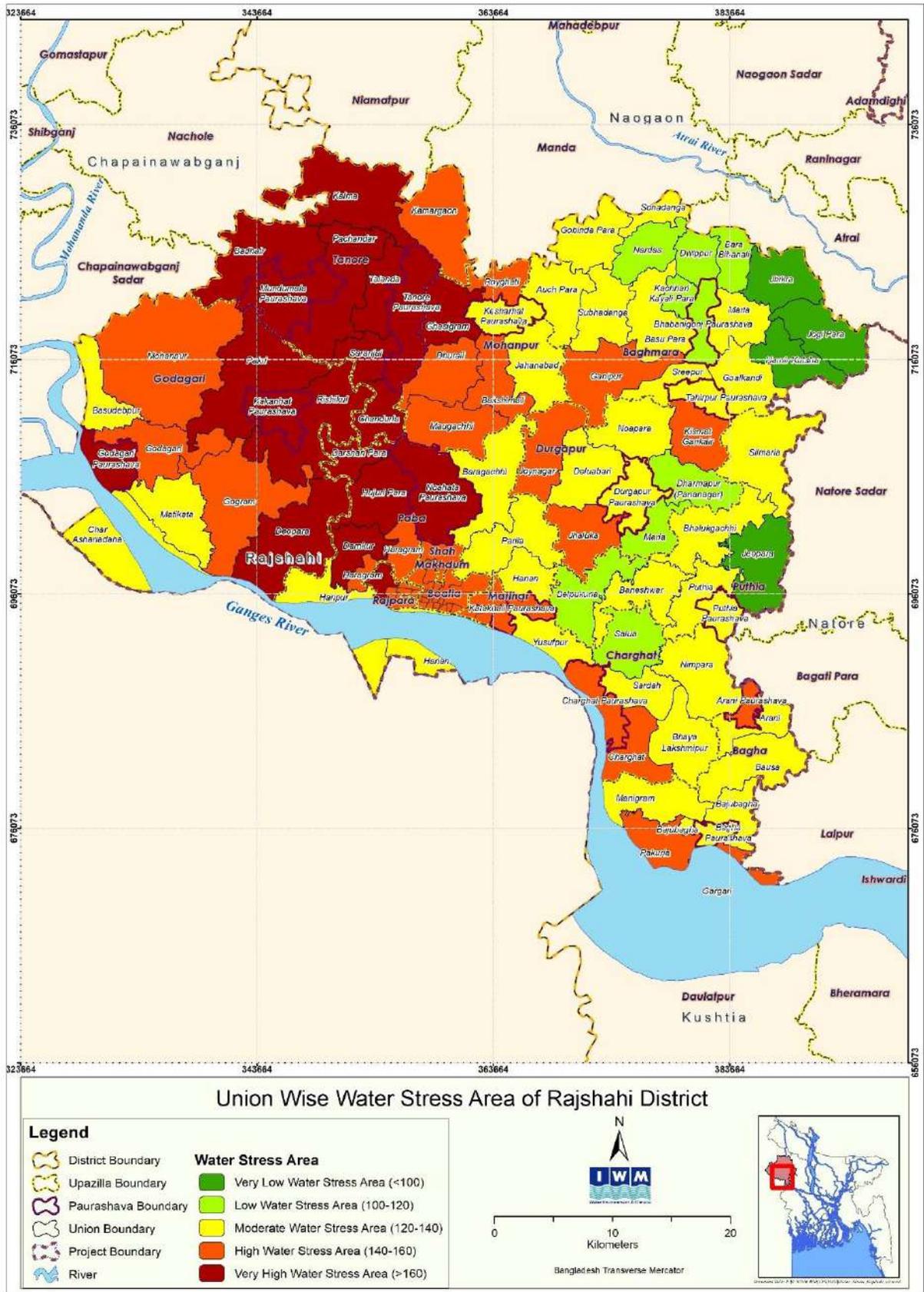


Figure E.5: Union Wise Water Stress Area for Rajshahi District

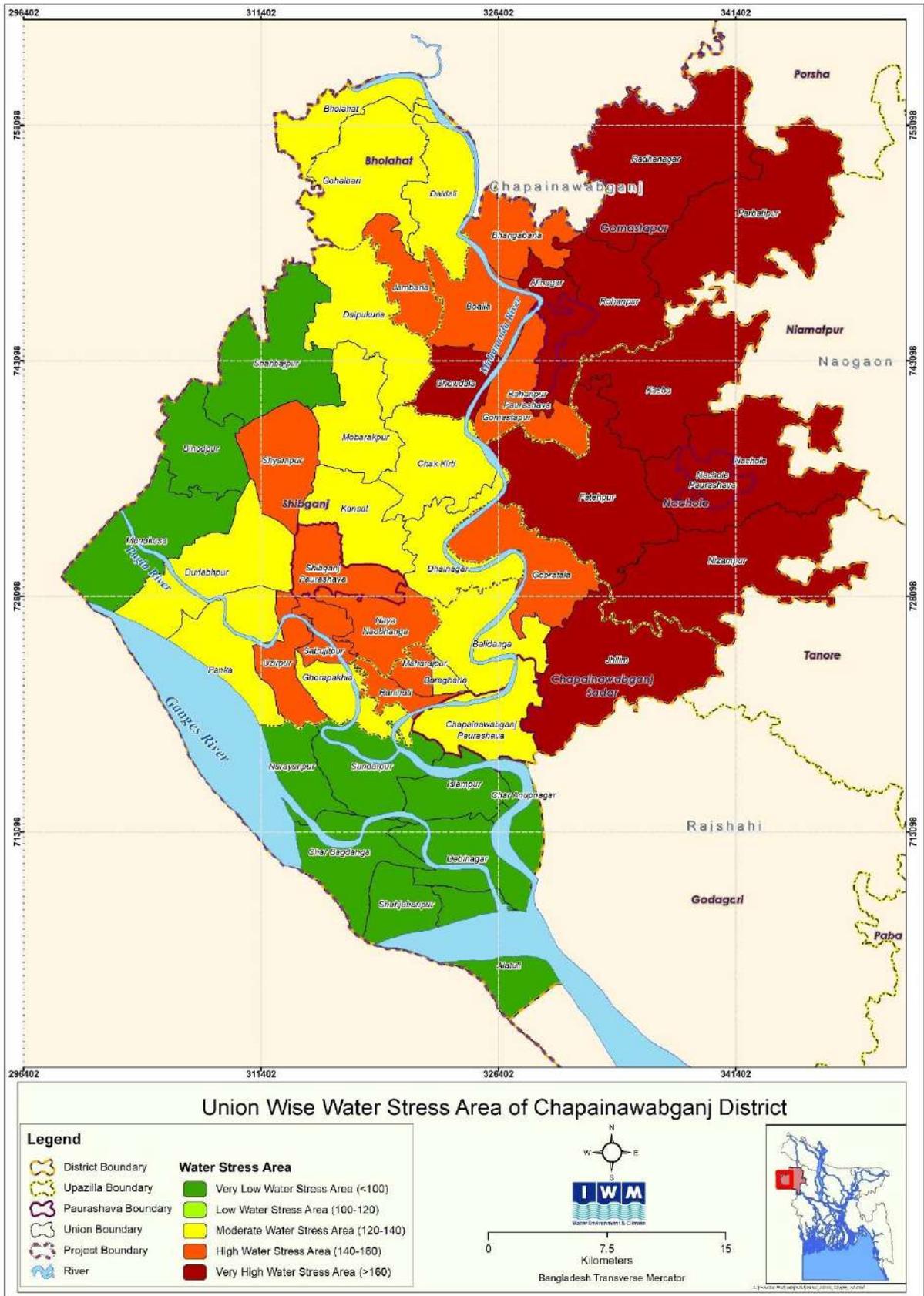


Figure E.6: Union Wise Water Stress Area for Chapainawabganj District

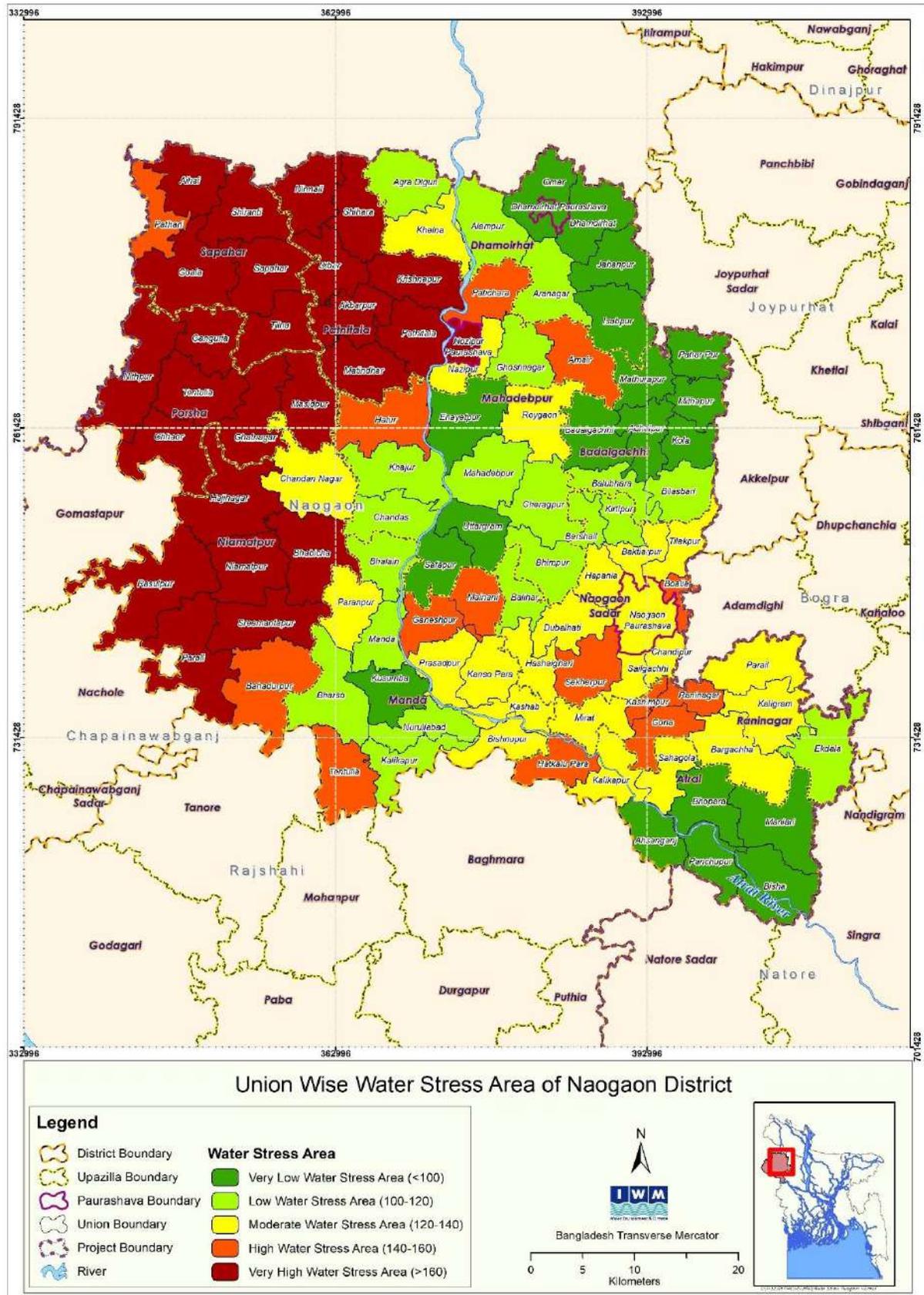


Figure E.7: Union Wise Water Stress Area for Naogaon District

E4.6. Scenario Analysis (Extreme Dry Condition and Climate Change Option)

Scenario analysis for extreme dry condition and climate change impact on groundwater table have been done using model simulation. For extreme dry hydrological condition, a 100-Yr return period event has been considered. The climate change scenario has been based on IPCC's 5th assessment report (AR5), with 5 simulations carried out considering different factors for rainfall and PET.

From analysis of extreme dry condition, it reveals that the groundwater table drops down about 1.0 m to 4.0 m compared to the groundwater table of base condition. It is also observed that groundwater table drops down by about 4.0 m to 10.0 m in some pocket's areas of Barind region. Climate change's impact on groundwater levels shows that the groundwater table fails to regain its original position in monsoon and post monsoon. From analysis it has been found that the groundwater table may drop down up to 6 m from base condition due to the impact of climate change, although these are subject to uncertainties in the predicted rainfall. Overall, these simulations indicate that groundwater levels will be immediately responsive to changes in rainfall and ET patterns.

E4.7. Surface Water Resources Assessment

Surface water resources have been assessed for some selected rivers. From the assessment it has been found that surface water development is possible during dry period using abstraction from the Atrai and Mohananda River as resources are available in these rivers. The possibility of increasing groundwater recharge by conservation of water in rivers and kharies have been analyzed for a selected area using modelling techniques. From the spatial distribution of impact map of depth to groundwater table, it has been found that groundwater tables increase by 0.05 m to 0.35 m with an impact area of about 137 km² due to conservation of water in Sib-Barnai River during dry period.

It has been found that existing potential wetlands may be re-excavated which cover an area of about 143 Km² and can store an amount of 286 Mm³ of water. In addition, a total 8200 ponds (>100 decimal) have been identified which can be re-excavated and can store 120 Mm³ of water.

Potential beels of Bagmara, Durgapur, Paba, Puthia and Tanore upazilas under Rajshahi district, Atrai, Raninagar, Manda, Naogaon Sadar, Sapahar, Porsha and Niamatpur upazilas under Naogaon district and Bholahat, Gomostapur and Nachol upazilas of Chapainawabganj district, that can be re-excavated to deeper extents and can be developed as potentials for surface water retention and preservation for irrigation year-round, fish culture and household purposes which will reduce the quantity of groundwater abstraction.

Drinking water can be provided in the water stress areas after storing surface water during the monsoon season by constructing reservoirs and necessary infrastructures (pipelines, water treatment plants, overhead tanks, etc.). As a pilot project, fresh water can be provided by conserving surface water through re-excavation of 3 bills namely: Beel Kumari of Tanore

Upazila in Rajshahi District, Jobai Beel of Sapahar Upazila in Naogaon District and Hugla Damas Beel of Nachol Upazila in Chapainawabganj District.

E5. Recommendations

The important recommendations that have been made for the study area are:

- Tanore and Godagari upazilas of Rajshahi district, Niamatpur, Porsha and Sapahar upazilas of Naogaon district and Chapainawabganj Sadar, Nachol and Gomostapur upazilas of Chapainawabganj district should be brought under restricted/limited abstraction areas.
- Deficiency of water demand in the high-water stress area should be filled up by supplying water from less water stress areas if possible.
- Potential beels of Bagmara, Durgapur, Paba, Puthia and Tanore upazilas under Rajshahi district, Atrai, Raninagar, Manda, Naogaon Sadar, Sapahar, Porsha and Niamatpur upazilas under Naogaon district and Bholahat, Gomostapur and Nachol upazilas of Chapainawabganj district, should be re-excavated to deeper extents.
- Use of surface water should be increased to reduce pressure on groundwater. Drinking water can be provided in the water stress areas after storing surface water during the monsoon season by constructing reservoirs and necessary infrastructures (pipelines, water treatment plants, overhead tanks, etc.).
- As a pilot project, fresh water can be provided by conserving surface water through re-excavation of 3 bills namely: Beel Kumari of Tanore Upazila in Rajshahi District, Jobai Beel of Sapahar Upazila in Naogaon District and Hugla Damas Beel of Nachol Upazila in Chapainawabganj District.
- In high water stress areas, at least one pond should be used for drinking water, one pond for bathing and domestic purposes and others for fish farming. In this case, sign boards should be provided in the reserved ponds based on usage.
- A total 8200 ponds (>100 decimal) have been identified in the study areas which can be re-excavated to a deeper extent for extensive use in fish farming and household purposes.
- The monitoring well installed under this project for the observation of groundwater level data should be kept under continuous monitoring. An IoT-based automation along with telemetry system should be developed to regularly monitor the changes in groundwater level.

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ACCRONYMS AND ABBREVIATION

BADC	Bangladesh Agricultural Development Corporation
BCAS	Bangladesh Centre for Advanced Studies
BIDS	Bangladesh Institute of Development Studies
BM	Benchmark
BMDA	Barind Multipurpose Development Authority
BWA	Bangladesh Water Act
BWDB	Bangladesh water Development Board
BWR	Bangladesh Water Rules
CapDev	Capacity Development
DASCOH	Development Association for Self-reliance, Communication and Health
DEM	Digital Elevation Model
DFR	Draft Final Report
DGPS	Differential Global Positioning System
DTW	Deep Tubewell
ECNWRC	Executive Committee of National Water Resources Council
FGD	Focus-Group Discussion
FIWR	Field Irrigation Water Requirement
FR	Final Report
GIS	Geographic Information System
GPRS	Geophysical Resistivity Survey
GWL	Groundwater Level
HD	Hydrodynamic
IoT	Internet of Things
IR	Inception Report
IWRM	Integrated Water Resources Management
LAI	Leaf Area Index
LG	Local Government
LGED	Local Government Engineering Department
LWC	Lower Well Casing
MoWR	Ministry of Water Resources
MSL	Mean Sea Level
MTR	Mid Term Report
NAM	Rainfall-runoff
NGO	Non-Governmental Organisation
NWMP	National Water Management Plan
NWPo	National Water Policy
NWRD	National Water Resources Database
NWRM	Northwest Regional Model
PR	Progress Report
PRA	Participatory Rural Appraisal
PVC	Polyvinyl Chloride
PWD	Public Works Datum

RDF	Root Depth Function
RHD	Roads and Highway Department
RS	Remote Sensing
S&P	Seepage and Percolation
SDC	Swiss Development and Cooperation
SoB	Survey of Bangladesh
SRC	Swiss Red Cross
SRDI	Soil Resource Development Institute
STW	Shallow Tube well
ToR	Terms of Reference
UWC	Upper Well Casing
VES	Vertical Electrical Sounding
WARPO	Water Resources Planning Organization
WL	Water Level
WSA	Water Scarce/Stress Area
WSI	Water Stress Index

1 INTRODUCTION

1.1 Background

As water is a critical element in development, and many efforts have been made in Bangladesh to improve safe drinking water coverage, while optimizing the use of water for irrigation, industrial use, and other uses; but these efforts often overlook the holistic perspective of sustainable development. Sustainable solutions to water problems require a paradigm shift from compartmental sub-sector-wise development to holistic water governance. Such a paradigm is encapsulated in the Integrated Water Resources Management (IWRM) concept. IWRM challenges conventional, fractional water development and management systems and emphasizes an integrated approach with coordinated decision making across sectors and scales. Furthermore, to face the growing challenges regarding water rights, protection of resources, water use, and water services management, Bangladesh has enacted a comprehensive legal framework called the Bangladesh Water Act (BWA) 2013, which received the President's assent on 2nd May 2013. This act outlines a coordinated and comprehensive regime for the development, management, extraction, allocation, use and conservation of water resources.

Therefore, to put the Bangladesh Water Act 2013 into practice and to understand local economic and social dynamics related to water management in line with IWRM concept, a project named 'Institutionalization of Integrated Water Resources Management (IWRM) process in compliance with the Bangladesh Water Act, 2013' has been implemented through Water Resources Planning Organization (WARPO) with the financial support from the Government of Bangladesh (GoB) and the Swiss Agency Development and Cooperation (SDC). The Phase I of the project (November 2014 – June 2018), in consultation with stakeholders, developed a set of rules, known as the Bangladesh Water Rules (BWR) 2018. In addition, in the Phase I of the project Water Management Guidelines has also been prepared and undertook various activities to organize local IWRM Committees and to pilot IWRM in water scarce area in Barind region.

Water Resources Planning Organization (WARPO) is an apex body under the Ministry of Water Resources (MoWR) dealing with nationwide water resources planning and is designated by the Bangladesh Water Act 2013 and is mandated as the lead agency and secretariat and administrative support to the Executive Committee of National Water Resources Council (ECNWRC) for the implementation of the Act and its Rules and the regulation of water resources development. On the other hand, the National Water Policy (NWPo) 1999 requires that WARPO will routinely update the water resources assessment of the country and monitor the state of water resources system so that, the implementation, performance, and the impacts of the National Water Management Plan (NWMP)/the National Water Resources Plan (NWRP) can adequately be addressed. Advancement in legislation and institutional reforms through the first IWRM project has eventually brought major changes in WARPO across the country, but it will take few years more to make its impacts visible to the external stakeholders. Recognizing that success breeds success, growing WARPO's role in the sector requires early demonstration

of its effectiveness in leading water resources management. The momentum that built up under the IWRM project (Phase I) should not be lost rather continued. Current activities in the Barind region offer an opportunity for WARPO to bring about a solution to water scarce problem in the short or medium term only. Although the problems of the Barind are relative and not so complex and are quite amendable to solution, building on the success of the first phase, a next phase of the project has been felt necessary to implement the Bangladesh Water Rules 2018 and to advance IWRM goal of achieving sustainable abstraction from the Barind aquifer and fair and adequate access to water, which leads to formulate the running study.

A detail analysis and modelling through a proven scientific tool will be required to enable the user to analyze and set the threshold limits for abstraction and usage to operationalize the Bangladesh Water Rules, 2018. The Bangladesh Water Rules, 2018 keeps the provision of determining the safe yield level of aquifer up to Union/Mouza level, and declaration of Water Stress Area for a specific period, which seeks a clear understanding of the state of water resources of the designated area to have proper monitoring of the implementation of the Bangladesh Water Rules through IWRM.

1.1.1 Relevance of National Policies, Laws and Framework

The Water Act 2013 is based on the National Water Policy, and designed for integrated development, management, extraction, distribution, usage, protection, and conservation of water resources in Bangladesh. In general, if one takes a critical look at the Act, the new law has provided the right framework for better management of water resources in the country.

Bangladesh Water Rules 2018 was prepared and finalized following Bangladesh Water Act, 2013. The Water Resources Planning Organization (WARPO) under the Ministry of Water Resources has taken the lead coordination role to make it happened and organized several consultations with relevant stakeholders.

As per the Act, all forms of water (e.g., surface water, ground water, sea water, rainwater and atmospheric water) within the territory of Bangladesh belong to the government on behalf of the people. The private landowners will be able to use the surface water inside their property for all purposes in accordance with the Act. A worthwhile initiative is the requirement for permits/licenses for large scale water withdrawal by individuals and organizations beyond domestic use. Without prior permission issued by the ECNWRC, no individuals or organizations will be allowed to extract, distribute, use, develop, protect, and conserve water resources, nor they will be allowed to build any structure that impede the natural flow of rivers and creeks.

The Table 1-1 shows the relevance of the relevant national policies, laws and frameworks in the context of the present study.

Table 1-1: Relevance of National Policies, Laws and Framework in the Context of the Present Study

National Policies, Laws and Frameworks	Linkage with Policies, Laws and Frameworks
Bangladesh Water Act 2013 and Bangladesh Water Rules 2018	<p>The Bangladesh Water Act 2013 comprises of the following sections which are related with the present study:</p> <p>Section 16: Issuance of clearance certificate for water resources developments.</p> <p>Section 17: Declaration of Water Scarce Area and management</p> <p>Section 18: Preferential use of water in the Water Scarce Area and exemption</p> <p>Section 19: Fixing the lowest safe yield level of aquifer and restrictions on abstracting groundwater.</p> <p>Section 28: Water pollution control</p> <p>The above sections require integrated water resources development and management, Water resources assessment, Protection of water resources, water quality, and aquatic ecosystem and finally Water and sustainable urban development which are most relevant with the present study.</p> <p>Bangladesh Water Rules 2018 has been prepared and finalized following Bangladesh Water Act, 2013. It keeps the provision of determining the safe yield level of aquifer up to Mouza level, and declaration of Water Stress Area for a specific period, which seeks a clear understanding of the state of water resources of the designated area to have proper monitoring of the implementation of the Bangladesh Water Rules through IWRM.</p>
Sustainable Development Goals (SDG), 2015	<p>Sustainable Development Goals (SDG) comprises of the following sections which are related with the present study:</p> <p>6.1 by 2030, achieve universal and equitable access to safe and affordable drinking water for all.</p> <p>6.2 by 2030, achieve access to adequate and equitable sanitation and hygiene for all, and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations.</p> <p>6.3 by 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater, and increasing recycling and safe reuse by x% globally.</p> <p>6.4 by 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity, and substantially reduce the number of people suffering from water scarcity.</p> <p>6.5 by 2030 implement integrated water resources management at all levels, including through transboundary cooperation as appropriate.</p> <p>6.6 by 2020 protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes.</p>

National Policies, Laws and Frameworks	Linkage with Policies, Laws and Frameworks
National Water Policy 1999	This policy requires to facilitate availability of safe and affordable drinking water. This aspect is very much applicable for the present study.
Safe Drinking Water Supply and Sanitation Policy 1998	The key objectives of the policy are: (i) to ensure proper storage, management and use of surface water and preventing its contamination; (ii) emphasis on the use of surface water over groundwater which mostly complies with the present study.
National Water Management Plan (NWMP)	The NWMP is meant as an operationalization of the National Water Policy. The NWMP was formulated for (a) the rational management and wise use of Bangladesh's water resources, (b) improvement of quality of life of people by the equitable, safe and reliable access to water for production, health and hygiene, and (c) ensure the clean water in sufficient and timely quantities for multi-purpose use and preservation of the aquatic and water dependent eco-systems which mostly complies with the present study.
Bangladesh Delta Plan 2100	Bangladesh Delta Plan 2100 has six goals among which the following goals are directly relevant with this study: <i>Goal 2: Enhance Water Security and Efficiency of Water Usages</i> Under this study, the water resources will be estimated, and the quality of water will also be determined which is under linked with this goal.
Eighth Five Year Plan (8 th FYP)	The Eighth Five Year Plan (8 th FYP) is the first in the series of 4 medium term development plans aimed at implementing the Perspective Plan 2041. The proposed study is linked with the strategic objectives of 8 th FYP by ensuring conjunctive use of surface and groundwater for sustainable irrigation, securing groundwater conservation.

1.2 Objectives of the Study

The main objective of the study is to develop numerical models to assess the state of surface and groundwater resources up to Union/Mouza level for supporting pilot operationalization of the Bangladesh Water Rules, 2018.

The specific objectives of this study are as follows.

- Investigating the present surface water and groundwater resources availability, use and demand through field investigation and mathematical modelling in the High Barind region,
- Providing necessary comprehensive data, map and information required for operationalizing the Bangladesh Water Act, 2013 and its Rules, and
- Facilitates monitoring with a view to create improved environment for sustainable water resources planning and management in the High Barind region.

1.3 Scope of the Works

The major scope of works of this study are (i) to assess the state of water resources in the High Barind region through survey, field investigation, conceptual and numerical modelling; (ii) to investigate the aquifer system and groundwater recharge for preparing aquifer maps; (iii) to determine the safe yield level of aquifer up to union/mouza level in the High Barind region; and (iv) to identify the Water Stress Area (WSA) considering present and future water uses.

The following activities are envisaged in achieving the study objectives:

1. Collect hydrological, meteorological, hydrogeological, morphological, cross section of the major rivers and their tributaries/distributaries, Digital Elevation Model (DEM), groundwater level, water quality, aquifer properties and other necessary data from secondary sources as per required for the assessment of surface water and groundwater resources availability in the study area.
2. Examine the present water use scenario, sectoral water demand and groundwater recharge mechanism in the study area based on the collected secondary data.
3. Conduct field cross section survey of major rivers and their tributaries/distributaries, install water level gauge and monitoring, discharge measurement and riverbed material sampling and analysis.
4. Preparation of Isohyetal maps depicting distributing of normal/annual/seasonal rainfall over the study area.
5. Exploratory drilling and install necessary groundwater monitoring wells to fill up data gap and put older wells back into service to study and monitor groundwater level, quality, aquifer system, aquifer behavior and subsurface lithology of the study area.
6. Carry out reconnaissance survey, well inventory, field tests and laboratory tests of aquifer material samples and to investigate sub-surface geological information, thickness of weathered zone, fracture density and spatial and temporal variations in groundwater quality.
7. Perform pumping test to investigate the hydraulic properties of the aquifer such as the specific storage, specific yield, porosity, transmissivity, hydraulic conductivity etc.
8. Carry out Geophysical Resistivity Survey (GPRS) through Vertical Electric Sounding (VES) study to fill up necessary data gap and to develop a Conceptual model to formulate the composition and nature of the aquifer system in the study area.
9. Determine the lateral and vertical extent, thickness and continuity of the aquifers and characterize the properties of aquifer sediments up to Mouza level in the study area
10. Identify and delineate recharge and discharge areas of the aquifer by integrating data on rainfall, surface water, groundwater, land use and soil types.
11. Prepare the aquifer maps with GIS datasets depicting aquifer geometry, aquifer properties, geophysical parameters, and water quality parameters.

12. Update rainfall-runoff (NAM) model, existing hydrodynamic model for river flow assessment, and any other model, if necessary, for the study area.
13. Develop a groundwater model to assess groundwater resources availability following the Conceptual model and evaluate the trend of the groundwater movement by mapping of groundwater depth contour (maximum depth to phreatic surface, minimum depth to phreatic surface, fluctuation etc.) in the study area.
14. Coupling of surface water and groundwater model to develop surface water-groundwater interaction model to get a complete natural hydrological scenario for assessment, analysis and prediction of groundwater and surface water resources of the study area.
15. Assess the present surface water and groundwater availability and recharge mechanism using the developed model and examine the impact of climate change on future water availability in the study area.
16. Determine and fix the safe yield level of aquifer up to Union/Mouza level of the study area based on water resources availability, use, demand, and recharge potential.
17. Identify the Water Stress Area (WSA) considering present and future water uses in the study area, including technical constraints on water access; and provide suitable solution for sustainable water management in the Water Stress Areas.
18. Identify the potential water bodies needed for conservation as a source of potable water, as aquatic habitat, and for recharging underground aquifers.
19. Develop and disseminate appropriate strategies for conjunctive use of rainwater, surface water and groundwater to improve efficiency of resource utilization and minimum groundwater abstraction.
20. Reporting: Inception, Progress, Mid Term Report, Draft Final and Final Reports.

1.4 Location of the Study Area

The study area is located in Chorghat, Paba, Bagmara, Puthia, Durgapur, Tanore, Mohonpur, Godagari, Bagha Upazilas of Rajshahi district, Patnitala, Raninagar, Dhamoirhat, Mohadevpur, Niamatpur, Manda, Porsha, Badalgachi, Atrai, Naogaon and Sapahar Upazilas of Naogaon district and Nachol, Bholahat, Shibganj, Chapainawabganj Sadar and Gomostapur Upzilas of Chapainawabganj District as shown in Figure 1-1. The area lies approximately between 24⁰23' to 25⁰15' N latitudes and 88⁰02' to 88⁰57' E longitudes. The area is bounded by Indian territory on the west and North, Ganges River on the South, and Joypurhat Sadar and Akkelpur Upazilas of Joypurhat District, Adamdighi and Nandigram Upazilas of Bogura District and Singra, Natore Sadar, Bagatipara, and Lalpur Upazilas of Natore District on the east. The project will promote and facilitate the operationalizing of the Bangladesh Water Rules, 2018. However, most of the activities have been targeted at piloting the implementation of the Rules, Guidelines, IWRM interventions and assessment of state of water resources in the administrative limits of Rajshahi, Chapainawabganj and Naogaon districts in the High Barind region.



Figure 1-1: Base Map of the Study Area

1.5 Structure of the Report

This report is the Final Report of “Hydrological Investigation and Modelling of the State of Surface and Groundwater Resources in the Barind Region”. This report contains the technical works carried out during the study period, findings, conclusions, and recommendations. The report is presented in four volumes for the sake of clarity and ease of comprehending the issues addressed during the study.

This is Volume-I: Main Report which comprises 13 chapters including a list of references mentioned in the report. A list of acronyms and abbreviations used in the report has been presented following the table of contents.

Chapter 1 focuses on the project background, study objectives, scope of work.

Chapter 2 collection and review of policies, acts & guidelines related to the study are briefly described in.

Chapter 3 focuses on the major data collection issues. It deals with the data requirements, data collection program from both the primary and secondary sources of different types of data such as hydrometric and hydrometeorological data, hydrologic and hydrogeological data etc.

Chapter 4 represents the hydrogeological settings of the study area. It also focuses on regional geological settings with district wise geological settings of the study area and focuses on the hydraulic properties of aquifer in the study area.

Chapter 5 focuses on the dynamics of groundwater in the study area. It deals with groundwater recharge and discharge characteristics and long-term trend of groundwater level of the study area.

Chapter 6 focuses on the groundwater sampling and quality assessment of the study area.

Chapter 7 provides a computation of water demand of the study area.

Chapter 8 describes the development, calibration and validation of surface water and groundwater model.

Chapter 9 represents the prospect of future surface water development.

Chapter 10 provides groundwater resource assessment, safe yield, water stress area of the study area.

Chapter 11 gives a brief on the workshops that have been conducted under the study at the national level.

Chapter 12 provides findings and recommendations on the study.

Chapter 13 cited the References of the reports and manuals consulted for the preparation of the report.

Annexure-A: Terms of Reference (ToR)

2 REVIEW OF POLICIES, ACTS & RULES AND PREVIOUS STUDIES

Since the inception of the study, IWM collected various reports, data, maps and related documents from relevant organizations. To obtain a preliminary idea on hydrological and hydrogeological issues pertaining the study and to identify information and data gaps for formulation of primary data collection program as well as to utilize judiciously the existing information, the review of previous studies has been conducted. Only some of the important reports/documents are listed in the following sections:

Table 2-1: List of Relevant Documents and Previous Studies Report Reviewed Under this Study

Sl. No.	Name of the Report	Study Conducted by	Year
1.	Groundwater and low-lift irrigation in the Northern part of East Pakistan	IECO	1964
2.	BADC / IDA Tube Well Project Consultant Report, Vol 3A	MacDonald	1977
3.	BADC / IDA Tube Well Project Consultant Report, Vol 3A	MacDonald	1978
4.	Northwest Bangladesh Groundwater Modelling Study, Final Report	MacDonald	1982
5.	Ground-Water Survey-Technical Report on Hydrogeologic Conditions of Bangladesh	UNDP-BWDB	1982
6.	Water Balance Studies of Bangladesh, Final Report	MacDonald	1983
7.	BARIND TRACT, Rajshahi - Groundwater Exploration Follow- Up Report	Asaduzzaman M	1983
8.	Upazila wise Groundwater Recharge conditions of Bangladesh	Karim, M.A	1984
9.	BARIND TRACT, Rajshahi - Groundwater Exploration Second Follow- Up Report	Asaduzzaman M	1985
10.	Technical Report no 5 on "Groundwater Resources"	MPO	1986
11.	Water Survey for Barind Integrated Area Development Project, Volume I, Main Report	BWDB-Bureau of Consulting Engineers Ltd & Etals	1990
12.	Barind Integrated Area Development Project	BIDS	1995
13.	National Water Management Project (NWMP) Volume 4 Annex C: Land and Water Resources	WARPO	2000
14.	Impact Evaluation- Barind Integrated Area Development Project	Kranti Associates Limited	2000
15.	Tubewell Spacing Study	IWM	2006
16.	Groundwater Model Study for Deep Tubewell Installation Project in Barind Area	IWM	2006
17.	Groundwater Resources Study and Decision Support System Development of Rajshahi, Naogaon, Chapainawabganj, Pabna and Natore Districts and Also Remaining Districts (Except Thakurgaon, Panchagarh, Dinajpur & Joypurhat	IWM	2012

Sl. No.	Name of the Report	Study Conducted by	Year
	Districts) of Rajshahi Division through Mathematical Model Study for Barind Integrated Area Development Project, Phase-III		
18.	Hot spot Barind, Rajshahi	Delta Atelier	2015
19.	Impact Evaluation of Barind Command Area Development and Training Project	IMED	2016
20.	Assessment of State of Water Resources	IWM	2016
21.	National Strategy for Water and Sanitation Hard to Reach Areas of Bangladesh	DPHE	2011
22.	Environmental Challenges and the Measures Taken by the BMDA for Sustainable Agriculture and Environment in the Barind Tract, North-West of Bangladesh	Mohammad Selim Reza	2020
23.	Farmer's Adaptation Strategies to Drought and their Determinants in Barind Tract, Bangladesh	M.S. Islam	2019
24.	The Bengal Water Machine: Quantified freshwater capture in Bangladesh.	Mohammad Shamsudduha	2022

In addition, the following Key Acts, Plans and Policies have been studied under this project:

- National Water Policy (1999)
- Bangladesh Water Act 2013 and its Rules 2018
- Safe Drinking Water Supply and Sanitation Policy 1998
- National Water Management Plan (NWMP)
- Bangladesh Delta Plan 2100
- Eighth Five Year Plan (8th FYP)
- Sustainable Development Goals (SDG), 2015

Some of the important findings of previous studies are narrated in the following sections:

IECO (1964) identified the project area as a good potential area for groundwater development. The groundwater recharge was estimated to be 610 mm per year.

MacDonald (1978) "BADC / IDA Tube Well Project Consultant Report, Vol 3A." The study reveals that annual potential recharge was estimated varying from about 600 mm to 800 mm, but available recharge would be less by 20% to 30% from the potential recharge.

UNDP-BWDB (1982) “Ground-Water Survey-Technical Report on Hydrogeologic Conditions of Bangladesh”. According to this report the study area has limited thick sandy aquifer especially in the high Barind area and transmissivity-value ranges 500m²/day to 1500m²/day. Annual recharge varied from a minimum of 80 mm to a maximum of 190 mm.

Karim, M.A. (1984) “Upazila wise Groundwater Recharge conditions of Bangladesh.” This report stated the potential recharge in the study area is in the range varying from 400 mm to 700 mm;

Master Plan Organization (MPO, 1986) Technical Report no 5 on “Groundwater Resources”. A ground water recharge model was developed from the study of catchments recharge simulation done in eight specific study areas. Potential and available recharge for the study area was estimated respectively to be in the range of 200 mm to 500 mm, and 100 mm to 400 mm respectively. Potential recharge for Bagmara upazila was estimated to be 350 mm.

BWDB-Bureau of Consulting Engineers Ltd & Etals-1990 “Water Survey for Barind Integrated Area Development Project, Volume I, Main Report” This report covering 17 upazilas of Rajshahi, Naogaon and Chapainawabganj districts have been prepared basing on the existing data, reports and primary data of test-drillings, ground -water monitoring wells and aquifer tests. Assessed upazila wise actual and available ground water recharge varied from 322 mm to 567 mm, and 243 mm to 411 mm respectively, balance of available recharge after existing uses and determined assuming all DTW of 2 cfs capacity running 13 hrs /day for 120 irrigation day and all STW of capacity 0.40 cfs of the same periods, the prospect of drilling additional 850 DTW with 50% safety of factor.

NWMP (2000) assessed countrywide water resources and planned for present and future development under National Water Resources Planning. Groundwater resources of the project area were also assessed. Groundwater potential recharge was estimated to be in the range of 600 mm and 800 mm.

WARPO (2000) Water Resources Planning Organization –National Water Management Project (NWMP) Volume 4 Annex C: Land and Water Resources. The estimated potential recharge values of the study-area are in the range of 304 mm to 700 mm against net requirement of 430 mm for full development by irrigation. Available recharge is in the range of 228 mm to 504 mm.

Institute of Water Modelling (IWM), (2012) “Groundwater Resources Study and Decision Support System Development of Rajshahi, Naogaon, Chapainawabganj, Pabna and Natore Districts and Also Remaining Districts (Except Thakurgaon, Panchagarh, Dinajpur & Joypurhat Districts) of Rajshahi Division through Mathematical Model Study for Barind Integrated Area Development Project, Phase-III”. Major findings of the study where the potential recharge in the study area varies from 357 mm to 725 mm. Total potential recharge in the project area was found 12782 mm, while in the MPO study it was 10002 mm and in the

NWMP study it was 11855 mm. Potential recharge of IWM study was 7.2% higher than NWMP study and 21.7% higher than MPO study. Potential recharge of this study was mainly higher in the low Barind area compared to NWMP and MPO study.

The details of literature and Acts, Plans & Policies and review of previous studies are given in Volume -II, Chapter 2 & 3.

3 DATA COLLECTION AND PROCESSING

3.1 General

The study project is designed for detail field investigation to develop numerical models to assess the state of surface and groundwater resources up to union level for supporting pilot operationalization of the Bangladesh Water Rules, 2018 in the Barind region. An integrated approach has been taken incorporating the land and water ecosystem, interaction between the surface and groundwater of the area to assess the availability, scarcity and safe yield of water resources. Prior to application of models for simulation, different data collected both from primary and secondary sources have been analyzed. Different type of data that has been collected under the proposed study is broadly classified into following groups:

- Hydro-meteorological
- Hydrological
- Hydrogeological
- Agriculture and Soils
- Water Abstraction
- Seepage and Percolation
- Water Quality

Different organizations such as BMD, BWDB, BADC, BMDA, DPHE, DAE, SRDI and LGED are the secondary sources for these data and information. To fulfill the study requirements, IWM has undertaken a field data collection programme.

3.2 Secondary Data

Hydro-meteorological data that has been collected for the study includes rainfall, evaporation, temperature, relative humidity, sunshine hours. BWDB and BMD have very good data collection network. Existing historical data has been collected from BWDB, BMD and other relevant agencies. The central database of IWM also contains historical time-series data for all monitoring stations in Bangladesh maintained by BWDB.

3.2.1 Rainfall

Rainfall data has been collected for 19 nos. of stations for the duration of 1985 to 2022. Quality checking of rainfall includes visual observation of plots of rainfall, preparation of double mass curves, estimation of yearly mean values, and comparison of monthly values. Details of rainfall data processing are given in Chapter 5, Volume -II.

The isohyetal approach is used to have an idea on spatial distribution of precipitation across an area. In this study, the isohyetal maps for annual average, pre-monsoon, monsoon, post-monsoon and dry-season rainfall are generated. The annual average annual rainfall distribution is shown in Figure 3-1.

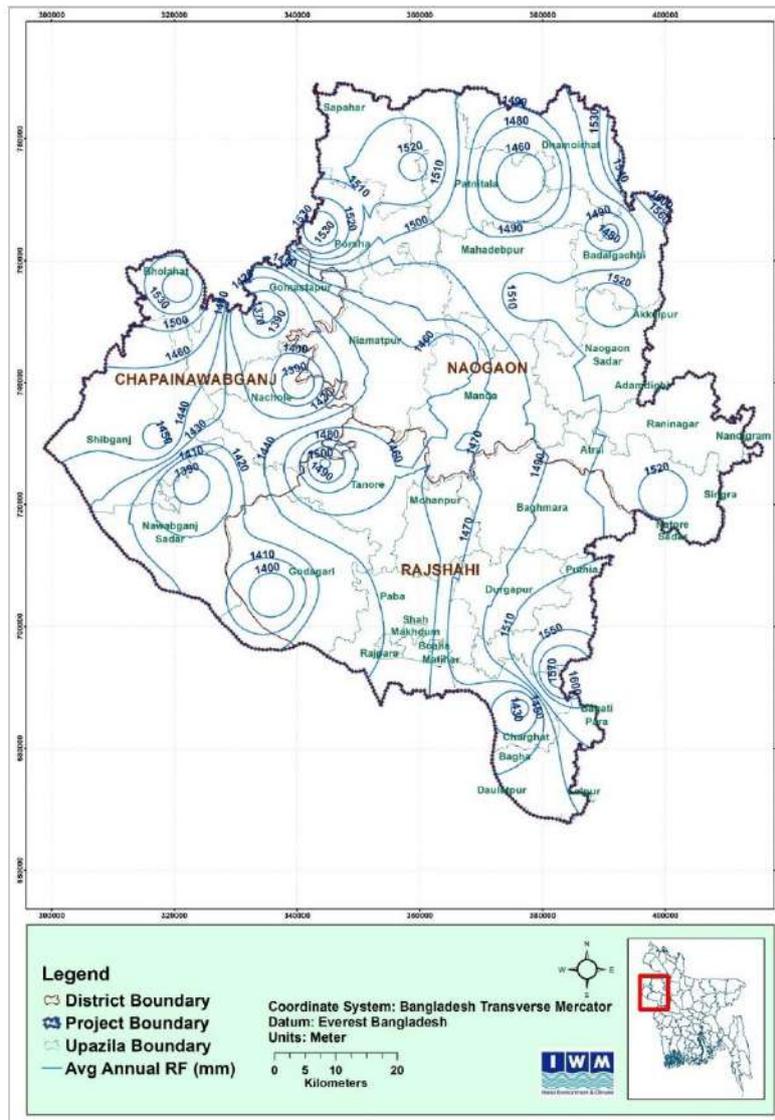


Figure 3-1: Isohyetal Map of the Study Area with Average Annual Rainfall

3.2.2 Evaporation

Evaporation data is required as an input to develop model. BWDB maintains 2 evaporation stations in the vicinity of the project area. Information of this station is given in Table 3-1. Data of those stations have been collected to develop model.

Table 3-1: List of Evaporation Stations for the Study Area

SL No.	Station ID	Station Name	Easting	Northing	Data Collected	
					From	To
1	CL195	Chapainawabganj	322600.03	723448.75	1997	2022
2	CL205	Boalia	347756.53	697868.12	1997	2022

3.2.3 Groundwater Level

There are 127 nos. of BWDB groundwater monitoring wells located in the study area which have been monitored by BWDB for a long period of time and have long time series data for modelling. To fill up the data gap and comparison with the existing data collected from secondary sources, 50 nos. of groundwater monitoring wells have been installed under this project. Groundwater level data is being checked for consistency following the standard procedures of IWM Handbook. Plot of groundwater level at Charghat (GT 8125055) along with rainfall of Rajshahi (R205) and Plot of groundwater level at Tanore (GT 8194046) along with rainfall of Tanore (R219) is shown in Figure 3-2. There is a negligible declining trend is seen in the groundwater level of Charghat. But from the analysis of groundwater level of Tanore, there is a huge and alarming declining trend is seen. About 8.0m decline has been found for Tanore area over the period of 2005 to 2022.

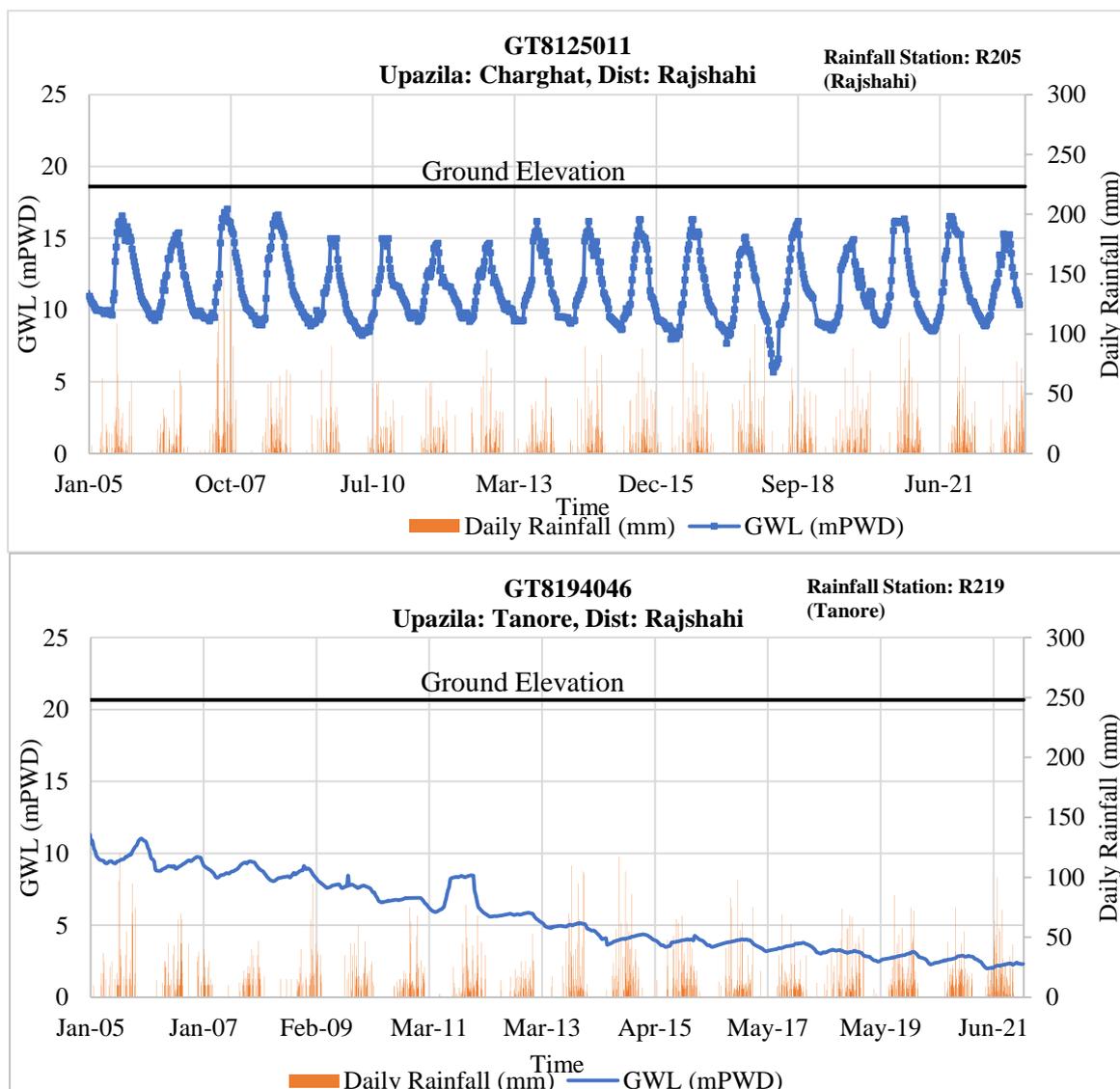


Figure 3-2: Plot of Groundwater Level Data at Charghat in GT 8125011 and at Tanore in GT 8194046

3.2.4 Surface Water Level

There are 15 nos. of BWDB surface water monitoring stations available with long time series data in the study area as shown.

in Figure 3-3. After necessary quality checking these data has been used in surface water model setup and various analyses have been carried out for evaluating seasonal variation and trend analysis.

The water level at Jote Bazar (SW 82, Fakirni Barnai River) is shown in Figure 3-3. There is a slight decreasing trend in the water level over the period 2003 to 2022.

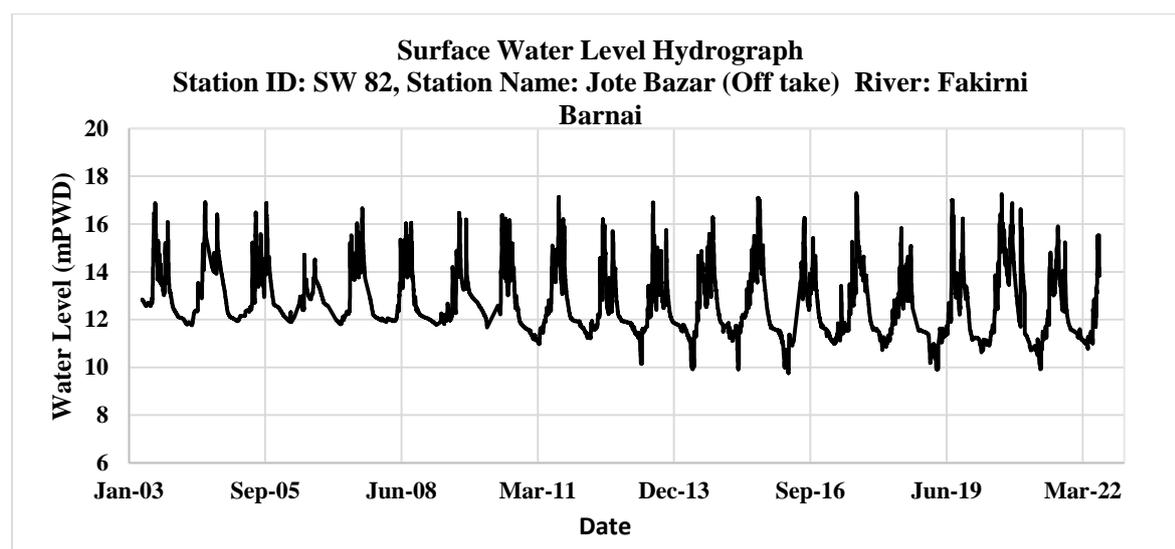
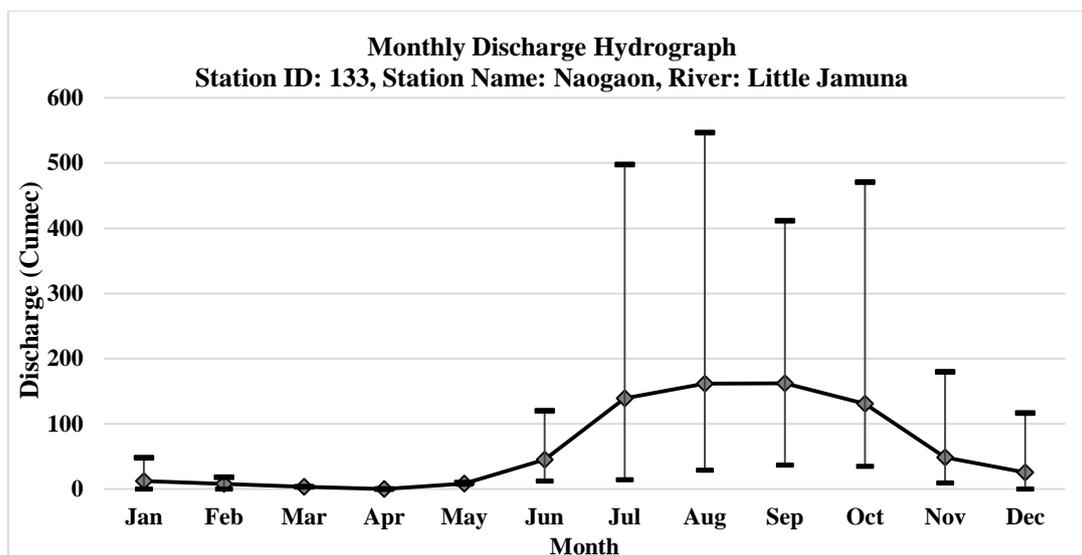


Figure 3-3: Water Level of Fakirni Barnai River at Jote Bazar (2003-2022)

3.2.5 Discharge Data

Long time series discharge data have been collected for 6 locations to define the boundary conditions of the surface water model as well as to calibrate the hydrodynamic model.

As shown in Figure 3-4, the average monthly discharge of the Little Jamuna River at Naogaon (SW133) varies from about 3.30 m³/s (in March) to 162.16 m³/s (in September). The high variability in flow is also highlighted by the wide range as shown in the Figure 3-4. For example, in July, the flow varies from 14.10 m³/s to 497.83 m³/s.



Note: points represent average value and range shown is for minimum and maximum monthly measured discharge.

Figure 3-4: Monthly Discharge Hydrograph of Little Jamuna River at Naogaon (1995-2022)

3.2.6 Bore Log Data

For assessing the aquifer geometry of different aquifer systems exist in and around the study area, 412 Nos. of litholog data have been collected from BADC, BMDA, BWDB, WARPO and DPHE to define the regional geology of the model area as well as lithologic cross section is shown in Table 3-2. The depth of collected data varies from 30m to 450m.

Table 3-2: Sources of Borehole Data

Sl. No.	District	Borelog	WARPO	BADC	BMDA	BWDB	DPHE
1	Rajshahi	220	19	5	3	172	21
2	Chapainawabganj	40	16	4	2	13	5
3	Naogaon	152	18	4	10	119	1
Total		412	53	13	15	304	27

A sample of lithologic cross section of Tanore upazila under Rajshahi district is shown in Figure 3-5. From the diagram it reveals that aquitard are mostly composed of clay and silty clay sediment materials and aquifers are mostly composed of medium to coarse sand with occasionally fine sand sediments. It also reveals that the northwestern part of the Rajshahi district is dominated by clay and silty clay layers and the opposite part (southeastern) is dominated by medium to coarse sand layers. The details of the lithologic cross sections have been given in Chapter 7, Volume -II.

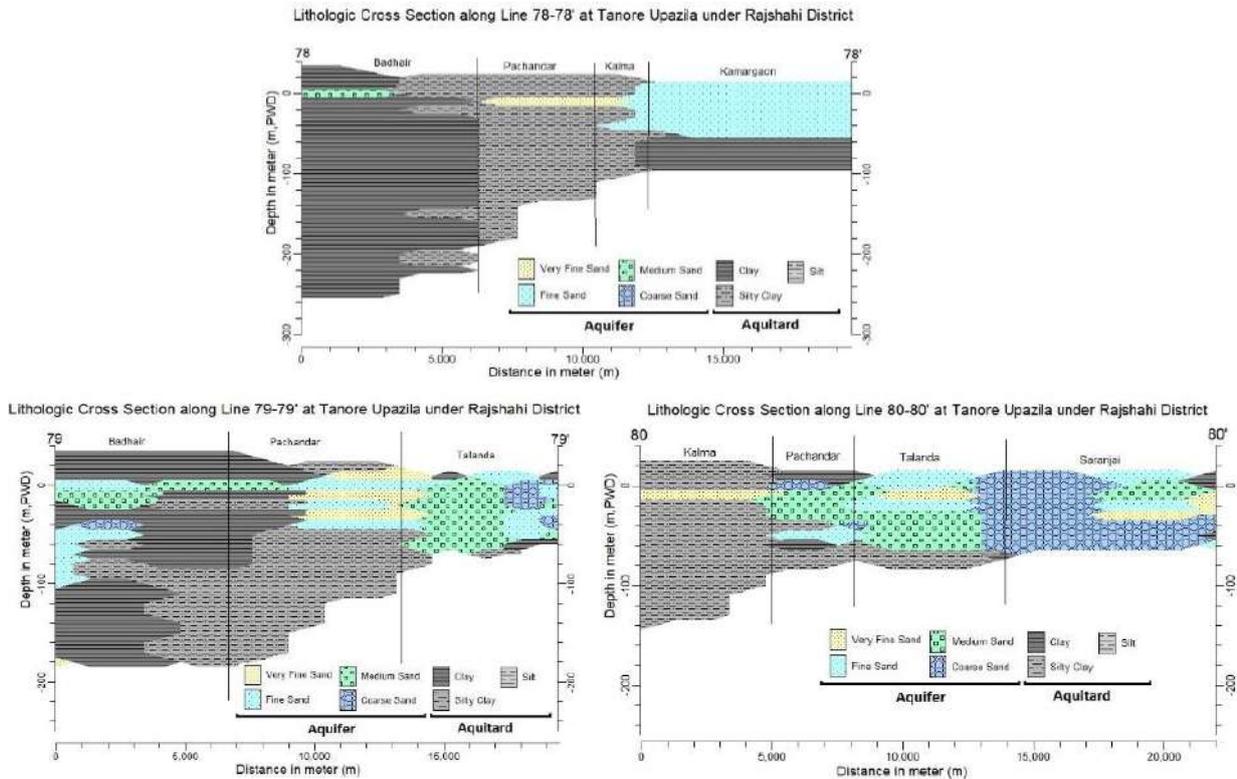


Figure 3-5: Lithologic Cross Sections of Different Unions Under Tanore Upazila.

3.2.7 Potential Water Body

The potential water bodies have been identified using remote sensing satellite data. The high resolution (<0.5m) remote sensing satellite data and GIS techniques have been used to mapping the potential water body of study area. A map for potential water bodies is given in Section 9.4, Chapter 9.

3.3 Primary Data

Existing hydrogeological data that includes groundwater level, lithologs and aquifer properties has been collected from available secondary sources. In addition, to fulfill the data gap, IWM has conducted a comprehensive field investigation program that includes (i) Exploratory drilling at 53 locations, (ii) Geophysical Survey at 30 locations, (iii) River Cross Section at 2000 locations, (iv) Installation of groundwater monitoring wells at 50 locations (v) Seepage and Percolation measurement at 30 locations (vi) Water quality sampling and analysis at 50 locations (vii) Discharge data collection at 12 locations (viii) Surface Water Level data collection at 12 locations of different rivers, (ix) Riverbed material collection and analysis at 12 locations, (x) Installation of Production well at 6 locations, (xi) Aquifer pump test at 30 locations. All data collection activities have been done under supervision of IWM and DASCOH representatives. The field activities also have been monitored by the professionals of WARPO and SRC. The locations are shown in Figure 3-6.

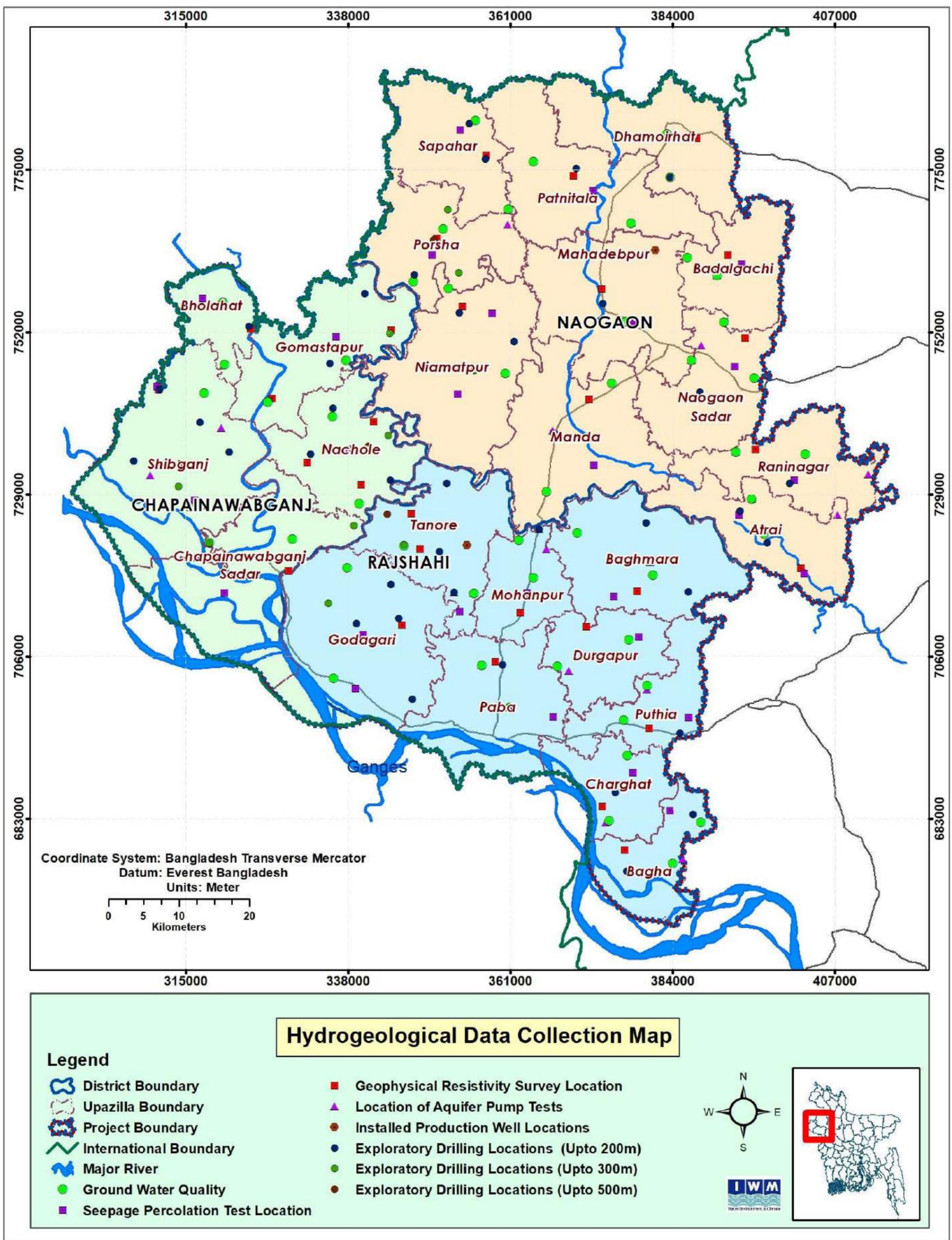


Figure 3-6: Hydrogeological Data Collection Map

3.3.1 Exploratory Drilling and Installation of Monitoring Well

Exploratory drilling has been done to define the regional geology as well as the lithologic cross section of the study area for development of model. A total of 53 nos. exploratory drillings have been completed as shown in Figure 3-6. Exploratory drilling depth of 40 nos. is 200 m, 10 nos. is 300 m and 3 nos. is 500 m. The test drilling locations are given in Figure 3-6 whereas the details of the exploratory drilling have been given in Chapter 5, Volume -II.

Depending on availability of potential aquifers, 50 nos of monitoring wells have been installed at the drilled locations. The details of the monitoring wells have been given in Chapter 5, Volume -II.

3.3.2 Groundwater Depth Monitoring

To observe the depth of the groundwater table, an observer has been appointed for each monitoring well. Daily groundwater depth monitoring has been started from May 2021. From time-to-time supervision is ongoing by the professionals of IWM, DASCOH and WARPO. The details of the groundwater depth monitoring have been given in Chapter 5, Volume -II.

3.3.3 Installation of Production Well

A total of 6 production wells have been installed under the present study at different locations. The locations are shown in Figure 3-6. These production wells have been used for aquifer pump tests to determine the hydraulic properties of the aquifer. The details of the production wells have been given in Chapter 5, Volume -II.

3.3.4 Aquifer Pump Test

To cover the entire study area and to get an updated understanding of aquifer properties, a total of 30 nos. of aquifer pump tests have been carried out, of which 6 were in newly installed production well and the remaining 24 were in existing BMDA tubewells. The location has been presented in Figure 3-7. Step drawdown test, aquifer pump test and recovery test were performed in 30 locations. For conducting the aquifer pump test, 3 nos. of observation wells have been constructed. The distance of the observation well was 3m, 30m, and 90m from the DTW (Pumping well) as shown in Figure 3-8. Aquifer pump tests were performed in a continuous pumping method with constant discharge rate. Pumping was continued until static water level achieved. Observation wells were installed at different distances to monitor the groundwater level and drawdown. Some photographs of conducting aquifer pump test are given in Figure 3-9. The aquifer pump test data have been analyzed by AQTESOLV software considering Theis's method, Cooper-Jacob method and Theis's Recovery methods, wherever applicable.

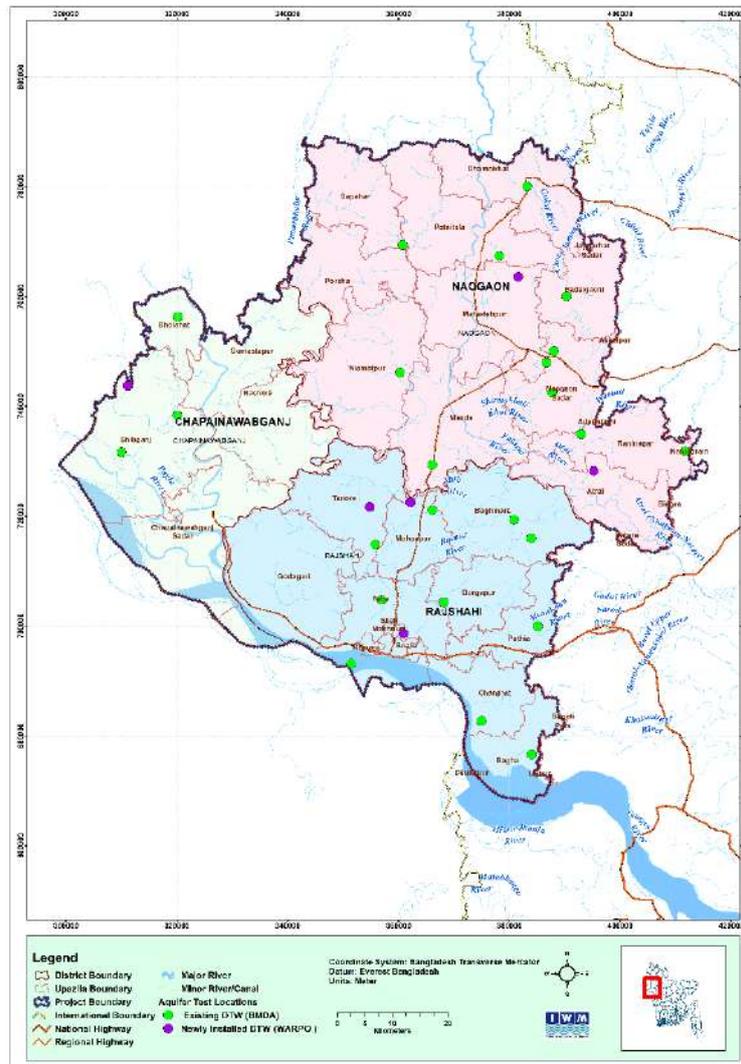


Figure 3-7: Map of Aquifer Pump Test Locations

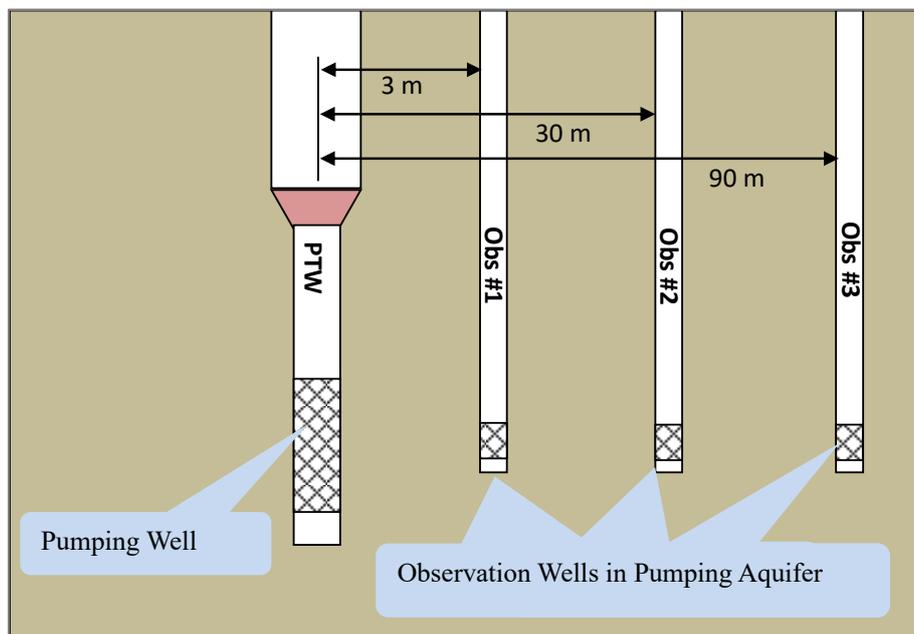


Figure 3-8: Layout Plan for Aquifer Pump Test



Figure 3-9: Some Photographs of Conducting Aquifer Pump Test

3.3.5 Geophysical Resistivity Survey

To understand the sub-surface geology as well as to fill up lithologic data gaps, Geophysical Resistivity Survey have been executed at 30 locations of Rajshahi, Naogaon and Chapainawabganj districts. Vertical Electrical Sounding (VES) with 600 m spread were carried out at the selected 30 different points in the study area as shown in Figure 3-6. The survey has been done by the Department of Geology and Mining, University of Rajshahi. The details of the Geophysical Resistivity Survey have been given in Chapter 5, Volume -II.

3.3.6 Water Quality

Fifty groundwater samples have been collected from 50 locations in the study area as shown in Figure 3-6. A total of 18 physicochemical parameters have been measured. Physical parameters such as pH, EC, Salinity, TDS, Temperature were measured in the field and hydro-chemical parameters such as Calcium, Magnesium, Sodium, Potassium, Bi-carbonate, Chloride, Nitrate, Phosphate, Sulphate, Iron, Fluoride, Arsenic and Manganese were examined in the laboratory. The depth range of the collected samples from the wells were 23 to 95m. The Department of Geology under University of Dhaka and Department of Public Health Engineering has conducted the laboratory test. The detailed analysis of groundwater quality data is given in Chapter 6 in this report and in Chapter 5, Volume -II.

Overall quality of groundwater in the study area for drinking and irrigation purposes is generally good, except for certain chemical elements such as bicarbonate, iron, and manganese, which exceed the permissible standard limits set by Bangladesh. The majority of collected groundwater samples exhibit elevated levels of bicarbonate (98% of samples), iron (80% of samples), and manganese (76% of samples).

According to the data collected under this study and the report of BGS 2001, the arsenic concentration has been found as beyond the drinking water limit (BD standard) at Durlabpur, Monakasha unions of Shibganj upazila and Ranihati union of Chapainawabganj sadar upazila in Chapainawabganj district, Jewpara union of Puthia upazila, Baksimoil union of Mohonpur upazila, Haripur and Hujuripara unions of Paba upazila in Rajshahi district and Nurullabad and Manda unions of Manda upazila in Naogaon district.

3.3.7 Cross Section Survey

A total of 2000 nos. of cross-sections survey in the river/channel has been carried out in different rivers and khals to fill data gaps. The cross-sections of rivers have been extended about 50 m in the countryside. For rivers with embankments nearby, some cross-sections have been extended to include the embankments. The spacing of the river sections has been adjusted to fulfil the regional hydrodynamic model requirement as well as to optimize the cost involvement. A cross-section survey for the deeper part of the river has been done using Digital Echo-sounder supported by DGPS and a notebook computer installed with Hydro Pro survey software. All cross-sections have been connected with SOB BM Pillars.

3.3.8 Installation of River Water Level Gauge and Data Collection

In addition to available secondary data, twelve (12) water level gauge stations are installed to fulfil gaps for supporting and updating the regional hydrodynamic model study for the project area as shown in Figure 3-10. Water level observations are being carried out from 6:00 AM to 6:00 PM at three-hour intervals. Periodical checking of gauge registers, checking of gauge “Zero-value” connections, consistency check of water levels with respect to time have been done during monitoring gauges. All water level gauges observations have been carried out during October 2021-September 2022. The details are given in Chapter 5, Volume -II.

3.3.9 Discharge Measurements

In addition to available secondary data, discharge measurements have been conducted at 12 locations as shown in Figure 3-10 using Vale port Current Meter. The measurement has been carried out fortnightly from November 2021 to April 2022. The velocity has been measured at 0.2 x depth, 0.6 x depth & 0.8 x depth by current meter. Discharge has been calculated from the measured data for the selected rivers as an input of model requirements. The details are given in Chapter 5, Volume -II.

3.3.10 Riverbed Material Collection and Analysis

Riverbed material has been collected at the location of discharge measurement points (12 no's points) to know the grain size distribution. Three samples have been collected from each point (one from the middle of the channel and the other two from the banks). Samplings have been made using Van Veen Bed Sampler (Grab). Analysis for other samples have been given in Chapter 5, Volume -II.

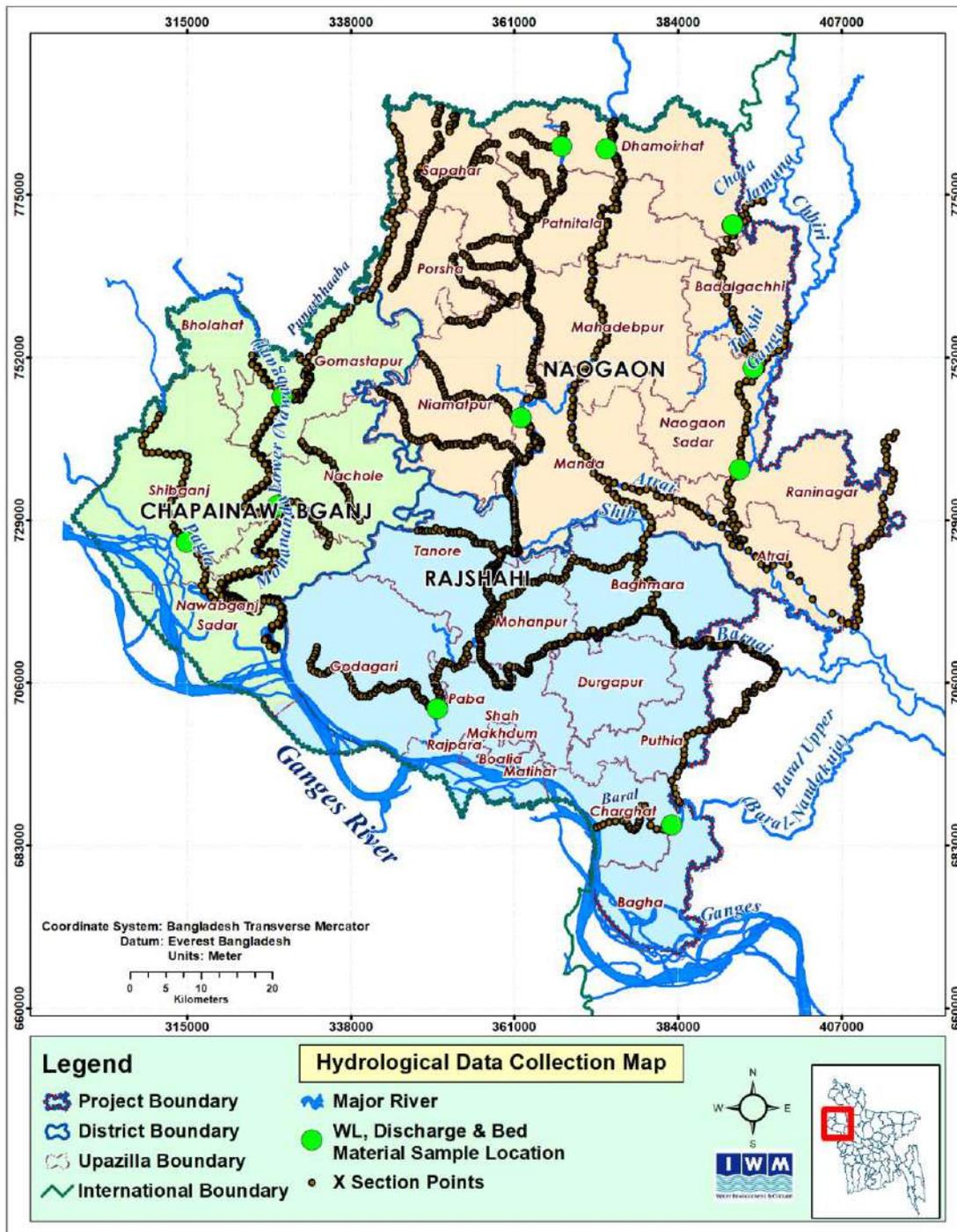


Figure 3-10: River Cross Section, Surface Water Level and Discharge Data Collection Location

3.3.11 Seepage and Percolation Measurement

For assessment of S&P rate of the soil of the study area, necessary data collection arrangement from the field has been made at 30 locations as shown in Figure 3-6. Data collection commenced in the 1st week of March 2022 and continued up to April 2022. Water on depth of water above the ground surface in the irrigated field has been collected and analyzed. The details are given in Chapter 5, Volume -II.

4 AQUIFER SYSTEM IN THE STUDY AREA

4.1 Hydrogeological Setting of the Study Area

Available aquifer information including borehole lithologic logs gives an idea about the depth and variable thickness of the aquifer in the study area. Hydrogeological parameters of an area are governed by the litho-stratigraphic characteristic and prevailing tectonic features, which is a part of regional hydrogeological setting. Hydrogeological conditions can be explored by the aquifer characteristics utilizing the lithologic cross section throughout the study area. Hydrogeological investigation for the study area has been carried out to define the aquifer system and properties of aquifer sediments through geophysical logging and lithological characterization including aquifer pump test.

The subsurface geology of Chapainawabganj, Rajshahi and some parts of Naogaon Districts is very complex. To identify the aquifer composition and extension, a total of 412 nos. borehole lithologs data have been collected from WARPO, IWM, BADC, BMDA, BWDB and DPHE, as shown in Table 4-1 and Figure 4-1. Among them 53 nos. of deep exploratory drilling have been conducted under this project. The depth of collected data varies from 30 m to 450 m.

Table 4-1: Sources of Borehole Data

Sl. No.	District	Borelogs	WARPO	BADC	BMDA	BWDB	DPHE
1	Rajshahi	220	19	5	3	172	21
2	Chapainawabganj	40	16	4	2	13	5
3	Naogaon	152	18	4	10	119	1
Total		412	53	13	15	304	27

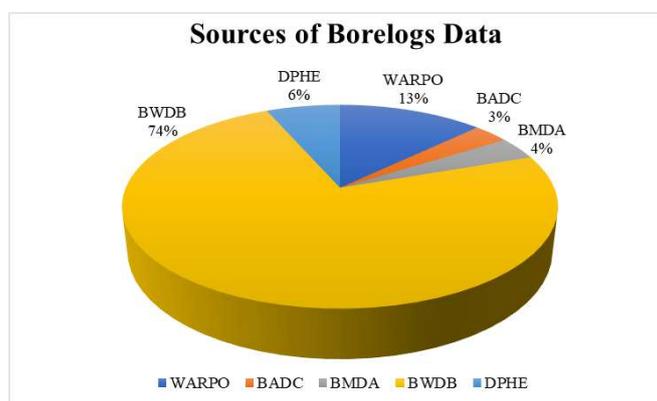


Figure 4-1: Sources of Collected Bore Log Data

To understand the aquifer geometry of different aquifer systems, exist in and around the study area, lithologic cross sections have been prepared. The details are given in Chapter 7, Volume -II.

Aquifer properties have been estimated based on aquifer pump test data analysis. A total of 30 nos. of aquifer pump tests have been conducted under this project at different locations in Chapainawabganj, Naogaon and Rajshahi districts. Among them 6 nos. of aquifer pump tests have been conducted in the newly installed production well (PW) and 24 nos. aquifer pump tests have been conducted in existing BMDA deep tubewell (DTW).

4.2 Aquifer System of Rajshahi District

Aquifer System Based on Lithologic-Logs

The Rajshahi district mostly falls under the two physiographic units: Barind Tract and Ganga River Floodplain. Tanore and Godagari upazilas fall under the unit of Barind Tract whereas there is one thin aquifer existed in the shallow depth throughout the area except some eastern part of Tanore and Godagari upazila. The thickness of the aquifer varies from 3 to 12 m. Groundwater table for 1st aquifer is 23 to 34 m. In Badhair union, there is no aquifer present below the 1st aquifer upto the drilling depth of 426m. Thick aquifers present in the eastern part of Tanore and Godagari upazila such as Soranjai, Pachandor, Talando and Kumargaon unions, where the aquifer thickness varies from 27 to 72 m, but the groundwater table decline down to the depth of 25-27 m. Rajshahi City Corporation, Puthia, Bagha, Paba, Charghat and Bagmara and Partly Mohonpur upazilas fall under the unit of Ganga River Floodplain where multi-aquifers are present throughout the area. The groundwater table exists within the suction limit (7 m) except for some areas of Rajshahi City Corporation, Mohonpur and Bagmara upazilas. In Mohonpur, Tanore and Godagari area, declining trend of water level is very alarming and further abstraction of groundwater is not recommended. Mundumala pourashava and Badhair union have critical conditions in terms of subsurface lithology and groundwater level declining trend that required special attention for further development. Lithologic Cross Sections diagram of Rajshahi district is shown in Figure 4-2. The union wise lithologic cross sections are shown in Chapter 7 in Volume-II and aquifer mapping based on lithologic layer and thickness are shown in Volume -III. A sample map of extension and thickness of the multi-layered aquifers under Tanore upazila are presented in Figure 4-3 to Figure 4-5.

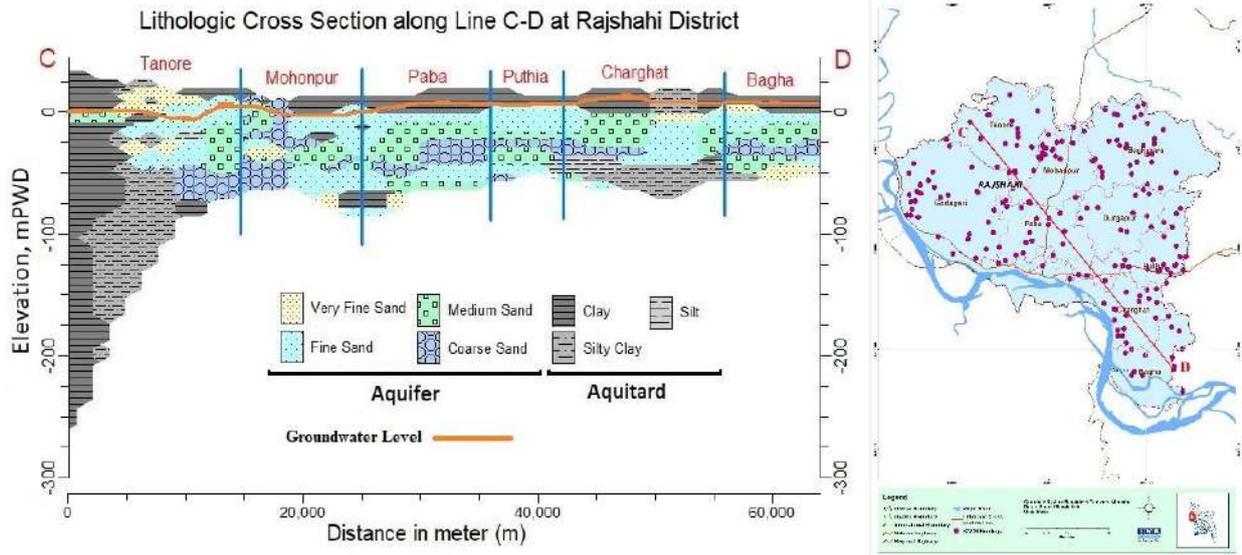


Figure 4-2: Lithologic Cross Sections Along Line C-D at Rajshahi District

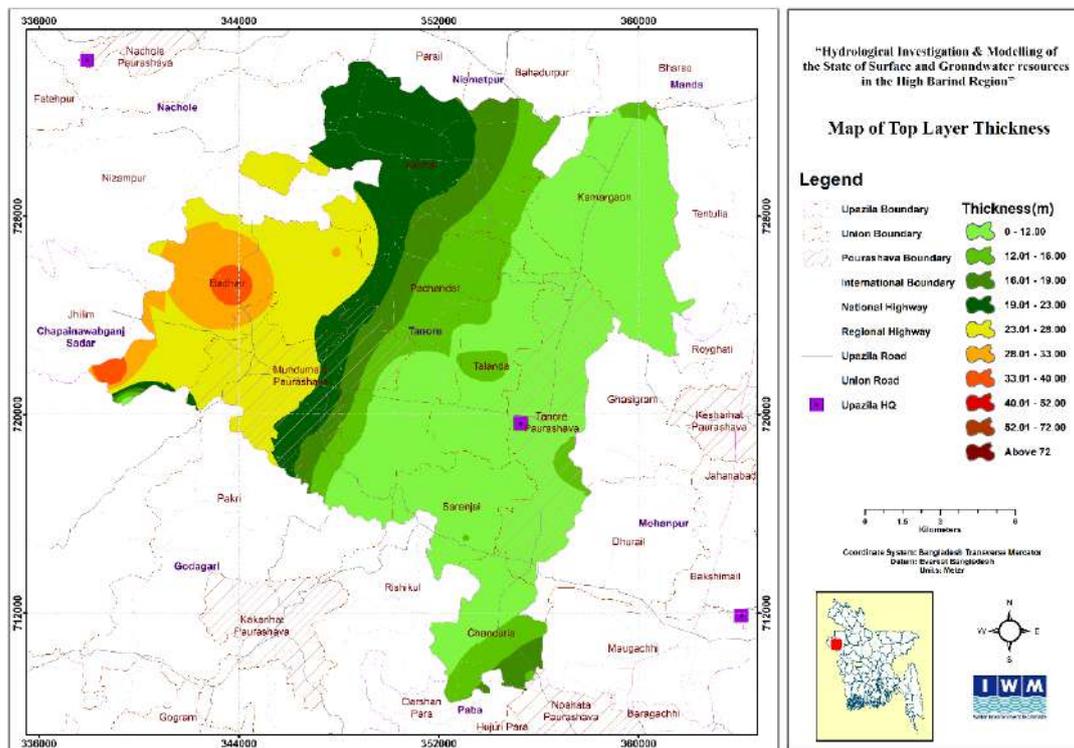


Figure 4-3: Map of Top Layer Thickness at Tanore Upazila under Rajshahi District

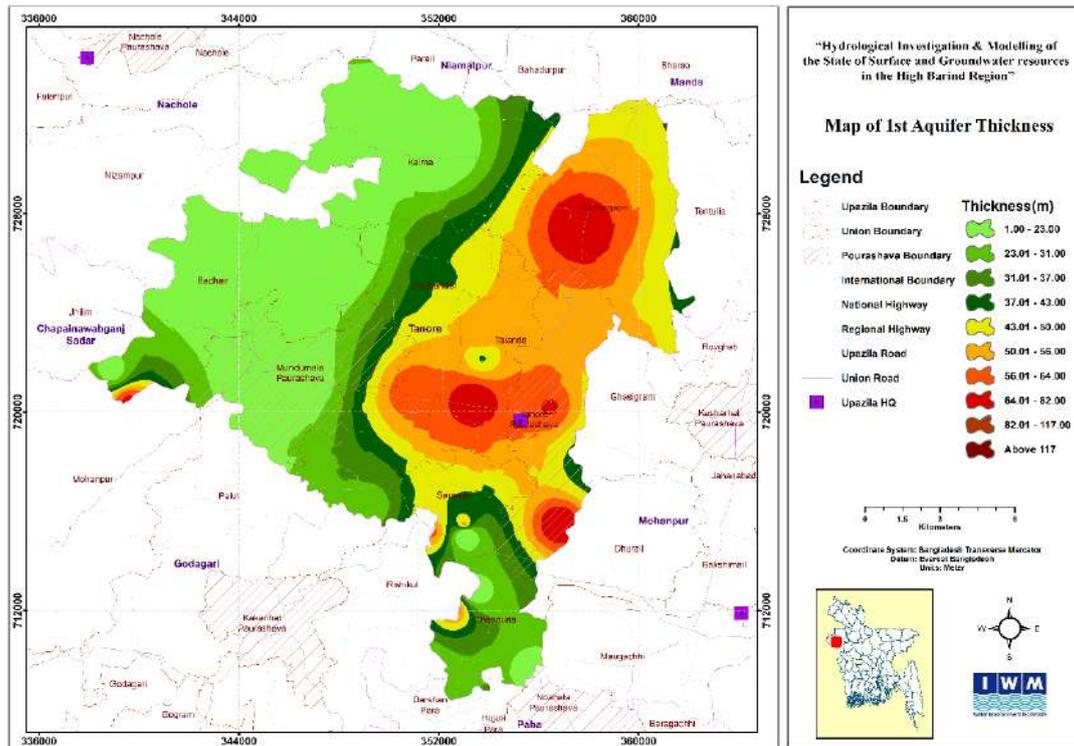


Figure 4-4: Map of 1st Aquifer Thickness at Tanore Upazila under Rajshahi District

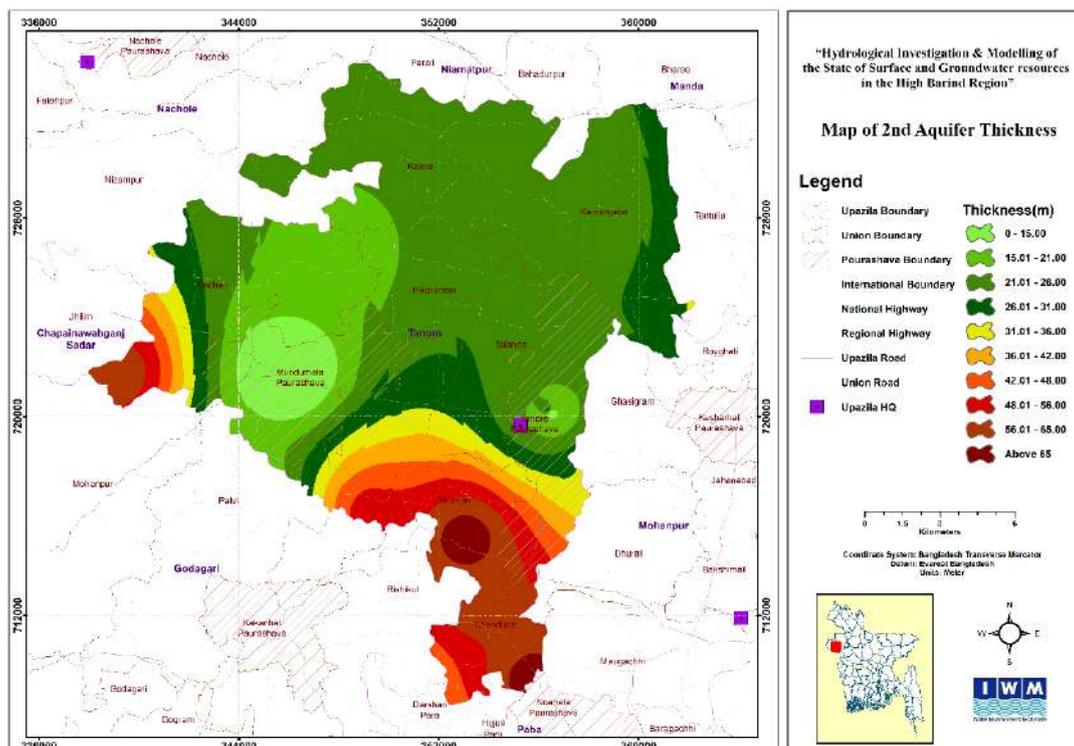


Figure 4-5: Map of 2nd Aquifer Thickness at Tanore Upazila under Rajshahi District

Hydraulic Characteristics of Aquifer Sediments

For the calculation of hydraulic properties of aquifer at Rajshahi district, 22 aquifer pump tests data were collected from 9 upazilas of Rajshahi district. Among them 10 aquifer pump tests were conducted in the existing Deep Tubewell (DTW) of BMDA, and 3 aquifer pump tests were conducted in newly installed Production Well (PW). The rest of the tests data are collected from secondary sources. The aquifer pump test data have been analyzed by AQTESOLV software considering Theis's method, Cooper-Jacob method and Theis's Recovery methods, wherever applicable. The location of collected aquifer pump tests data from different sources are shown in Table 4-2.

The transmissivity values at Rajshahi district vary from 643 to 7437 m²/day whereas the storage coefficient ranges from 0.0000124 to 0.0133 for 1st aquifers. At Bagha, Bagmara, Durgapur, Mohonpur, Puthia, Paba and Rajshahi City Corporation, the aquifer possesses moderate to high transmissivity values. At Charghat upazila, the aquifer has low value in Sardah union whereas Chandpur, Kakramari and Nimpara union have moderate transmissivity value. These types of variation occur due to aquifer thickness as well as lithologic variation in shorter distance. In Kalma union of Tanore upazila has moderate transmissivity value whereas at Talando, Tanore and Chanduria unions have high transmissivity value. At Godagari upazila, the aquifer in Dewpara union has lower transmissivity value. Storage coefficient values and geological section indicates that the aquifer might be semi-confined to confined in nature. A sample map of aquifer properties at Durgapur upazila are presented in Figure 4-6 to Figure 4-7. The union wise aquifer properties are shown in Chapter 7 in Volume -II and aquifer mapping based on aquifer properties are shown in Appendix -F to Appendix -H, Volume -III.

Table 4-2: Hydraulic Properties of Aquifer Sediment Based on Aquifer Pump Test at Rajshahi District.

Sl. No	Upazila	Union	Pump Locations		Transmissivity (m ² /d)	Storage Coefficient
			Latitude	Longitude		
Aquifer Pump Test Data Collected Under Present Study						
1	Bagha	Bajubagha	24.20068	88.85528	5003	0.0005013
2	Bagmara	Bhabaniganj	24.58628	88.81994	2702	0.0009173
3	Bagmara	Goalkandi	24.55623	88.85174	2278	0.0006804
4	Charghat	Chandpur Kakramari	24.25474	88.76562	2198	0.0004545
5	Charghat	Nimpara	24.34713	88.83285	2422	0.0133153
6	Durgapur	Joynagar	24.44962	88.69660	4668	0.0011549
7	Mohonpur	Raighati	24.60125	88.67437	4678	0.0004678
8	Paba	Nawhata	24.45239	88.58545	2600	0.0004121
9	Puthia	Jewpara	24.41109	88.86434	2091	0.0034492
10	Tanore	Tanore	24.54381	88.57348	6387	0.0071758
Secondary Aquifer Pump Test Data						
11	Bagha	Manigram	24.21000	88.79630	2226	0.001000
12	Bagmara	Gobindapara	24.67376	88.74136	2363	0.0000527

Sl. No	Upazila	Union	Pump Locations		Transmissivity (m ² /d)	Storage Coefficient
			Latitude	Longitude		
13	Charghat	Sardah	24.31260	88.72550	916	0.000551
14	Durgapur	Maria	24.44425	88.76186	2919	0.000072
15	Godagari	Dewpara	24.42289	88.50383	643	0.000671
16	Mohonpur	Royghati	24.62365	88.66596	3165	0.0000181
17	Puthia	Puthia	24.37152	88.83786	2814	0.001773
18	Tanore	Chanduria	24.52011	88.56024	4734	0.0020146
19	Tanore	Kalma	24.67630	88.56220	1363	0.000357
20	Mohonpur	Royghati	24.61305	88.63559	4433	0.0004269
21	Rajshahi City Corporation	Shah Makhdum	24.39777	88.62563	3949	0.0004525
22	Tanore	Talando	24.60519	88.56337	7437	0.0000124

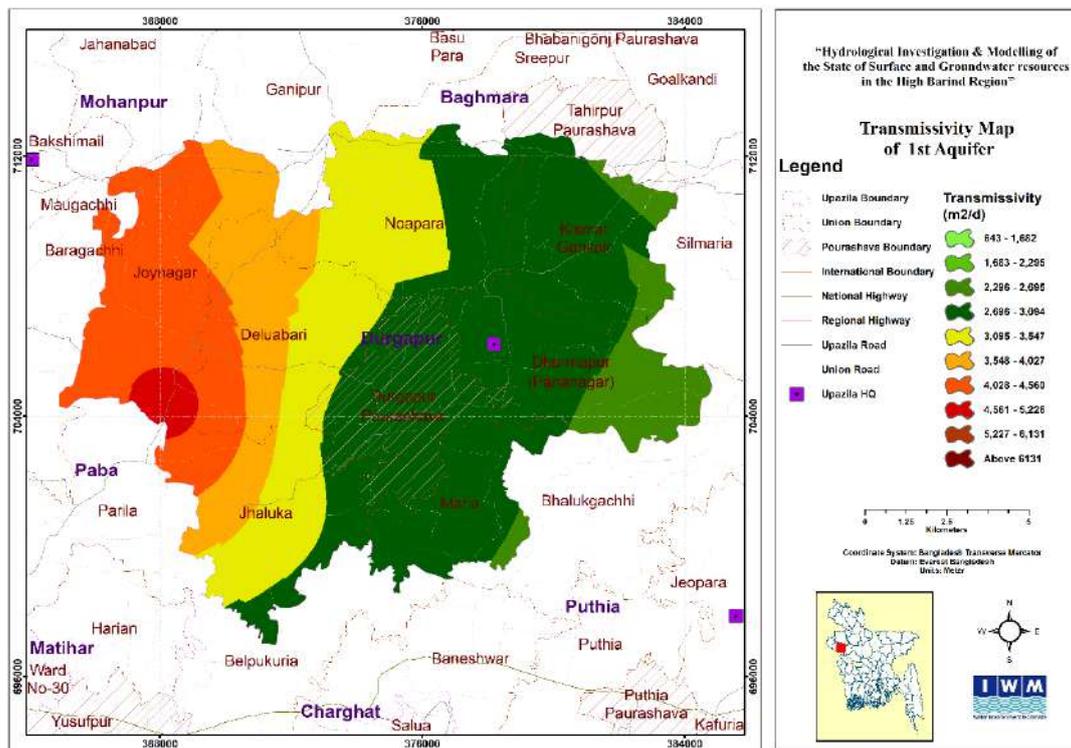


Figure 4-6: Transmissivity Map of 1st Aquifer Thickness at Durgapur Upazila under Rajshahi District

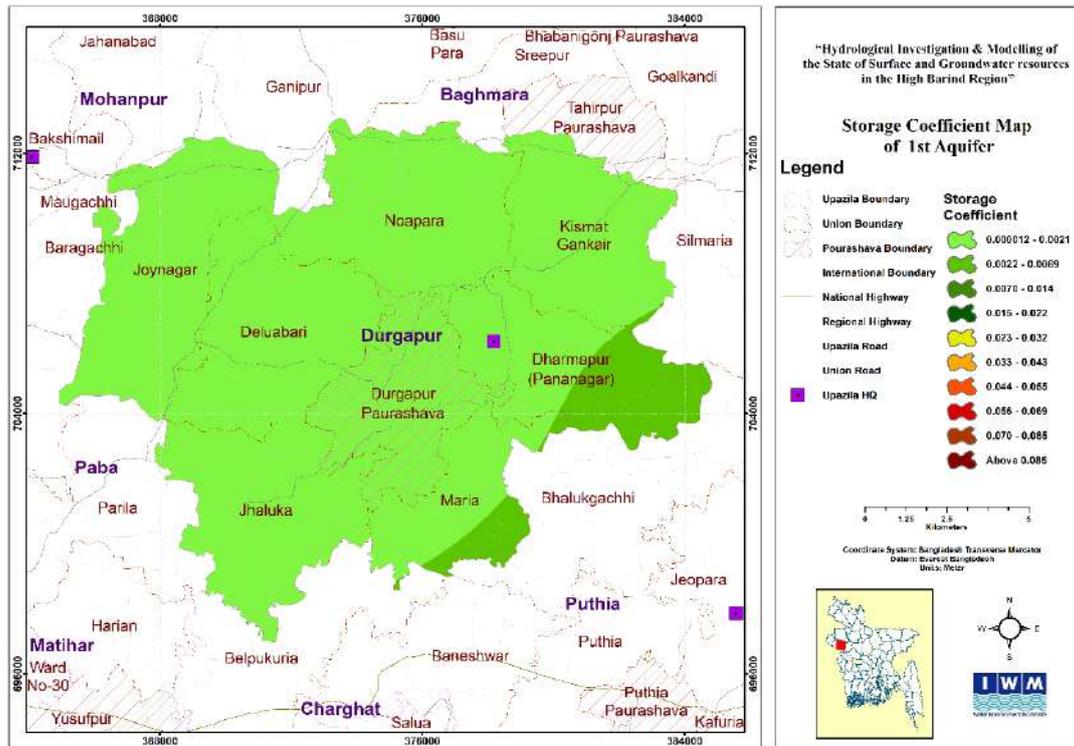


Figure 4-7: Storage Coefficient Map of 1st Aquifer Thickness at Durgapur Upazila under Rajshahi District

4.3 Aquifer System of Chapainawabganj District

Aquifer System Based on Lithologic-Logs

The Chapainawabganj district mostly falls under three physiographic units: Ganga River Floodplain, Teesta Floodplain and Barind Tract. Nachol, eastern part of Chapainawabganj Sadar and Gomostapur upazilas fall under the unit of Barind Tract where there is one thin aquifer existed in the shallow depth throughout the area except part of Nachol pourashava area. The thickness of the aquifer varies from 6 to 18 m which is the only drinking water source for these areas. At Nachol pourashava there is only one thick aquifer that exists down to the drilling depth of 432 m. The groundwater table varies from 30 to 32 m which dropped down beyond the suction limit (7 m) that may create a very alarming situation for this area. Due to the less thickness of aquifer, the groundwater table condition of Nachol, Kosba, Fatehpur, Jhilim, Parbatipur, Rohanpur and Radhanagar unions are very alarming where the groundwater table varies from 27 to 35 m which dropped down to the suction limit. On the other hand, Bholahat, western part of Gomostapur, western part of Chapainawabganj and Shibganj upazila falls under the unit of Ganga River Floodplain and Teesta Floodplain where there is one thick aquifer present in the area except Shibganj pourashava area. The Thickness of aquifer varies from 18 to 60 m. At Shibganj pourashava there are two very fine to fine sand aquifers exist upto the drilling depth of 265 m. The groundwater table condition of Shibganj, Monakasha, Chakkirti, Mobarakpur, Ranihati, Bholahat and Shahabajpur unions are relatively good. The groundwater table ranges from 4 to 12 m. Lithologic Cross Sections diagram of Chapainawabganj district is

shown in Figure 4-8. The union wise lithologic cross section is shown in Chapter 7 in Volume -II and aquifer mapping based on lithologic layer and thickness are shown in Volume -III.

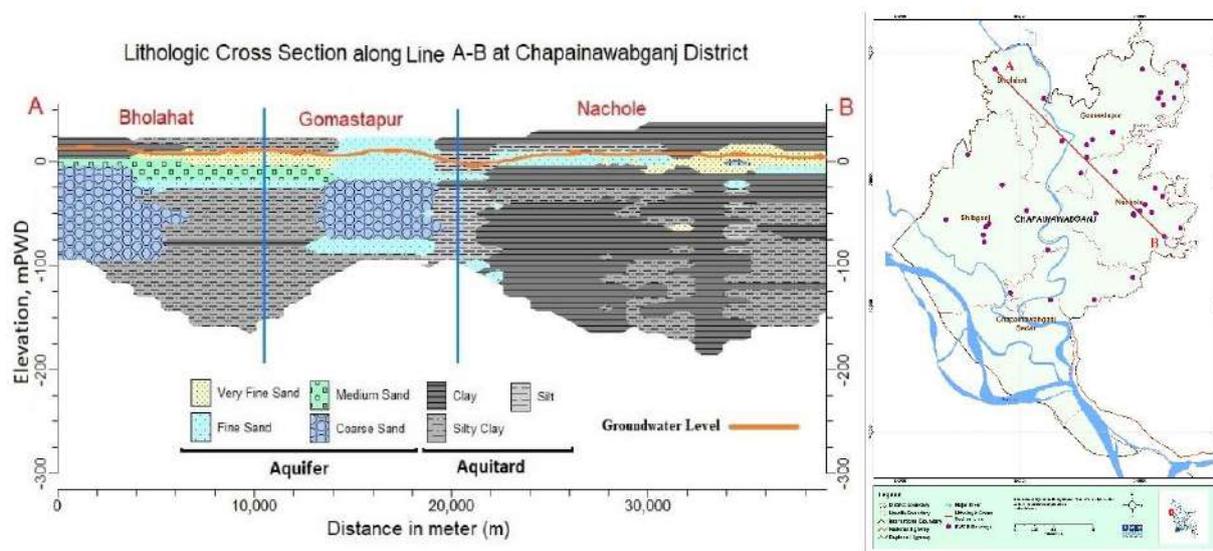


Figure 4-8: Lithologic Cross Sections Along Line A-B at Chapainawabganj District

Hydraulic Characteristics of Aquifer Sediments

For the calculation of hydraulic properties of aquifer at Chapainawabganj district, 14 aquifer pump tests data have been collected from 5 upazilas. Among them 3 aquifer pump tests have been conducted in existing Deep Tubewell (DTW) of BMDA, and 1 aquifer pump test has been conducted in newly installed Production Well (PW). The rest of the tests data have been collected from secondary sources. The aquifer pump test data have been analyzed by AQTESOLV software considering Theis's method, Cooper-Jacob method and Theis's Recovery methods, wherever applicable. The location of collected aquifer pump tests data from different sources are shown in Table 4-3.

The transmissivity values at Chapainawabganj district vary from 89 to 4648 m²/day whereas the storage coefficient ranges from 0.0000748 to 0.1781 for 1st aquifers. In Chapainawabganj upazila, Jhilim union has lower transmissivity value whereas in Alatuli union have higher transmissivity value. At Nachol upazila, most of the unions have lower transmissivity values. At Shibganj upazila, Shibganj and Mobarakpur unions have lower transmissivity value whereas in Durlabhpur and Shahabajpur unions have higher transmissivity value. At Gomostapur upazila, Radhanagar union shows the lowest transmissivity value. At Bholahat upazila, Gohalbari has moderated transmissivity value. Storage coefficient values and geological section indicates that the aquifer might be semi-confined to confined in nature except some parts of Gohalbari union, Alatuli, Radahnagar and Shibganj union where the aquifer is unconfined in nature. The union wise aquifer properties are shown in Chapter 7 in Volume -II and aquifer mapping based on aquifer properties are shown in Appendix -F to Appendix -H, Volume -III.

Table 4-3: Hydraulic Properties of Aquifer Sediment Based on Aquifer Pump Test at Chapainawabganj District.

Sl. No	Upazila	Union	Pump Locations		Transmissivity (m ² /d)	Storage Coefficient
			Latitude	Longitude		
Aquifer Pump Test Data Collected Under Present Study						
1	Shibganj	Shahabajpur	24.79987	88.12909	3409	0.0000748
2	Bholahat	Gohalbari	24.91368	88.21666	2097	0.0006724
3	Shibganj	Durlabhpur	24.69030	88.11923	4648	0.0007006
4	Shibganj	Mobarakpur	24.75188	88.21794	524	0.0003214
Secondary Aquifer Pump Test Data						
5	Bholahat	Gohalbari	24.93938	88.21049	1293	0.016693
6	Chapainawabganj	Alatuli	24.48831	88.24748	2528	0.178101
7	Chapainawabganj	Jhilim	24.61049	88.31893	484	0.0001488
8	Gomostapur	Gomostapur	24.77923	88.28735	311	0.0002965
9	Gomostapur	Radhanagar	24.94066	88.41563	89	0.010076
10	Nachol	Fatehpur	24.73948	88.29743	635	0.0003700
11	Nachol	Nachol	24.73390	88.44370	423	0.004366
12	Shibganj	Dhainagar	24.67250	88.26300	918	0.001940
13	Shibganj	Shibganj Pourashava	24.68308	88.18303	427	0.0001761
14	Shibganj	Shibganj Pourashava	24.68681	88.15725	484	0.041203

4.4 Aquifer System of Naogaon District

Aquifer System Based on Lithologic-Logs

The Naogaon district mostly falls under three physiographic units: Teesta Floodplain, Lower Atrai Basin and Barind Tract. Naogaon Sadar, Atrai, Raninagar, Mohadevpur, Manda, Badalgachi and some Part of Patnitala and Dhamoirhat falls under the unit of Teesta Floodplain and Lower Atrai Basin where there is one thick aquifer present in the area. On the other hand, Porsha, Sapahar, Niamatpur and some parts of Patnitala and Dhamoirhat upazilas fall under the unit of Barind Tract where there is only one thin aquifer present in the area. Even in some areas of Porsha and Sapahar upazilas such as Chaor, Ganguria, and Tetulia union, there is no suitable aquifer found upto the drilling depth of 300 m. The groundwater level of the Porsha, Niamatpur, partly Sapahar, Patnitala and partly Dhamoirhat upazilas dropped down beyond the suction limit (7 m) which creates a very alarming situation for those areas. Lithologic cross sections diagram of Naogaon district is shown in Figure 4-9. The union wise lithologic cross section are shown in Chapter 7 in Volume -II and aquifer mapping based on lithologic layer and thickness are shown in Volume -III.

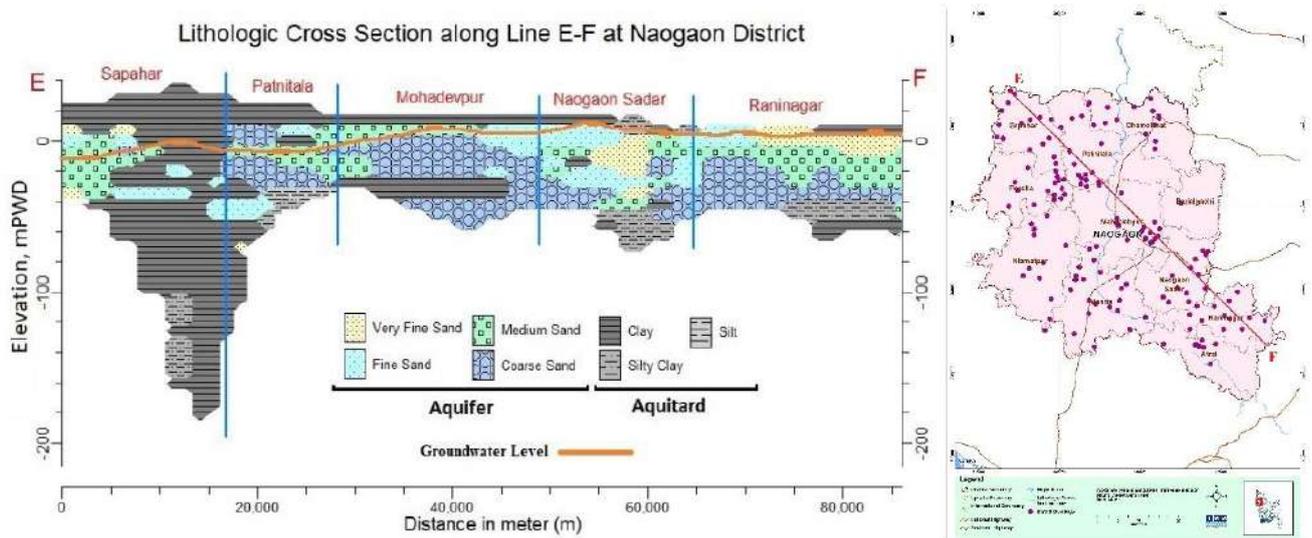


Figure 4-9: Lithologic Cross Sections Along Line E-F at Naogaon District

Hydraulic Characteristics of Aquifer Sediments

For the calculation of hydraulic properties of aquifer at Naogaon district, 31 aquifer pump tests data have been collected from 11 upazilas of Naogaon district. Among them 11 aquifer pump tests have been conducted in existing Deep Tubewell (DTW) of BMDA, and 2 aquifer pump tests have been conducted in newly installed Production Well (PW). The rest of the tests data have been collected from secondary sources. The aquifer pump test data have been analyzed by AQTESOLV software considering Theis’s method, Cooper-Jacob method and Theis’s Recovery methods, wherever applicable. The location of collected aquifer pump tests data from different sources are shown in Table 4-4.

The transmissivity values at Naogaon district vary from 527 to 8226 m²/day whereas the storage coefficient ranges from 0.0000152 to 0.15 for 1st aquifers. At Atrai, Raninagar, Badalgachi and Mohadevpur upazilas, the aquifer has moderate to high transmissivity values. At Dhamoirhat upazila, the aquifer in Umar and Alampur unions have moderate transmissivity value. At Manda upazila, the aquifer in Kansopara union has lower transmissivity value whereas the higher transmissivity value found in Tetulia union. These types of variation occur due to aquifer thickness as well as lithologic variation in shorter distance. In Naogaon Sadar upazila, the aquifer in Hapania and Boalia unions have higher transmissivity values whereas in Dubalhati, Naogaon pourashava and Adhaipur unions have moderate transmissivity value. In Niamatpur Upazila, Bhabicha union has higher transmissivity value whereas in Hajinagar and Sreemantapur shows lower transmissivity value. At Patnitala Upazila, most of the unions have moderate transmissivity values. At Sapahar upazila, the aquifer of Tilna union has higher transmissivity value. At Porsha upazila, there is no aquifer pump test data found, so transmissivity values have been collected from development test data. It shows that the aquifer of Ganguria and Nitpur unions have low transmissivity values whereas Murshidpur and Ghatnagar unions have moderate transmissivity values. Storage coefficient values and geological section indicates that the aquifer might be semi-confined to confined in nature

except some parts of Kansopara, Raigaon, Tilakpur, Shihara, Akdala unions where the aquifer is unconfined in nature. The union wise aquifer properties are shown in Chapter 7 in Volume - II and aquifer mapping based on aquifer properties are shown in Appendix -F to Appendix -H, Volume -III.

Table 4-4: Hydraulic Properties of Aquifer Sediment Based on Aquifer Pump Test at Naogaon District.

Sl. No	Upazila	Union	Pump Locations		Transmissivity (m ² /d)	Storage Coefficient
			Latitude	Longitude		
Aquifer Pump Test Data Collected Under Present Study						
1	Atrai	Shahagola	24.66753	88.96165	2848	0.0009720
2	Mohadevpur	Raigaon	24.98572	88.82402	6334	0.0157488
3	Badalgachi	Badalgachi	24.95413	88.91064	7634	0.0000152
4	Dhamoirhat	Umar	25.13444	88.83852	2361	0.0000262
5	Manda	Tetulia	24.67539	88.67409	3094	0.0002807
6	Mohadevpur	Vimpur	24.84527	88.87579	3728	0.0007676
7	Naogaon Sadar	Dubalhati	24.79583	88.88622	2874	0.0038287
8	Naogaon Sadar	Hapania	24.86380	88.88888	8226	0.0053613
9	Niamatpur	Bhabicha	24.82690	88.61450	3557	0.0140425
10	Patnitala	Ghosnagar	25.01981	88.78972	1967	0.0152767
11	Raninagar	Akdala	24.70076	89.12458	3677	0.0178633
12	Raninagar	Kashimpur	24.72791	88.93872	2217	0.0015721
13	Sapahar	Tilna	25.03657	88.61669	5991	0.0019177
Secondary Aquifer Pump Test Data						
14	Atrai	Shahagola	24.66331	88.96219	3453	0.000247
15	Badalgachi	Mathurapur	25.01140	88.90940	2588	0.000218
16	Dhamoirhat	Alampur	25.11410	88.78000	1472	0.001578
17	Manda	Kanso Para	24.74640	88.81110	580	0.056124
18	Mohadevpur	Enayetpur	24.98185	88.76175	1784	0.0001724
19	Mohadevpur	Uttargram	24.89386	88.78199	7349	0.0076244
20	Naogaon Sadar	Boalia	24.79857	88.97949	5411	0.0000884
21	Naogaon Sadar	Naogaon Pourashava	24.78784	88.95164	2089	0.000881
22	Naogaon Sadar	Tilakpur	24.84731	88.95813	1778	0.016001
23	Niamatpur	Hajinagar	24.88833	88.54444	707	0.070172
24	Niamatpur	Sreemantapur	24.79638	88.54357	527	0.004083
25	Patnitala	Patnitala	25.05460	88.72620	1265	0.000089
26	Patnitala	Shihara	25.12703	88.66848	1218	0.150701
27	Raninagar	Kashimpur	24.74519	88.95411	1473	0.002417
28	Porsha	Ghatnagar	24.95788	88.547025	1100	-
29	Porsha	Nitpur	25.0285	88.452685	290	-
30	Porsha	Murshidpur	25.01331	88.598106	1136	-
31	Porsha	Ganguria	25.03436	88.536276	328	-

4.5 Aquifer System Based on the Geophysical Resistivity Survey

To evaluate the groundwater potentiality of the project area lithologs, resistivity map of the top aquitard (Clay, Silty Clay layer) (Figure 4-10), contour maps of the depth to the top and bottom top aquifer, isopach of the top aquifer, five lithological cross sections across VES stations (locations of the directions of cross sections are given in Figure 4-11), lithological fence diagram (panel diagram) (Figure 4-12) has been constructed on the basis of the results of interpretation of Vertical Electrical Sounding (VES) data obtained from field survey carried out in thirty stations of the study area. Moreover, for clear visualization of the respective aquifer position an Arc Scene Map representing 3-D schematic representation of the top aquifer zone has been constructed. And finally on the basis of the finding about the subsurface lithological structure obtained from the VES interpretation aquifer potentiality zoning map has been constructed.

The Aquifer potentiality zoning map of the study area depicts three zones: single aquifer, double aquifer, and multiple aquifer zones. Single aquifer zone covers part of Shibganj, Nachol, Porsha, Gomostapur, Niamatpur, Mohadevpur, Naogaon Sadar, Manda and Bagmara Upazilas. Zone covering Chapainawabganj Sadar, Durgapur, Puthia, Charghat, Bagha and Dhamoirhat Upazilas is characterized by multiple aquifers, while the rest of the area occupies the zone with double aquifers. The detailed Geoelectric characteristics of Subsurface formation are given in Chapter 7, Volume -II.

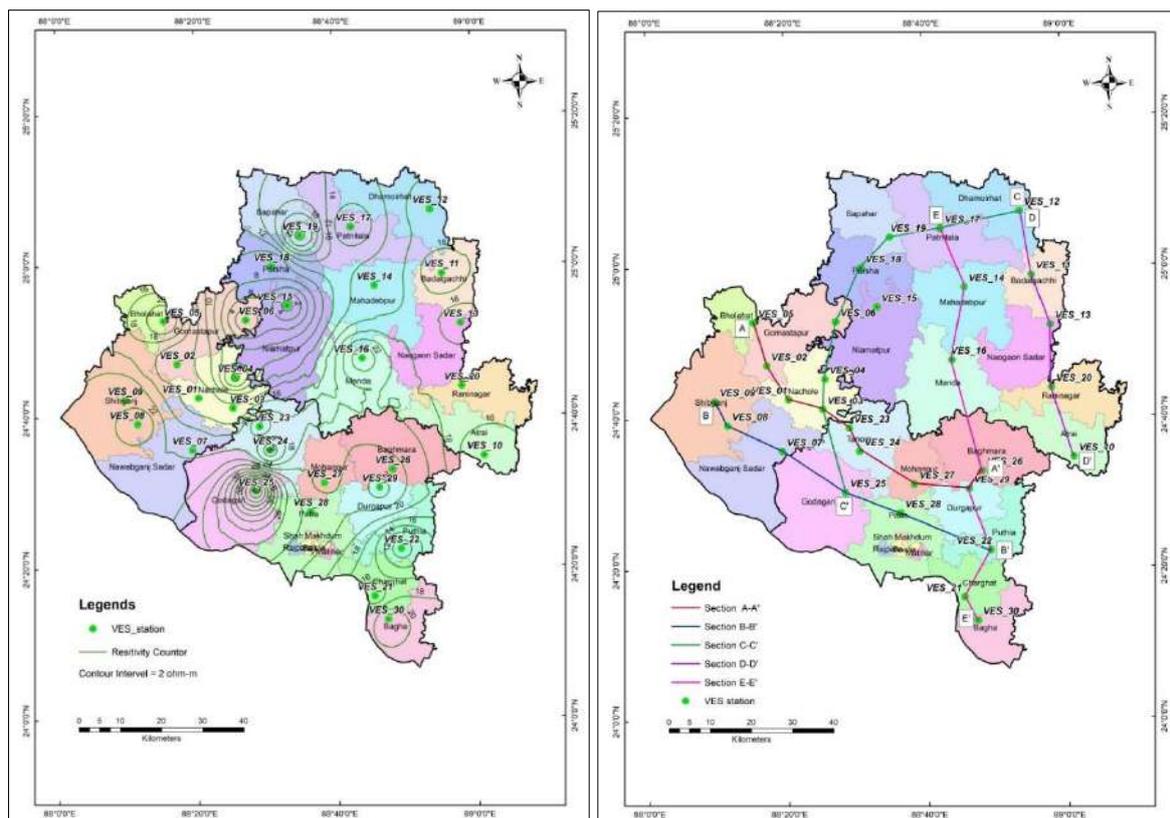


Figure 4-10: Isoresistivity Map of the Top Aquitard (Clay, Silty Clay layer) at Rajshahi, Chapainawabganj and Naogaon Districts (Left) and Locations of Lithological Cross Sections Across VES Stations at Rajshahi, Chapainawabganj and Naogaon Districts (Right)

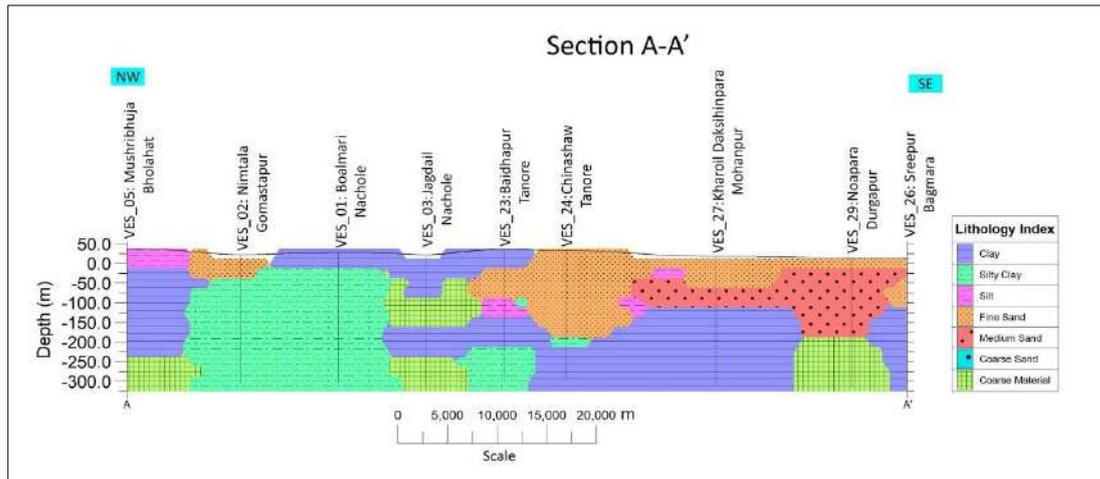


Figure 4-11: Lithological Cross Sections Across VES Stations at Rajshahi, Chapainawabganj and Naogaon Districts Along Line A-A'

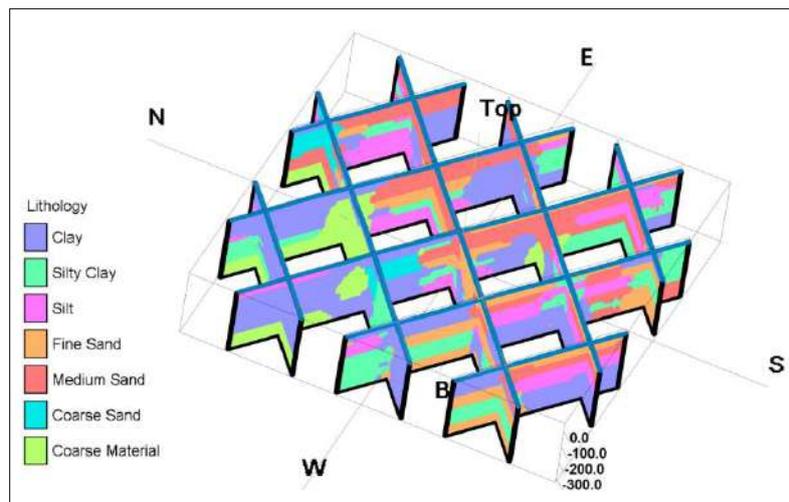


Figure 4-12: Lithological Fence Diagram of Subsurface Formation in the Study Area as Derived from Vertical Electrical Sounding (VES) Data

5 DYNAMICS OF GROUNDWATER IN THE STUDY AREA

5.1 Groundwater Recharge and Discharge Areas and Its Characteristics

Recharge means the replenishment of groundwater storage that is depleted by withdrawal of groundwater with tube wells and by natural processes. The sources of groundwater replenishment of the study area are deep percolation of rainwater and irrigated water from the crop fields, seepage from the rivers, khals, ponds and other water bodies, and horizontal flow of groundwater from the surrounding areas. Recharge to groundwater depends on different physical and climatic conditions as well as hydraulic properties related to soil, aquifer and water. Recharge to groundwater begins with the rainfall from late May and continues up to October while recharge from irrigated crop field occurs from December to the end of March.

The aquifer becomes full in the months of August/September, but excess rain is available to recharge till October, if there is room for recharge. By creating additional storing space, the magnitude of annual replenishment of groundwater may be increased but it depends on the availability of water and the percolation rate of soil. Direct percolation occurs during the rains from naturally submerged fields and un-submerged lands. Excess rainwater is also stored within the bund that surrounds the paddy field and in the depressed areas. This water is also available for recharging the groundwater after meeting the demand of evapotranspiration. The long-term average of annual replenishment of groundwater may be considered as safe yield. Groundwater storage reduces due to withdrawal for irrigation, domestic and other uses and outflow to rivers, canals, ditches, ponds and other water bodies. The loss of groundwater due to evaporation from water table and transpiration by plants is also attributed to depletion of groundwater storage.

Groundwater recharge and discharge are important aspects of the global hydrological cycle and are critical to the analysis of groundwater flow systems and water budgets. Under this study, the recharge zone has been considered the area where topsoil thickness is less than 6 m. A recharge area map has been prepared which is shown in Figure 5-1.

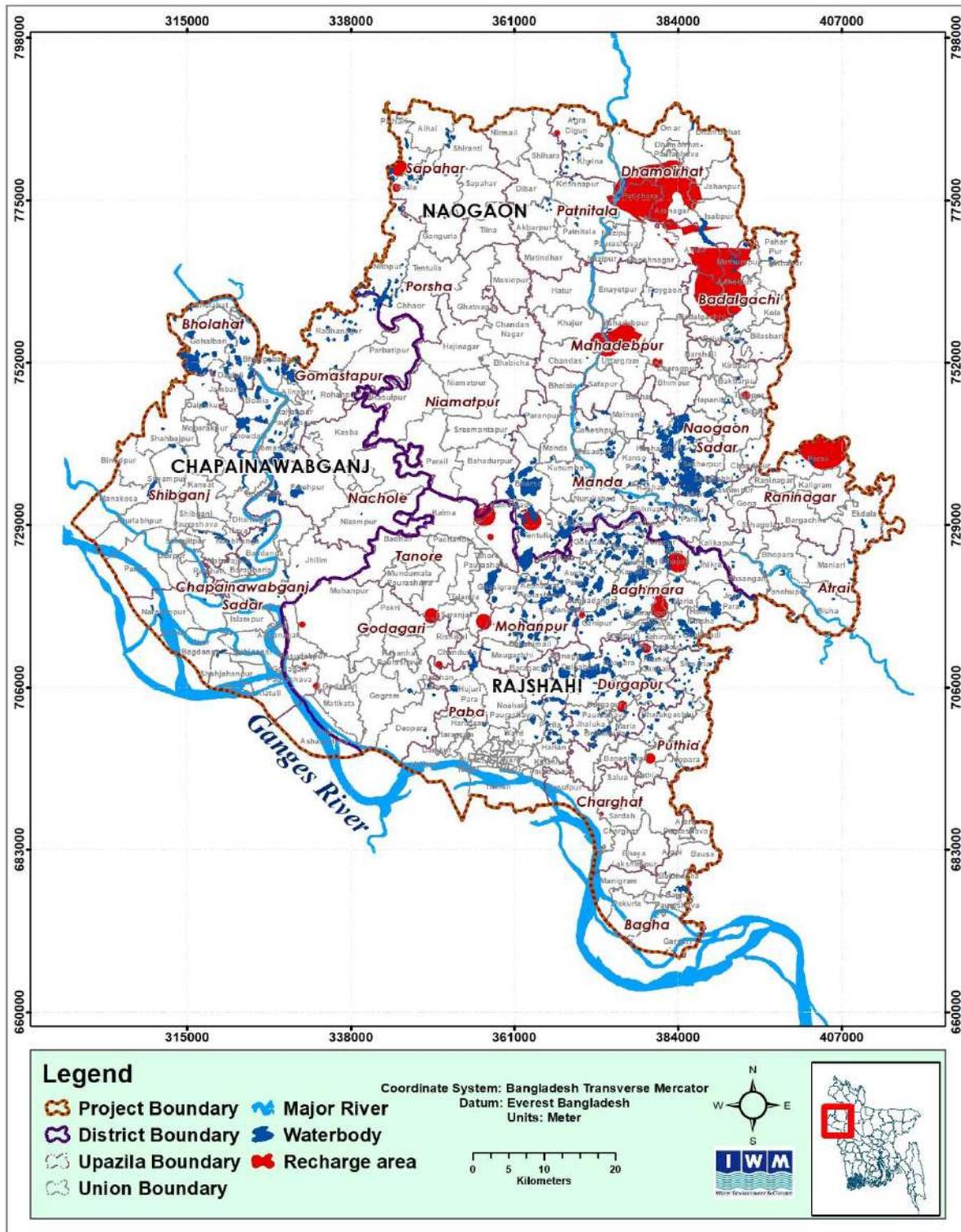


Figure 5-1: Map of Recharge Area

Major discharge of groundwater mainly occurs by the abstraction for irrigation, domestic and industrial purposes. A discharge areas map has been prepared for the study area based on density of DTWs and STWs as surveyed during PRA study. A discharge area map based on DTW and STWs density for the study area is given below.

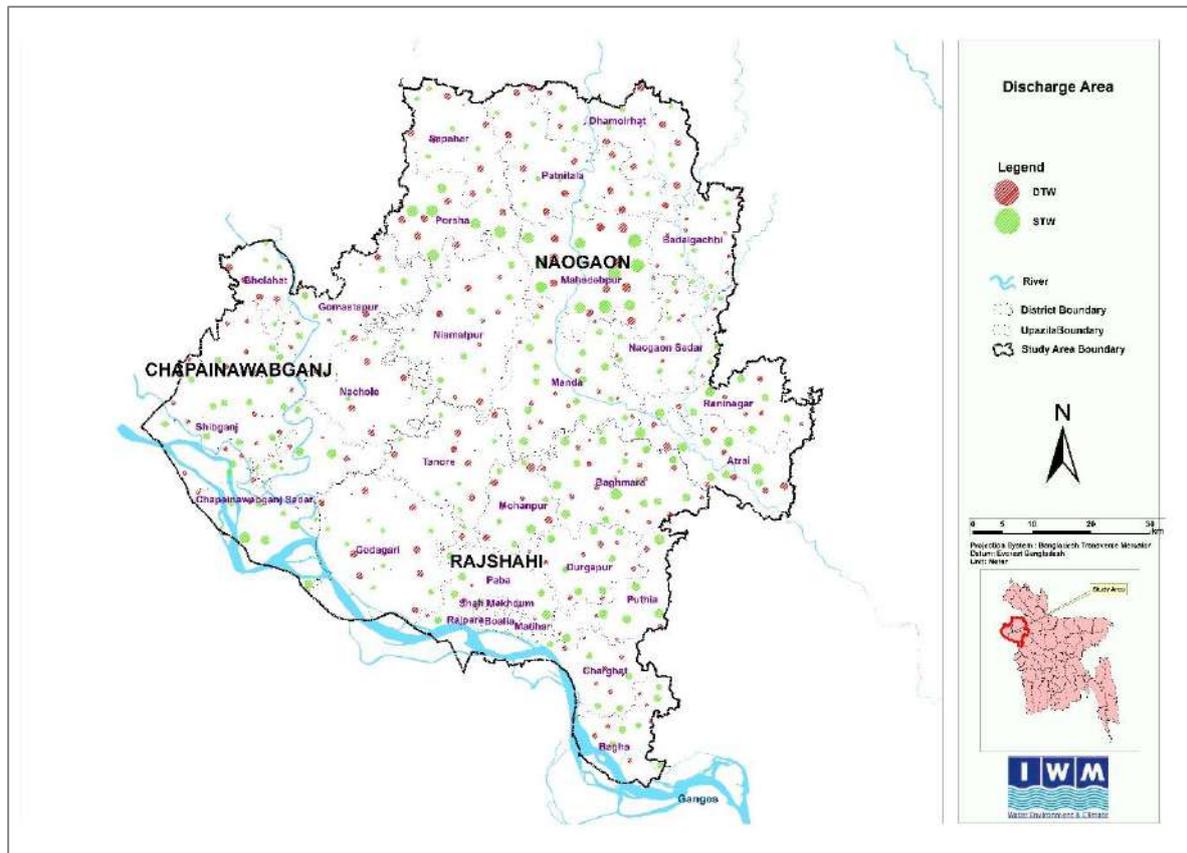


Figure 5-2: Map of Discharge Area

Moreover, discharge from aquifer to river or from river to aquifer round the year has been considered and taken into account during the water balance to calculate actual recharge after development of calibrated and validated GW-SW interaction model.

5.2 Maximum and Minimum Groundwater Table

BWDB has about 172 groundwater monitoring wells within the study area, out of which the data from 122 wells have been used for the study considering the quality of the data with long time series. To fill up the data gap and for calibration and validation purpose of the model, an additional 50 Groundwater monitoring wells has been installed by IWM. In order to see the spatial distribution of groundwater table with respect to ground surface, the contour maps have been prepared for the groundwater table of 30th April and 30th October are given in Figure 5-3. Analysis of present groundwater table data reveals that groundwater table varies from 4.95 to 31.1 m in Rajshahi, 5.52 to 35.2 m in Chapainawabganj and 4.54 to 29.2 m in Naogaon district in the month of April. In the month of October groundwater table varies from 1.81 to 29.4 m in Rajshahi, 3.13 to 34.2 m in Chapainawabganj and 1.7 to 18.3 m in Naogaon district. It is observed that maximum depth to groundwater table occurs at the end of April and minimum depth to groundwater table occurs at the end of October as mentioned in Figure 5-3.

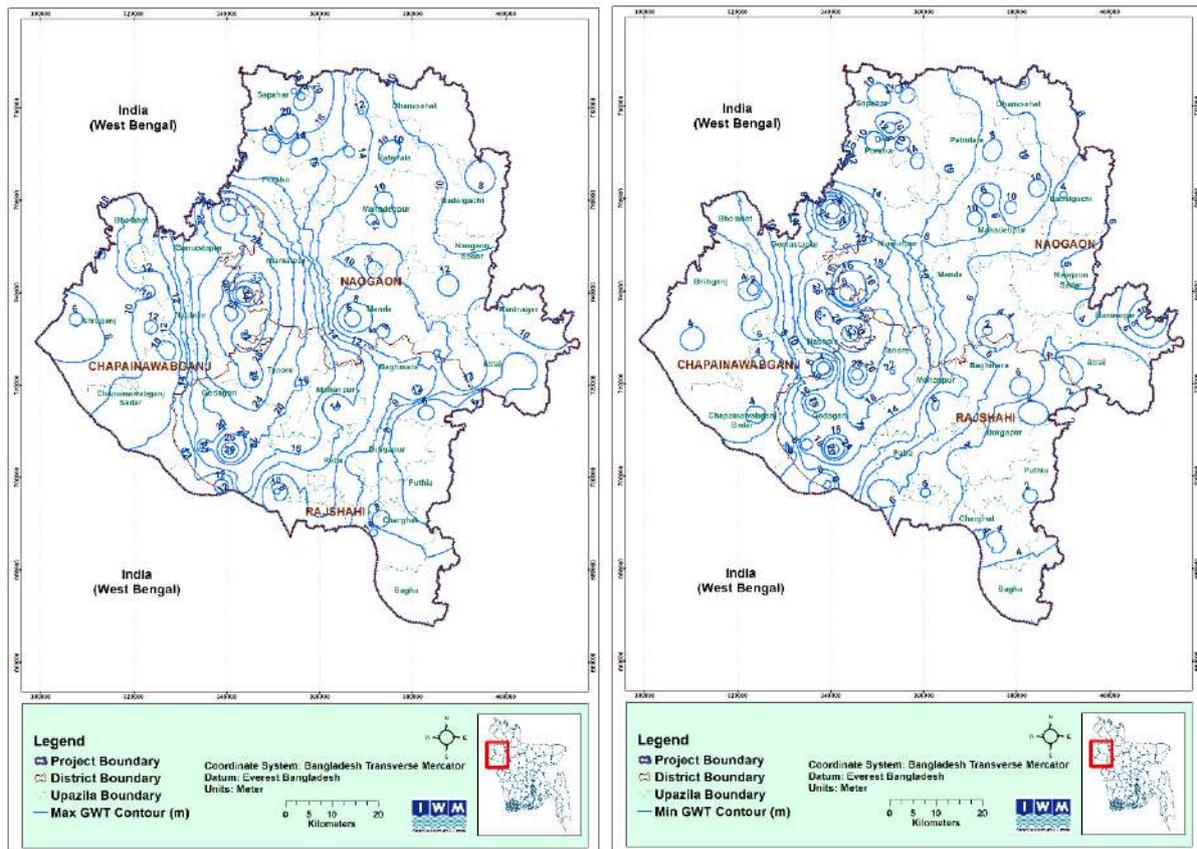


Figure 5-3: Maximum Depth to Groundwater Table at the end of April, 2021 (Left), Minimum Depth to Groundwater Table at the end of October 2021 (Right)

5.2.1 Groundwater Trend Analysis

To assess the trend of groundwater level variation over time, the yearly rate of rise and fall of the maximum and minimum depth to groundwater table over the period of 1985 to 2021 was determined for the 122 observation wells selected from the BWDB database. Four common trends were evident in these data which related to the amount and rate of decline in groundwater levels observed. During the development of the trend type codes for individual wells, it became apparent that some wells did not fit any of the 4 trend type behaviors (see types 1-4 in Table 5-1) which were considered as either type 5 or type 6.

To perform the trend analysis a groundwater database and a set of queries have been developed to extract individual well data and analyze the groundwater depth. This has been achieved through a combination of a Microsoft Access/Excel database and Python scripting to automate the processing of the time series groundwater data. For each well, the annual maximum and minimum water table depth readings have been extracted from the Access database and a linear regression performed on each set. The rate of variation (slope) of each set has been extracted and classified into the trend types according to the definitions shown in Table 5-1.

Table 5-1: Different Classes of Groundwater Level Variation or ‘Trend Types’

TYPES	RATE OF VARIATION (MAXIMUM DEPTH)	RATE OF VARIATION (MINIMUM DEPTH)	DESCRIPTION
Type-1	falling @ > 0.00 m/yr	falling @ > 0.15 m/yr	These wells have strongly declining levels in both minimum groundwater depths and maximum groundwater depths. There is little or no wet season recovery observed. Note that some of the early stage decline patterns have characteristics of Type 2. In this case abstractions and losses are much higher than annual recharge leading to rapid declines in both maximum and minimum depths of the water table.
Type-2	falling @ 0.00 to 0.58 m/yr	falling @ 0.025 to 0.15 m/yr	Groundwater trends where the dry season minimum groundwater depth is declining, and the wet season induced recharge top-up appears insufficient to fully restore groundwater levels. This type is characterised by strong declines in the maximum depth of the water table and some decline in the minimum depth. Whilst recharge is being induced by a deeper water table at the end of the dry season abstractions and losses, the monsoon top-up appears insufficient to return the water table to its previous position
Type-3	falling @ 0.025 to 0.30 m/yr	falling @ 0.025 to rising @ 0.08 m/yr.	Groundwater trends where the maximum depth is declining but there is no decline in the minimum depth. The decline in seasonal maximum water table depth reflects increasing abstractions and losses. There is some induced recharge occurring due to increased capacity for recharge during the wet season. The wet season recharge is currently sufficient to make up the dry season deficit
Type-4	falling @ 0.025 to rising @ 0.025 m/yr	falling @ 0.025 to rising @ 0.025 m/yr	Both minimum depth and maximum depth show no trend. These wells have steady groundwater levels which fluctuate seasonally but the wet season recharge is at least sufficient, or more than sufficient, to account for the dry season losses and abstractions
Type-5	rising @ >0.00 m/yr	rising @ >0.00 m/yr	Both minimum depth and maximum depth show significant rising trends. This can be a sign of suspicious data or driven by some shorter-term climate signal. There are generally few wells of this type in Bangladesh where most water tables have failing or steady hydrographs. Rising trends could indicate the abandonment of production wells nearby, a land-use change (eg. Urbanisation of previously agricultural land) or some other influence on local groundwater levels. Erroneous data could be the reason for some wells of this type are identified as having rising trends
Type-6	All other rates	All other rates	Both minimum depth and maximum show diverging or converging trends. This type usually indicates suspicious data and should prompt a closer inspection of the data. There is no typical type 6 response as wells of these type are those that do not satisfy the criteria for the other 5 types. Wells of this type should be examined for erroneous data points and cleaned if possible or removed from the analysis if the data are suspicious

The annual maximums and minimums have been correlated to the pre-monsoon period and post-monsoon period respectively. The pre-monsoon period represents the time after which irrigation water abstraction for dry season cropping has ceased (typically April/May). In the post-monsoon period (September/October) water tables are generally much closer to the surface as a result of high rainfall and flooding associated with the wet season which recharges (tops up) the shallow aquifer bringing it closer to the surface. Groundwater use is also minimal in the wet season. Table 5-2 and Figure 5-4 shows different trend types of the study area. From the trend analysis of groundwater level data at 122 locations, it has been found that 46 nos. fall under Type 1 (these wells have strongly declining levels in both minimum groundwater depths

and maximum groundwater depths), 48 nos. fall under Type 2 (groundwater trends where the dry season minimum groundwater depth is declining and the wet season induced recharge top-up appears insufficient to fully restore groundwater levels), 24 nos. fall under Type 3 (groundwater trends where the maximum depth is declining but there is no decline in the minimum depth) and only 4 nos. fall under Type 4 (both minimum depth and maximum depth show no trend) indicating occurrence of insufficient recharge to compensate abstractions in most part of the study areas which is very alarming.

Table 5-2: Different Trend Types based on Observation Wells

District	Upazila	No of Observation Wells			
		Type-1	Type-2	Type-3	Type-4
Rajshahi	Bagmara		3	1	
	Charghat		6		
	Durgapur			1	
	Godagari	3	10		
	Mohonpur		3		
	Paba	1	7		
	Puthia		1	1	1
	Tanore	4			
Chapainawabganj	Bholahat		2		
	Chapainawabganj Sadar	1	3	1	
	Gomostapur	3	1	3	
	Nachol	6	1		
	Shibganj			7	
Naogaon	Atrai		1	2	
	Badalgachi				3
	Dhamoirhat			7	
	Manda		2		
	Mohadevpur	3	2	1	
	Naogaon Sadar	1	2		
	Niamatpur	8			
	Patnitala	7	1		
	Porsha	5	1		
	Raninagar	1	1		
	Shapahar	3	1		
Total		46	48	24	4

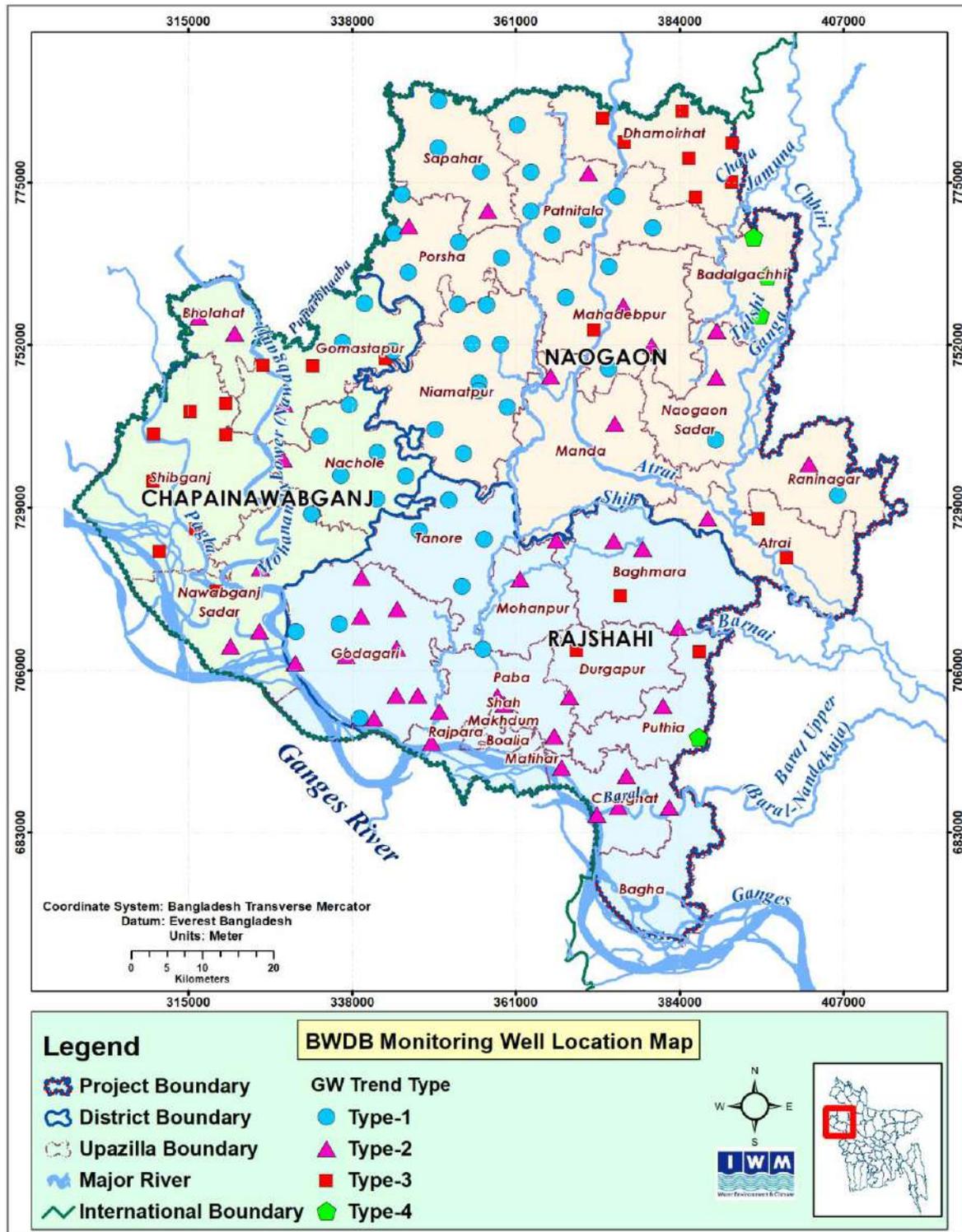


Figure 5-4: Different Groundwater Variation or Trend Types of the Study Area

Sample plots of groundwater level trends are shown in Figure 5-5 to Figure 5-6. Chapter 6 of Volume -II contains the rest of the hydrographs for all wells assessed in the analysis for the study area.

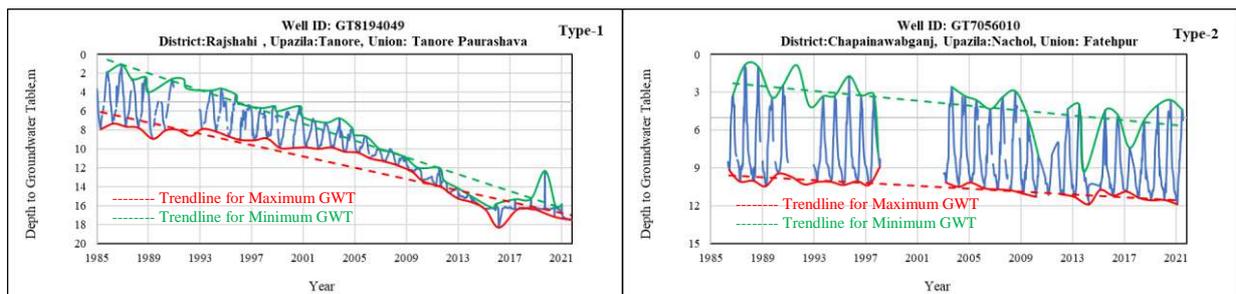


Figure 5-5: Groundwater Level Trend Analysis for Tanore Upazila of Rajshahi District (Left) and Groundwater Level Trend Analysis for Nachol Upazila of Chapainawabganj District (Right)

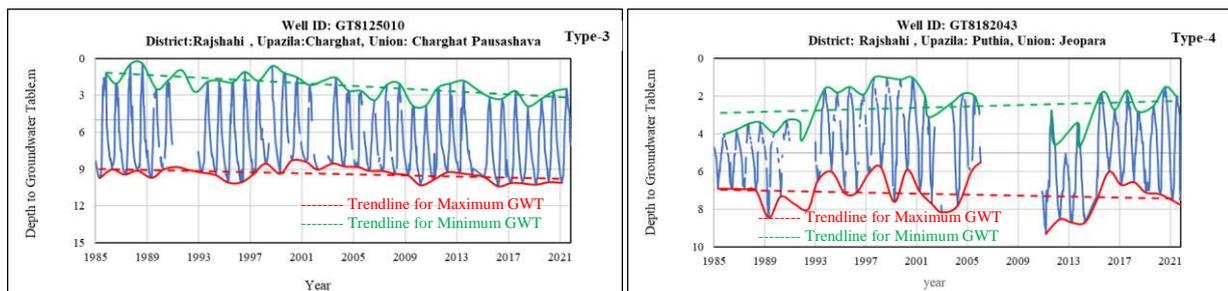


Figure 5-6: Groundwater Level Trend Analysis for Charghat Upazila of Rajshahi District (Left) and Groundwater Level Trend Analysis for Puthia Upazila of Rajshahi District (Right)

The trend type analysis classifies the trends evident within the groundwater monitoring data into four main types to attempt to highlight the problem areas concerning declining water levels. Type 1 sites have rapidly declining water levels in both maximum and minimum annual depths and are therefore the most concerning with respect to the sustainability of groundwater abstraction. These sites indicate there is insufficient recharge occurring to compensate for the volume extracted. Type 2 sites show rapidly decreasing water levels in the maximum depth but less rapid declines in the minimum depth suggesting they may be at a tipping point where abstraction is becoming greater than recharge. Without intervention, it is likely that most of these sites will continue declining and exhibit type 1 behavior in the future. Sites with type 3 behavior indicate that whilst the maximum depth is declining, the minimum depth is stable suggesting that the aquifer is being fully replenished during the monsoon despite the dry season abstraction. That is, the water table is declining, and induced recharge is occurring, but the annual top-up is sufficient to return the water table to the pre-abstraction water level. Continuous monitoring of groundwater levels will help to identify if individual sites are in transition from type 3 to type 1 and 2 and enable early intervention. Type 4 sites show no trend in either maximum or minimum water table depth suggesting there is sufficient recharge occurring to compensate for any abstraction. Such sites may be capable of supplying more groundwater during the dry season however this should be continually monitored.

5.2.2 Analysis of Historical Groundwater Depth

Groundwater depth surfaces are useful to compare the position of the water table through time as well as calculate the water table difference (the quantum of change either positive or negative) over selected periods. Dates corresponding to the pre-monsoon periods have been chosen to target the maximum water table depths similarly to the trend analysis methodology.

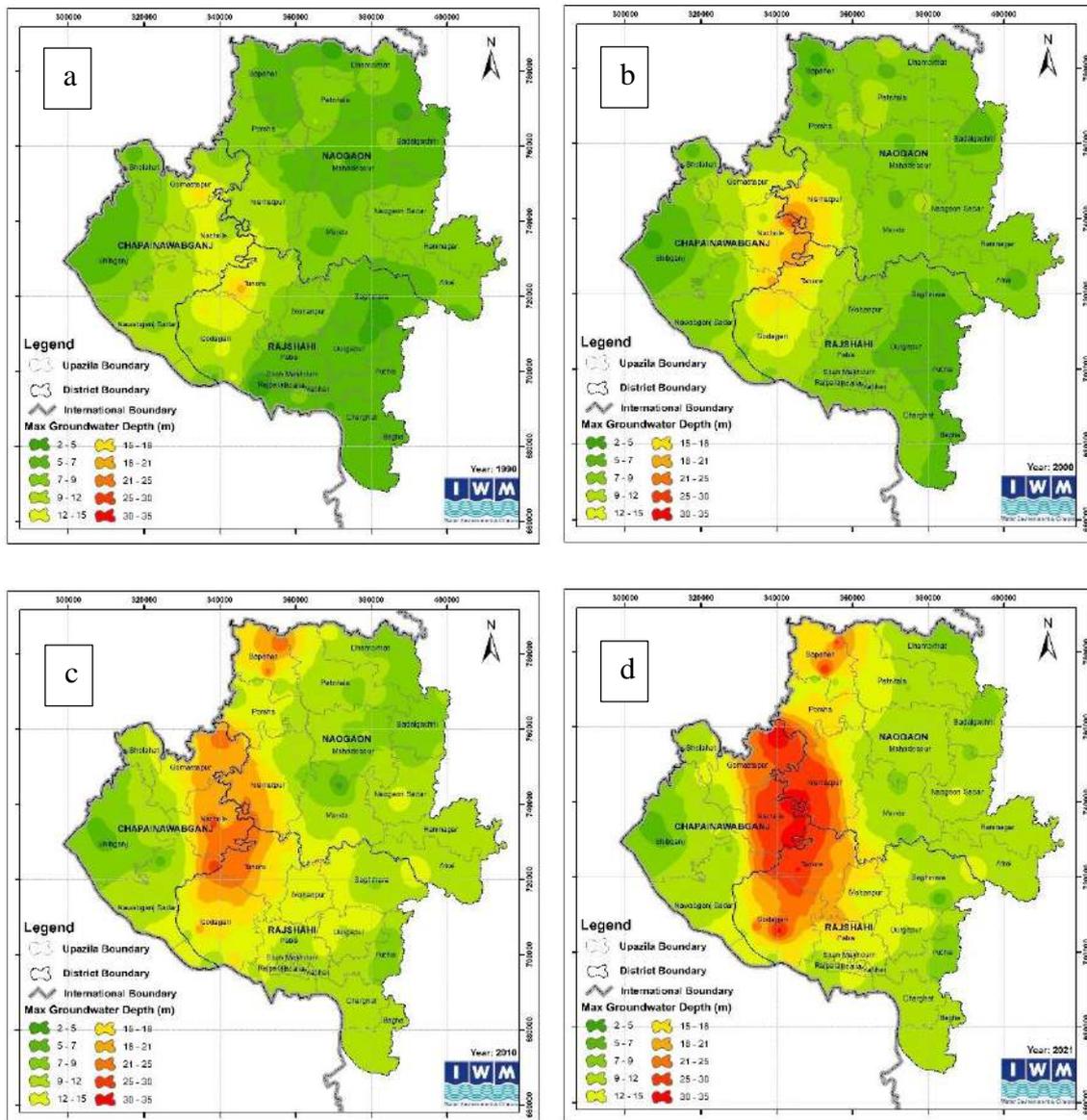


Figure 5-7: Maximum Water Table Depth Maps for a) 1990, b) 2000, c) 2010 and d) 2021

Figure 5-7 show the pre-monsoon water table depth in 1990, 2000, 2010 and 2021 and the water table differences between 2000 and 1990, 2010 and 2000, and 2020 and 2010. The pre-monsoon period is the end of the dry season when water tables would be likely at or close to their maximum depth. The depth of the water table in 1990 (Figure 5-7a) represents a period prior to widespread groundwater abstraction and dry season irrigation. In the Barind Tract where higher elevation area exists, located (Figure 5-7a), the groundwater depths are relatively deeper than the areas in north and east where water tables are comparatively near to the surface.

By 2010 (Figure 5-7c) the water tables depth has increased beyond 15 m (red) and an increased area deeper than 10 m (orange) in the Barind tract area. Water table depth has increased with covering more area in 2021 than that of 2010 (Figure 5-7d). Figure 5-7d shows the depth of the water table for the pre-monsoon period in 2021 with further increases in depths greater than 10 m and 15 m in the southwest high barind tract but no major change elsewhere. In the water table difference map showing changes between 2010 and 1990 (Figure 5-8b), the majority of the southwest area has seen declines in groundwater between 2 and 10 m over the 20 years. The comparison between 1990 and 2021 (Figure 5-8c) shows further declines in the high Barind Tract area but no major changes in the other areas.

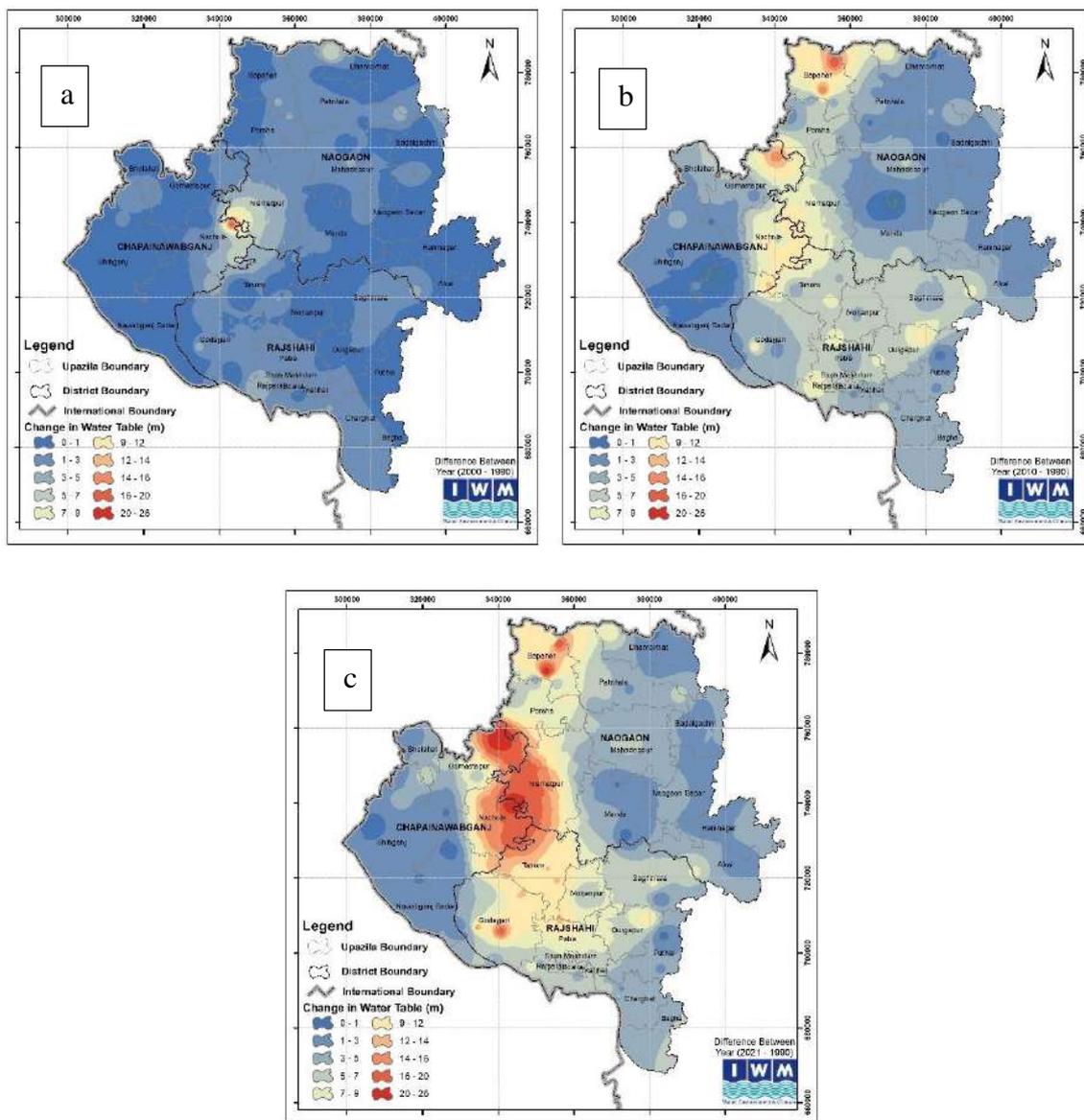


Figure 5-8: Maximum Groundwater Table Difference Between a) 2000-1990, b) 2010-1990, c) 2021-1990

Groundwater is important in the northwest not just due to the value of dry season cropping but also to serve to supply domestic water needs to a large number of people. The majority of villages in the region rely on suction pumps (hand tube wells) for domestic water supply and

the depth limit for these is approximately 6-8 meters. If the groundwater drops below that level, the village water supply may be threatened. In some areas, deep tubewells have been installed to overcome this issue but that may still impact at a local level whereby villagers need to transport water from the deep tubewell to the household daily. Piping programs are occurring to address this also. Shallow tubewells (deep set shallow tubewells) also use suction pumps and declining the water level below the suction limit (7 m) affects irrigation in the critical dry months. In those affected areas farmers set shallow tube wells below the ground surface to capture the suction limit. From the critical depth analysis data, it has been found that there is an increasing number of sites impacted by the water tables exceeding 7 m depth and an increasing trend in the duration (number of months) may occur. Furthermore, the number of sites where the groundwater sits at between 6-7 m is also increasing over time which may indicate suction pump failure depending on the pump condition and the hydraulic conductivity of the aquifer. Details have been given in Volume II.

6 GROUNDWATER QUALITY ASSESSMENT

Understanding the factors that influence groundwater quality is essential for developing strategies to protect and manage this valuable resource. This may involve implementing best management practices to reduce pollution and contamination, monitoring groundwater quality over time, and developing regulations and policies to ensure that groundwater is protected for current and future generations. To assess the suitability of groundwater for different uses, hydrochemical investigation has been carried out such as groundwater sampling, in-situ physical parameter and hydro chemical parameters measurement.

Groundwater samples have been collected from 50 wells where the depth of wells vary from 23 m to 95 m. The location of groundwater sampling is presented in Figure 6-1. A total of 18 physio-chemical parameters have been measured for collected samples from the project area. Physical parameters such as pH, EC, Salinity, TDS, Temperature have been measured in the field and hydro-chemical parameters such as Calcium, Magnesium, Sodium, Potassium, Bicarbonate, Chloride, Nitrate, Phosphate, Sulphate, Iron, Fluoride, Arsenic and Manganese have been examined in DPHE laboratory and Department of Geology, University of Dhaka. The measured physical parameters and analyzed hydro-chemical parameters are presented in Table 6-1 and Table 6-2 respectively.

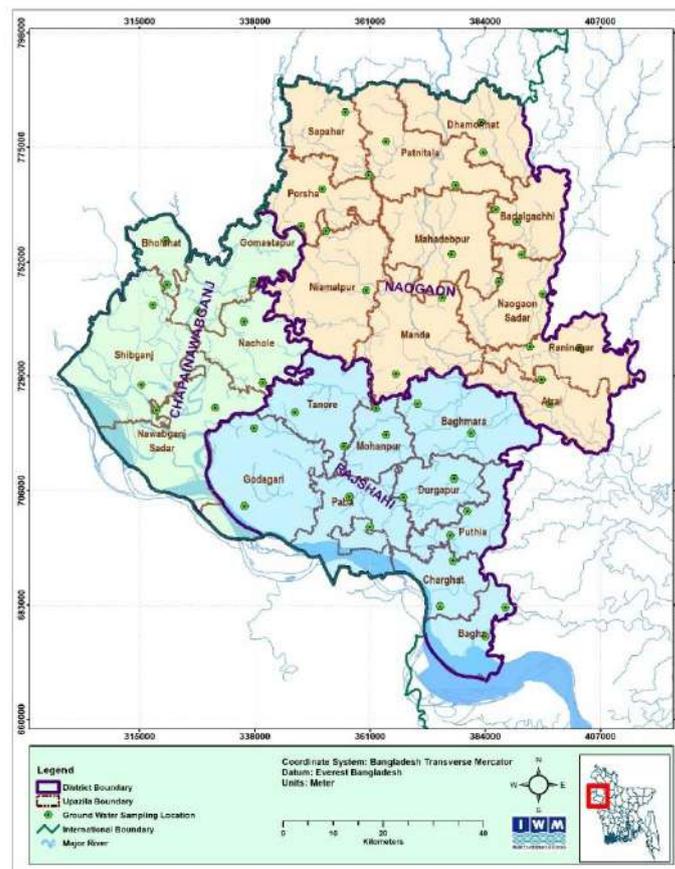


Figure 6-1: Groundwater Sampling Location

Table 6-1: Groundwater-related Field Physical Parameters

Sl. No.	Sample ID	Upazila	Union	Well Depth (m)	pH	EC (µs/cm)	TDS (mg/l)	Salinity (ppt)	Temp (°C)
1	RSMPWQ_1	Mohonpur	Royghati	71	6.29	791	366	0.36	27.3
2	NGMDWQ_2	Manda	Tentulia	63	6.75	1169	559	0.56	26.6
3	NGMDWQ_3	Manda	Monim Durgapur	64	6.69	423	200.6	0.2	25.8
4	NGMPWQ_4	Mohonpur	Bakshimoin	61	6.92	1090	518	0.52	26.9
5	RSCHWQ_5	Charghat	Shalua	40	6.91	931	455	0.46	25.3
6	RSCGWQ_6	Charghat	Charghat	40	6.88	967	465	0.46	26.1
7	RSBGWQ_7	Bagha	Bajubagha	58	7.02	679	327	0.35	25.6
8	RSBGWQ_8	Bagha	Bausha	55	6.9	862	415	0.42	25.9
9	RSPBWQ_9	Paba	Nawhata	52	6.93	746	364	0.36	25
10	RSTNWQ_10	Tanore	Tanore Pourashava	62	6.78	571	272	0.27	26
11	RSTNWQ_11	Tanore	Mundumala Pourashava	40	7.39	838	396	0.39	26.8
12	RSGGWQ_12	Godagari	Mohonpur	49	6.89	925	447	0.45	26
13	RSGGWQ_13	Godagari	Matikata	43	6.73	745	352	0.35	26.6
14	RSRSWQ_14	Rajshahi	Shah Makhdum	46	7.01	1190	580	0.58	25.7
15	CHCHWQ_15	Chapainawabganj	Jhilim	37	7.01	605	318	0.32	24.6
16	CHSGWQ_16	Shibganj	Mobarakpur	26	6.99	898	431	0.43	26.1
17	CHBHWQ_17	Bholahat	Jambaria	23	6.81	1012	480	0.48	26.8
18	CHBHWQ_18	Bholahat	Gohalbari	46	6.81	743	357	0.36	25.7
19	CHSGWQ_19	Shibganj	Chatrajitpur	35	7.01	1054	540	0.54	23.2
20	CHCHWQ_20	Chapainawabganj	Ranihati	37	7.19	903	441	0.44	25.2
21	CHNCWQ_21	Nachol	Nezampur	39	6.95	866	417	0.42	25.8
22	CHNCWQ_22	Nachol	Kosba	44	6.82	651	308	0.31	26.4
23	CHGPWQ_23	Gomostapur	Gomostapur	39	6.8	793	370	0.37	27.2
24	CHGPWQ_24	Gomostapur	Parbatipur	45	6.95	720	341	0.34	26.4
25	RSPTWQ_25	Puthia	Banessor	61	7.13	851	419	0.42	24.8
26	RSPTWQ_26	Puthia	Bhalukgachi	58	7.02	736	351	0.35	26.2
27	RSDPWQ_27	Durgapur	Naopara	69	7.26	899	436	0.44	25.6
28	RSBMWQ_28	Bagmara	Bhabaniganj	52	7.07	685	324	0.32	26.5
29	RSDPWQ_29	Durgapur	Joynagar	67	7.21	717	346	0.35	25.6
30	RSBMWQ_30	Bagmara	Auspara	55	7.09	810	392	0.39	25.6
31	NGNPWQ_31	Niamatpur	Bhabicha	38	6.93	614	292	0.29	26.1
32	NGMPWQ_32	Mohadevpur	Uttargram	35	6.82	285	134	0.13	25.8
33	NGMPWQ_33	Mohadevpur	Vimpur	61	6.91	534	252	0.25	26.1
34	NGRNWQ_34	Raninagar	Kasimpur	52	6.63	543	263	0.26	25
35	NGATWQ_35	Atrai	Shahagola	49	6.95	502	239	0.24	25.8
36	NGATWQ_36	Atrai	Bhupara	30	7.11	612	294	0.29	25.6
37	NGRNWQ_37	Raninagar	Bilkrishopur	49	7	462	218.2	0.22	26.1
38	NGNGWQ_38	Naogaon	Sadar	59	6.86	592	293	0.29	24.1
39	NGNGWQ_39	Naogaon	Kirtipur	27	6.73	357	171	0.17	25
40	NGBGWQ_40	Badalgachi	Badalgachi	58	6.95	386	187.3	0.18	24.6

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Sl. No.	Sample ID	Upazila	Union	Well Depth (m)	pH	EC ($\mu\text{s/cm}$)	TDS (mg/l)	Salinity (ppt)	Temp ($^{\circ}\text{C}$)
41	NGBGWQ_41	Badalgachi	Chakrail	24	6.79	394	186.6	0.19	25.7
42	NGPTWQ_42	Patnitala	Ghosnagar	32	6.83	359	169.9	0.17	25.7
43	NGDHWQ_43	Dhamoirhat	Aranagar	26	6.27	186	82.5	0.82	28.1
44	NGDHWQ_44	Dhamoirhat	Umar	45	6.78	200.3	95.2	0.95	25
45	NGPSWQ_45	Porsha	Chaor	95	7.38	759	385	0.39	23.3
46	NGPSWQ_46	Porsha	Tentulia	93	7.12	849	440	0.44	23
47	NGSPWQ_47	Sapahar	Sironti	52	7.04	551	260	0.26	26.3
48	NGPTWQ_48	Patnitala	Dibor	40	6.88	374	175	0.18	26.1
49	NGSPWQ_49	Sapahar	Tilna	60	6.93	434	204	0.2	26.3
50	NGNPWQ_50	Niamatpur	Hajinagar	56	6.87	446	208.7	0.21	26.5

Table 6-2: Results of Chemical Analysis of all Major, Minor and Trace Constituents

Sample ID	Upazila	Union	Depth (m)	Major Constituents (mg/l)								Minor Constituents (mg/l)			Trace Constituents (mg/l)	
				Cations				Anions				PO ₄ ³⁻	F ⁻	Fe	Mn	As
				Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	HCO ₃ ⁻	Cl ⁻	SO ₄ ²⁻	NO ₃ ⁻					
RSMPWQ_1	Mohonpur	Royghati	71	56	28	56.38	3	366.00	60	1	bdl	0.12	0.31	2.65	0.89	0.002
NGMDWQ_2	Manda	Tentulia	63	63	32	110.80	40	350.75	170	2	0.36	0.10	0.27	3.70	0.86	0.001
NGMDWQ_3	Manda	Monim Durgapur	64	20	14	35.05	2	228.75	30	1	1.00	0.14	0.19	3.72	0.81	0.001
NGMPWQ_4	Mohonpur	Bakshimoin	61	84	29	85.38	3	549.00	100	1	1.48	0.10	0.39	1.80	0.23	0.002
RSCHWQ_5	Charghat	Shalua	40	106	31	30.07	2	640.50	40	1	1.93	0.10	0.41	1.20	0.68	0.001
RSCGWQ_6	Charghat	Charghat	40	120	33	31.47	5	610.00	50	1	2.47	0.10	0.48	1.60	2.13	0.002
RSBGWQ_7	Bagha	Bajubagha	58	76	22	14.73	2	457.50	30	2	2.37	0.14	0.18	4.20	0.37	0.006
RSBGWQ_8	Bagha	Bausha	55	107	26	21.43	5	533.75	40	1	3.13	0.10	0.17	3.80	0.89	0.004
RSPBWQ_9	Paba	Nawhata	52	65	31	35.33	2	518.50	30	2	0.71	0.10	0.41	1.60	1.12	0.005
RSTNWQ_10	Tanore	Tanore Pourashava	62	38	15	37.53	5	289.75	25	1	bdl	0.12	0.20	5.90	0.67	0.001
RSTNWQ_11	Tanore	Mundumala Pourashava	40	47	22	80.67	1	472.75	40	1	5.51	0.10	0.37	1.53	0.03	0.001
RSGGWQ_12	Godagari	Mohonpur	49	63	26	44.54	1	488.00	30	1	4.04	0.11	0.30	1.20	0.07	0.001
RSGGWQ_13	Godagari	Matikata	43	56	15	36.95	2	366.00	30	2	10.84	0.10	0.24	1.00	0.09	0.001
RSRSWQ_14	Rajshahi	Shah Makhdum	46	140	43	36.81	4	671.00	60	2	0.79	0.12	0.31	0.98	2.50	0.001
CHCHWQ_15	Chapainawabganj	Jhilim	37	54	18	38.23	2	381.25	25	1	7.24	0.10	0.30	2.60	0.03	0.001
CHSGWQ_16	Shibganj	Mobarakpur	26	78	36	35.00	3	579.50	30	2	0.33	0.12	0.44	1.27	0.48	0.002
CHBHWQ_17	Bholahat	Jambaria	23	90	29	41.78	4	564.25	40	1	bdl	0.10	0.34	2.42	0.78	0.002
CHBHWQ_18	Bholahat	Gohalbari	46	62	15	34.16	2	381.25	30	1	1.61	0.12	0.21	2.40	1.79	0.005
CHSGWQ_19	Shibganj	Chatrajitpur	35	123	24	23.58	5	579.50	50	1	10.95	0.10	0.11	3.50	1.21	0.032
CHCHWQ_20	Chapainawabganj	Ranihati	37	88	25	27.61	3	472.75	46	2	0.87	0.10	0.06	0.60	0.68	0.070
CHNCWQ_21	Nachol	Nezampur	39	57	26	77.04	2	533.75	35	1	7.26	0.13	0.27	1.20	0.05	0.002
CHNCWQ_22	Nachol	Kosba	44	52	20	35.81	1	381.25	25	1	0.92	0.10	0.29	0.65	0.03	0.001
CHGPWQ_23	Gomostapur	Gomostapur	39	65	21	36.05	1	442.25	25	2	4.23	0.11	0.36	5.20	2.30	0.008
CHGPWQ_24	Gomostapur	Parbatipur	45	83	28	35.77	2	472.75	30	1	0.84	0.10	0.36	0.94	0.03	0.001
RSPTWQ_25	Puthia	Banessor	61	94	26	23.13	3	549.00	35	1	2.99	0.10	0.23	1.00	0.67	0.004
RSPTWQ_26	Puthia	Bhalukgachi	58	71	23	25.60	2	411.75	30	1	2.97	0.10	0.34	5.30	0.78	0.047
RSDPWQ_27	Durgapur	Naopara	69	90	31	32.39	4	533.75	40	2	0.93	0.12	0.21	1.80	0.33	0.002
RSBMWQ_28	Bagmara	Bhabaniganj	52	70	20	24.06	2	411.75	30	1	2.16	0.13	0.71	1.60	0.39	0.001
RSDPWQ_29	Durgapur	Joynagar	67	75	20	24.48	2	457.50	30	1	0.71	0.10	0.38	1.00	0.74	0.001

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RSBMWQ_30	Bagmara	Auspara	55	77	21	51.54	3	533.75	40	1	0.34	0.10	0.42	1.60	0.60	0.027
NGNPWQ_31	Niamatpur	Bhabicha	38	42	16	37.36	3	305.00	30	1	2.52	0.10	0.31	2.29	0.56	0.001
NGMPWQ_32	Mohadevpur	Uttargram	35	16	7	14.62	2	167.75	20	1	0.33	0.11	0.24	4.49	0.38	0.001
NGMPWQ_33	Mohadevpur	Vimpur	61	22	11	46.97	1	411.75	50	2	bdl	0.10	0.18	2.60	0.45	0.001
NGRNWQ_34	Raninagar	Kasimpur	52	31	15	35.89	3	350.75	45	1	3.15	0.10	0.23	12.90	2.32	0.001
NGATWQ_35	Atrai	Shahagola	49	38	13	24.56	2	533.75	30	1	6.14	0.10	0.24	2.30	0.43	0.004
NGATWQ_36	Atrai	Bhupara	30	63	14	20.29	2	472.75	35	2	1.99	0.12	0.29	0.80	0.34	0.001
NGRNWQ_37	Raninagar	Bilkrishopur	49	41	12	21.16	3	488.00	30	1	0.94	0.10	0.25	1.70	0.30	0.001
NGNGWQ_38	Naogaon	Sadar	59	37	23	31.70	2	381.25	40	2	0.80	0.10	0.18	6.60	0.91	0.002
NGNGWQ_39	Naogaon	Kirtipur	27	22	8	14.18	3	259.25	25	1	bdl	0.10	0.19	5.50	0.94	0.016
NGBGWQ_40	Badalgachi	Badalgachi	58	17	7	26.92	1	350.75	30	1	3.14	0.10	0.25	2.00	0.31	0.007
NGBGWQ_41	Badalgachi	Chakrail	24	20	10	27.80	2	503.25	30	1	2.40	0.10	0.26	3.20	0.69	0.001
NGPTWQ_42	Patnitala	Ghosnagar	32	26	8	20.86	2	381.25	30	2	0.95	0.11	0.25	2.30	0.91	0.005
NGDHWQ_43	Dhamoirhat	Aranagar	26	1	4	22.48	1	518.50	20	1	0.65	0.12	0.05	0.60	0.03	0.001
NGDHWQ_44	Dhamoirhat	Umar	45	2	4	17.10	1	350.75	20	1	1.71	0.10	0.15	1.30	0.28	0.001
NGPSWQ_45	Porsha	Chaor	95	52	26	84.48	2	350.75	40	1	0.78	0.10	0.62	0.80	0.05	0.002
NGPSWQ_46	Porsha	Tentulia	93	70	32	62.45	3	320.25	40	1	1.25	0.10	0.51	0.71	0.03	0.001
NGSPWQ_47	Sapahar	Sironti	52	46	15	24.22	1	259.25	30	1	bdl	0.10	0.37	1.10	0.03	0.001
NGPTWQ_48	Patnitala	Dibor	40	24	9	18.97	1	564.25	25	2	0.97	0.10	0.29	3.70	0.46	0.001
NGSPWQ_49	Sapahar	Tilna	60	38	8	28.26	2	427.00	30	1	1.23	0.10	0.34	3.80	0.21	0.001
NGNPWQ_50	Niamatpur	Hajinagar	56	35	11	28.30	2	472.75	30	1	0.87	0.10	0.27	0.60	0.03	0.001

The most desirable limit of EC in drinking water is prescribed as 1500 $\mu\text{S}/\text{cm}$ (WHO 2004). EC value of collected groundwater samples from the project area ranges from 186 to 1190 $\mu\text{S}/\text{cm}$ whereas salinity of collected groundwater samples from the project area ranges from 0.13 to 0.95 ppt. The TDS value of collected groundwater samples from the project area ranges from 82 to 580 mg/l. From the classification of TDS, it is observed that there are 46 samples that exist within the desirable for drinking and remaining 4 samples exist within permissible for drinking. The temperature of collected groundwater samples from the project area ranges from 23 to 28.1°C.

Calcium concentration in groundwater of the project area ranges from 1 to 140 mg/l and the Magnesium concentration ranges from 4 to 43 mg/l. The Sodium and Potassium concentration in groundwater of the project area ranges from 14 to 110 mg/l. and 1 to 5 mg/l respectively except in Tetulia union under Manda upazila where the potassium value is 50 mg/l.

Chloride concentration in groundwater of the project area ranges from 20 to 60 mg/l except Tetulia and Baksimoil unions under Manda and Mohonpur upazila respectively where the value of chloride is 170 mg/l for Tetulia union and 100 mg/l for Baksimoil union. Fluoride concentration varies from less than 0.05 to 0.71 mg/l whereas Nitrate concentration ranges from less than 0.3 to 10.95 mg/l.

Bi-carbonate concentration in groundwater of the project area ranges from 167 to 671 mg/l. Sulfate concentration in groundwater of the project area ranges from less than 1 to 2 mg/l. Phosphate concentration in groundwater of the project area ranges from 0.10 to 0.14 mg/l.

Iron concentration in groundwater of the project area ranges from 0.60 to 6.60 mg/l. Higher concentration is found in Kashimpur union under Raninagar upazila where the concentration is 12.90 mg/l. Manganese concentration in groundwater of the project area ranges from less than 0.03 to 2.5 mg/l. Arsenic concentration in groundwater of the project area ranges from less than 0.001 to 0.047 mg/l except Ranihati union under Chapainawabganj upazila where the concentration of As is 0.07 mg/l.

In addition, available surface water quality parameters data of Naogaon district collected from secondary sources have been analyzed. The summary of surface water quality analysis for Naogaon area is given in Table 6-3.

Table 6-3: Summary of Surface Water Quality at Naogaon District

Sl. No.	Parameters	Surface Water		Bangladesh Standards	
		Min	Max	Drinking Limit	Irrigation Limit
1	pH	6.7	8	6.5 - 8.5	6.0 - 9.0
2	EC ($\mu\text{s}/\text{cm}$)	103	447	600 - 1000	1200
3	TDS (mg/l)	72	312	1000	2100
4	T.-Alkainity (mg/L)	40	160	-	-
5	T.-Hardness (mg/L)	36	132	-	-
6	Temp ($^{\circ}\text{c}$)	26.1	28.7	-	-
7	Ca^{2+} (mg/l)	8	32	75	-
8	Mg^{2+} (mg/l)	3.84	12.48	30 - 50	-
9	K^{+} (mg/l)	<6	20	12	-
10	Cl^{-} (mg/l)	20	40	150 - 600	600
11	SO_4^{2-} (mg/l)	<50	<50	400	-
12	PO_4^{3-} (mg/l)	0	0.2	6	10
13	$\text{NO}_3\text{-N}$ (mg/L)	0	4	10	-
14	Fe (mg/l)	0	1	0.3 -1.00	1.00-2.00
15	As (mg/l)	0	0	0.05	1

7 COMPUTATION OF SECTORAL WATER DEMAND

7.1 Irrigation Water Requirement

Computation of Irrigation Water Requirement (IWR) is necessary to make an assessment of the amount of water that is being presently used for irrigation as well as to assess present and future water requirements for the development of model. As seepage & percolation is a dominating factor for water demand of Boro, which varies from upazila to upazila. So, water demand for Boro in different upazilas are different. Considering these factors, crop water demand has been calculated upazila wise using CROPWAT version 5.7 (FAO, 1992). After calculating crop water demand, Irrigation Water Requirement (IWR) for different crops for different upazilas have been estimated. Details are given in Chapter 9, Volume -II.

Different sectoral water demand for the study area has been calculated and verified during PRA study (Component- 1) through Focus Group Discussion (FGD). District wise water demand for different sectors are given in Table 7-1, Table 7-2 and Table 7-3 whereas union wise values are given in Chapter 9, Volume -II and Volume -IV, Appendix-E. These water demands have been used for the development of mathematical models using MIKE SHE.

Table 7-1: Different Aspects of Water Resource Usage and Demand in Rajshahi District

Upazila	Nos. of Ponds (>25 decimal)	Nos. of Tube Wells		Sector-Wise Water Demand (MCM per Year)				Total Water Uses (MCM)
		STW	DTW	Domestic	Agricultural	Fisheries	Industries	2021
Bagha	520	18,288	52	2.68	99.21	2.55	0.48	104.92
Bagmara	4330	26,456	913	6.12	119.14	23.67	0.43	149.36
Charghat	466	24,438	75	3.24	81.06	2.6	1.17	88.07
Durgapur	2568	13,907	340	3.06	106.73	14.18	2.46	126.43
Godagari	2463	13,614	774	5.22	270.67	15.24	3.2	294.33
Mohonpur	1992	11,950	322	2.9	88.6	10.78	0.4	102.68
Paba	1630	31,235	245	4.41	126.18	14.52	-	145.11
Puthia	2171	32,410	281	3.33	116.62	14.78	1.06	135.79
Tanore	2668	8,210	654	2.65	111.25	14.18	1.92	130
Total	18808	180508	3656	33.61	1119.46	112.5	11.12	1276.69

Table 7-2: Different Aspects of Water Resource Usage and Demand in Naogaon District

Upazila	Nos. of Ponds (>25 decimal)	Nos. of Tube Wells		Sector-Wise Water Demand (MCM per Year)				Total Water Uses (MCM)
		STW	DTW	Domestic	Agricultural	Fisheries	Industries	2021
Atrai	2344	48061	294	3.7	166.17	14.53	1.28	185.68
Badalgachi	1047	10242	320	3.26	138.89	5.59	0.74	148.48
Dhamoirhat	2135	44310	359	3.26	198.75	15	1.43	218.44
Manda	3590	55000	483	6.94	266.69	18.18	-	291.81
Mohadevpur	4077	70596	571	5.62	234.83	20.06	4.77	265.28
Naogaon Sadar	1625	37230	249	4.91	152.25	8.29	3.98	169.43
Niamatpur	4049	18716	790	4.77	218.11	23.32	0.62	246.82
Patnitala	3725	39906	443	4.04	183.78	23.33	7.65	218.8
Porsha	2127	4124	282	2.12	121.91	11.73	0.27	136.03
Raninagar	2374	11660	419	3.06	135.9	11.43	2.48	152.87
Sapahar	1784	1099	323	3.08	130.95	9.25	0.01	143.29
Total	28877	340944	4533	44.76	1948.23	160.71	23.23	2176.93

Table 7-3: Different Aspects of Water Resource usage and Demand in Chapainawabganj District

Upazila	Nos. of Ponds (>25 decimal)	Nos. of Tube Wells		Sector-Wise Water Demand (MCM per Year)				Total Water Uses (MCM)
		STW	DTW	Domestic	Agricultural	Fisheries	Industries	2021
Bholahat	155	8093	246	1.77	73.9	0.5	0.16	76.33
Chapainawabganj Sadar	827	52118	206	6.77	278.28	15.66	0.8	301.51
Gomostapur	1144	19435	425	4.41	175.94	1.91	0.39	182.65
Nachol	2017	3255	522	2.48	134.18	3.78	0.22	140.66
Shibganj	801	13517	245	10.75	211.81	2.61	0.3	225.47
Total	4944	96418	1644	26.18	874.11	24.46	1.87	926.62

8 DEVELOPMENT OF MATHEMATICAL MODEL

8.1 Modelling Method Overview

The groundwater resources of Rajshahi, Chapainawabganj and Naogaon districts in the Barind region of Bangladesh are intimately connected with the surface water resources. The annual dynamics of the groundwater resource is influenced by the recharge processes comprising, inflow from diffuse recharge following rainfall, irrigation and flooding, exchanges with rivers and discharge through pumping for irrigation and other uses, contribution to natural evapotranspiration and draining into rivers. To understand groundwater dynamics in this region, it is important to do integrated water resources assessment using appropriate modelling tools. Usually coupled surface water - groundwater interaction models are ideally the best choice of models to simulate complex hydrological processes in regional river basins. Hence, to understand groundwater dynamics in this region, it is important to do integrated water resources (GW-SW) assessment using appropriate modelling tools. In this study, the existing hydrodynamic model has been updated and coupled with groundwater model. MIKE 11 and MIKE SHE modelling tools have been used for this purpose.

8.1.1 Development of Conceptual Model

The first step in the procedure of groundwater flow model is the development of a conceptual model of the problem of the assigned area. The conceptual model for the study area has been developed using bore log data obtained from secondary sources and exploratory drilling conducted under this project. The conceptual model has been approved by the Panel of Expert (PoE) and Technical Committee (TC) of the project. Figure 8-1 is a schematic three-dimensional view illustrating the flow model conceptualization for the study area. The aquitard layers are composed mostly of clay and silty clay whereas the aquifer layers are composed of medium to coarse sand with occasional fine sand.

Infiltration from rainfall and surface water bodies through the uppermost layer is the main source of groundwater recharge. Evapotranspiration from the area by which water is lost from the aquifer system also occurs from this layer. This aquitard-1 is fully or partially cut by rivers in the study area which allows direct hydraulic connectivity between the river, Aquitard-1 and Upper aquifer. The river can either gain or lose water depending on the difference in head between the aquifer and the river. The summary of conceptual model can be stated as shown in Table 8-1.

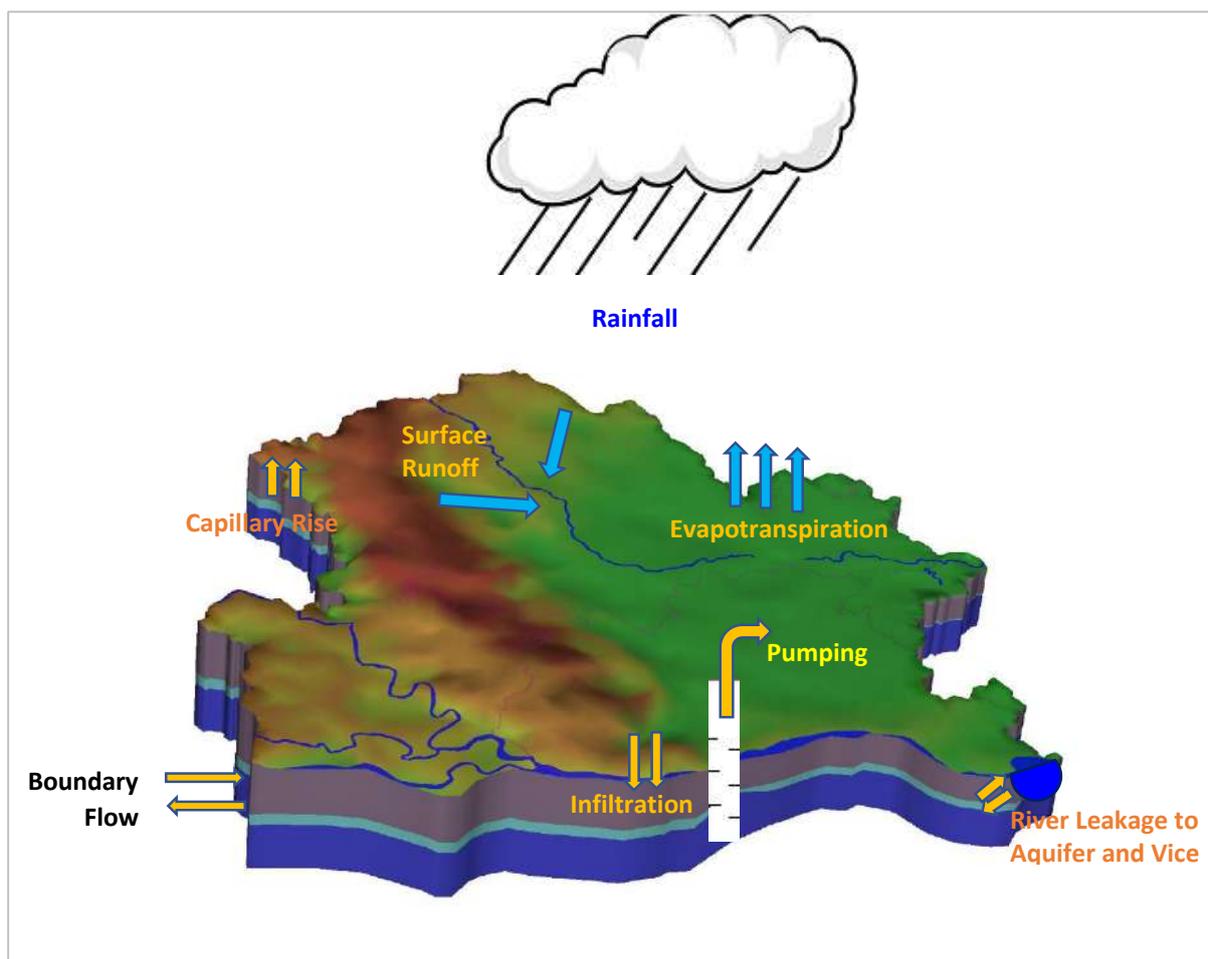


Figure 8-1: Conceptual Model of the Study Area

Table 8-1: Summary of Conceptual Model

Component	Findings
Rainfall	<ul style="list-style-type: none"> The mean annual rainfall varies between 1200 mm to 2000 mm.
Topography	<ul style="list-style-type: none"> Topography of the study area varies from 9.50 mPWD to 47.0 mPWD.
Landuse	<ul style="list-style-type: none"> The model area mainly covered by agricultural land.
Unsaturated Zone	<ul style="list-style-type: none"> Silt and silty clay are mostly present in unsaturated zone.
Saturated Zone	<ul style="list-style-type: none"> The aquifer layers are composed of medium to coarse sand with occasional fine sand.
Boundary	<ul style="list-style-type: none"> Time varying head boundary has been used.

8.1.2 Development of Hydrodynamic Model

Physically based hydrodynamic modelling has been used to develop the surface water model. The surface water model comprises a hydrological (rainfall-runoff) model and a hydrodynamic (river/channel/floodplain hydraulics) model. MIKE 11 of MIKE Zero platform developed by the DHI Water & Environment; Denmark has been applied in developing these models. MIKE 11 modelling system requires a large amount of high-quality data including river channel bathymetry, water level and discharge measurements. Both the rainfall runoff model (NAM)

and hydrodynamic (HD) model have been calibrated and validated against observed data. Then the HD model has been coupled with groundwater model of the study area to get the groundwater and surface water interaction and to see the impact of groundwater abstraction. MIKE SHE modelling tools have been used to develop the coupled model. Another purpose of developing the model is to assess surface water resources in the study area. The surface water model covers the entire study area incorporating the existing river systems with updated cross-sections as per ToR. A detailed description of the development of model setup activities is presented in Chapter 10, Volume -II.

8.1.3 Development of Groundwater Model

The major activities in connection with groundwater modelling includes identification of the area of model domain (area to be modeled), river system that would be included in the model, delineation of catchment area, identification of hydraulic structures, identification of geological layers and their hydraulic properties, identification of boundary stations and conditions, land use and of preparation various hydro-meteorological input data, calibration and validation of models, coupling of surface water and groundwater model, selection of design year, option formulation and simulations, analysis and interpretation of results etc. Necessary data has been collected and checked for consistency and processed for model input. The description of the model setup activities is presented in Chapter 10, Volume -II.

8.1.4 Sensitivity Analysis

Sensitivity analysis is a procedure for quantifying the impact on an aquifer's simulated response due to an incremental variation in a model parameter or a model stress. The purpose of sensitivity analysis is to identify those parameters which are most important in determining the aquifer behavior. First parameters were ranked in order of importance, and then priorities have been set for focusing field investigations on key parameters to reduce model uncertainty. Sensitivity analysis was carried out for the horizontal hydraulic conductivity, detention storage, boundary condition and subsurface drainage. The hydraulic conductivities have been multiplied by 2 and 0.5 times to its base condition whereas detention storage has been considered as 50 mm instead of 100 mm as in base condition. The bias induced due to the boundary condition was checked by considering no flow boundary condition in all the layers. The sensitivity of the above-mentioned are presented in Figure 8-2 and Figure 8-3.

The sensitivity analysis shows that subsurface drainage has a great influence followed by horizontal hydraulic conductivity in the model calibration. The sensitivity plot also indicates that the detention storage and boundary does not have significant influence on model calibration. As the boundary condition does not have much influence on model simulation so it can be concluded the model is unbiased with respect to boundary condition.

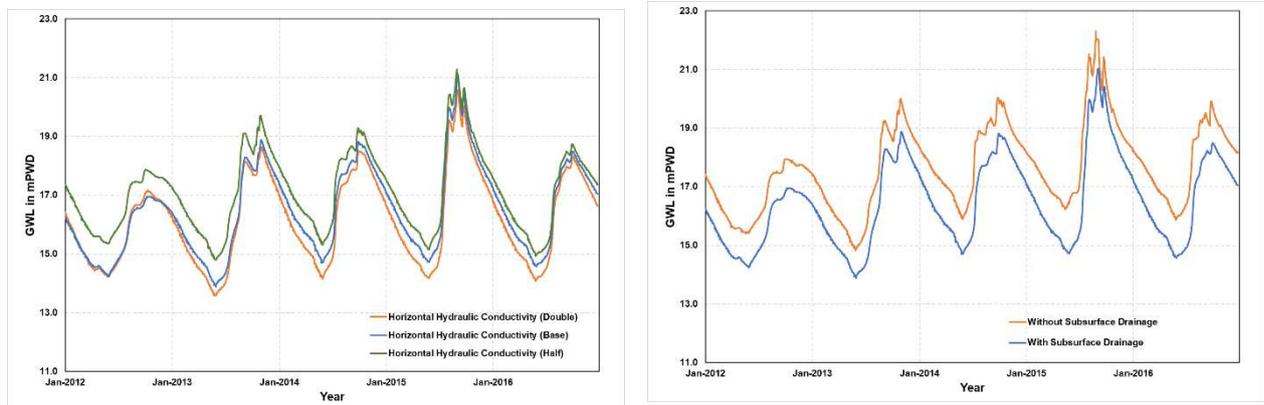


Figure 8-2: Sensitivity Analysis for Double, Half and Base Horizontal for Conductivity (Left) and With and Without Subsurface Drainage (Right)

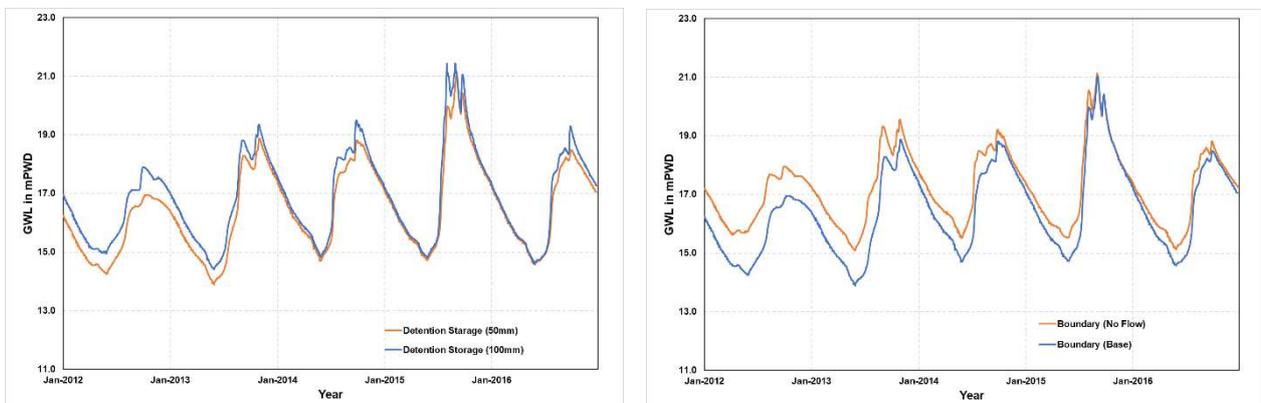


Figure 8-3: Sensitivity Analysis for Detention Storage (50mm and 100mm) (Left) and No Flow Boundary Condition (Right)

8.2 Simulation for different Scenarios and Climate Change Impact

Analyses of short-term (annual) changes in groundwater levels corresponding to three scenario options comprising different rainfall characteristics and different groundwater abstractions due to cropping pattern changes were simulated using the MIKE SHE models. Simulation of differences in short-term groundwater level changes for 5 climate scenarios was also undertaken using the MIKE SHE models. The details of the scenarios are described in the following.

8.2.1 Simulation for different Scenarios

Rainfall events with different return periods together with future irrigation demand were considered to evaluate groundwater level changes and sustainability. MIKE SHE model scenario options were formulated based on crop coverage and irrigation demands in different hydrological situations of the study area. A sample analysis of the study area is described below.

There are 18 rainfall stations which fall in and around the study areas. Rainfall data for these 18 stations for a period of 36 years (1985–2021) have been considered for statistical analysis. The data of year 2022 has not been considered because of data gap at various stations. Rainfall data have been fitted to a Log Normal distribution to analyze and to identify the year which matches with different return period events. The statistical software HYMOS 4.0 has been used for this purpose. The results of the analysis for 2-yr, 5-yr, 25-yr and 100-yr return period are presented in Table 8-2. Due to the randomness of rainfall events, all rainfall events for each station will not represent a unique design year and it is necessary to select a design year on the basis of stations which represent a unique design year.

Table 8-2: Rainfall Data Corresponding to 2-yr, 5-yr, 25-yr and 100-yr Return Periods for the Study Area

Station Name	2 Yr	Matching Year	5 Yr	Matching Year	25 Yr	Matching Year	100 Yr	Matching Year
Rohanpur	1275	2019	1027	2008	748	2012	695	2013
Mohadevpur	1486	2017	1252	2012	695	2013	748	2012
Atrai(Ahsanganj)	1443	2013	1338	2016	708.4	1997	708.4	1997
Bholahat	1491	2017	1232	2021	782.3	1990	782.3	1990
Godagari	1372	2017	1145	2014	906.5	2010	906.5	2012
Manda	1338	2016	1265	2021	851	2010	708.4	1997
Nachol	1320	2021	1063	2017	886.4	2012	886.4	2012
Nazirpur (Patnitala)	1377	2016	1082	2020	800	2013	691	2008
Nithpur	1421	2018	1216	2012	852.6	2014	784.9	2009
Rajshahi	1337	2014	1193	2012	960.5	2009	789.3	1992
Sapahar	1470	2011	1234	2013	981	2008	981	2008
Sardah	1338	2016	1183	2019	708.4	1997	708.4	1997
Shibganj(Rajshahi)	1403	2015	1232	2019	851	2010	708.4	1997
Tanore	1194	2017	1400	2012	815.1	2008	734.7	1994
Naogaon	1481	2020	1262	2011	1029.4	2006	1029.4	2006
Badalgachi	1462	2020	1090	2014	804	2018	648	2016
Chapainawabganj	1340	2021	1176	2017	897.95	2009	835.4	1992
Puthia	1511	2019	1135	2016	663	2009	663	2009

It was found that 4 stations match the year 2017 as 2-yr return period (50% dependable or exceedance probability of 0.5) event, 4 stations match the year 2012 as 5-yr return period (80% dependable or exceedance probability of 0.8) event and 4 stations match the year 1997 as 100-

year return period (99% dependable or exceedance probability of 0.99) event. As such, 2017, 2012 and 1997 have been selected as the design year (50% dependable), dry year (80% dependable) and extreme dry year (99% dependable) respectively.

The scenario options are briefly described in Table 8-3:

Table 8-3: Brief Description of the MIKE SHE Simulation Scenarios

Scenarios Name	Brief Description
Option 0: Base option, i.e. average condition (design year)	<ul style="list-style-type: none"> • Hydrological condition for 2-Yr return period event (50% dependable rainfall) • Crop coverage for existing condition (60% area under HYV Boro) • Irrigation demand for the existing cropping pattern and crop coverage • Domestic (rural & urban) and industrial demands for existing condition etc. • Water application: as per crop demand and irrigation coverage
Option I: Future option with 80% dependable rain (dry year)	<ul style="list-style-type: none"> • Hydrological condition for 5-Yr return period event (80% dependable rainfall) • Crop coverage for future condition (considering 90% area under HYV Boro) • Irrigation demand for future cropping pattern and crop coverage considering 90% area under HYV Boro • Domestic (rural & urban) and industrial demands for future condition • Water application: as per crop demand and irrigation coverage
Option II: Future option with 99% dependable rainfall (extreme dry year)	<ul style="list-style-type: none"> • Hydrological condition for 100-Yr return period event (99% dependable rainfall) • Crop coverage for future condition (considering 90% area under HYV Boro) • Irrigation demand for future cropping pattern and crop coverage considering 90% area under HYV Boro • Domestic (rural & urban) and industrial demands for future condition • Water application: as per crop demand and irrigation coverage

8.2.2 Simulation of the Scenarios

Hydraulic parameters comprising hydraulic conductivity, transmissivity, specific yield and storage coefficient obtained through calibration were kept unchanged throughout the simulation of management options. Number of geological and computational layers along with their top and bottom elevations, soil properties and soil moisture retention curves, DEM of the study area, crop data base (leaf area index, root zone depth, crop growth stages and growing season) of individual crops were also kept the same. Meteorological data (rainfall, evaporation, temperature, humidity etc.), hydrological data (river water level and discharge at the boundary locations) and hydrogeological data (groundwater level at boundary locations) were provided according to the hydrological year considered for the three different scenario options. The initial conditions were kept as those corresponding to the beginning of the selected matching year (Table 8-3) for the respective option. Changes that were considered in different option simulations were:

- land use and crop coverage
- water abstractions.

With the above necessary changes, the calibrated and validated surface water–groundwater interaction model was used to complete the option simulations. Results of the option simulations were analysed, presented and compared with the base condition as:

- groundwater level hydrographs
- spatial distribution map of depth to groundwater table.

8.2.3 Option 0: Base (i.e., average) Condition

The base condition includes hydrological situation for the average year (2017) and all other existing situations that prevail in the field. The main purpose of this option is to understand the present state of the study area under base year in terms of volume of water presently being used and for comparison with future condition with changed water abstraction.

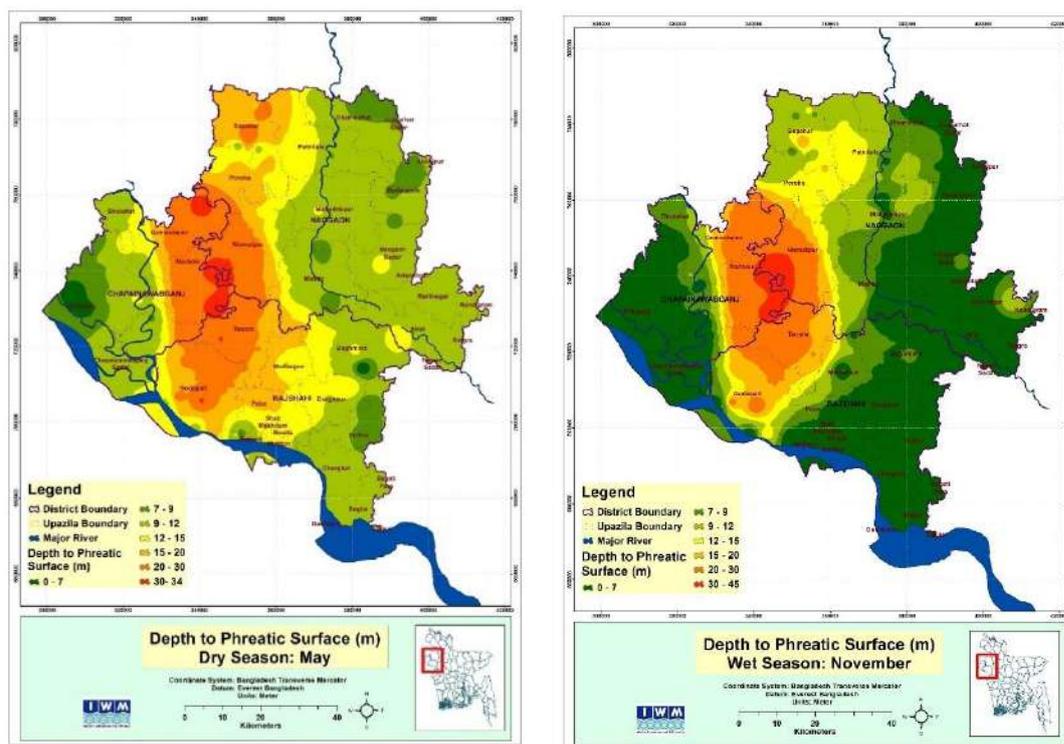


Figure 8-4: Maximum Depth to Groundwater Table on 1st May (Left) under Minimum Depth to Groundwater Table on 1st November Option 0 (Base Condition) (Right)

8.2.3.1 Groundwater Table for Base Condition

Hydrographs of simulated groundwater tables for selected locations showed that the maximum and minimum depth to groundwater table occur at the end of April and end of October respectively. Hydrographs of observed water table also support the above findings. Based on these findings, maps of maximum and minimum depth to groundwater tables were prepared for 1st May and 1st November respectively for the 3 districts of the project area for base condition as shown in Figure 8-4 to see the effect of pumping during irrigation season and also to see whether the groundwater table regains to its original positions or not. In the High and Medium Barind Area the maximum depth to groundwater table goes beyond the 9.0 m level on

1st May as shown in Figure 8-4. From Figure 8-4, it is observed that during the peak time of monsoon (1st November), the groundwater table also remains beyond 9.0 m level. In the Low Barind Area the maximum depth to groundwater table also goes beyond the 9.0 m level on 1st May in most of the areas. But during the peak time of monsoon (1st November), the groundwater table bounds back close to the ground surface in most of the areas of the Low Barind Area.

8.2.4 Option I: Future Option

Option I explore a potential future development, which includes future cropping pattern, crop coverage and abstraction of water from groundwater to meet future irrigation demand. Water demand for crops has been estimated considering that the existing 90% cropped area is covered by HYV Boro. Hydrological condition for 5-yr return period event (80% dependable rainfall) has been considered to simulate this option (relatively dry year). The purpose of this option is to assess the impact of future development on groundwater levels when rainfall is less than average.

8.2.4.1 Hydrograph Analysis

The hydrograph of simulated groundwater levels for this option is compared with simulated groundwater levels for the base condition (option 0) at selected locations. Sample comparison plots of hydrographs are shown in Figure 8-5. These reveal that, in some places, groundwater level drops down by about 1 to 2.5 m compared to the groundwater level for base condition during irrigation period. This situation occurred due to higher abstraction in option I compared to the base case.

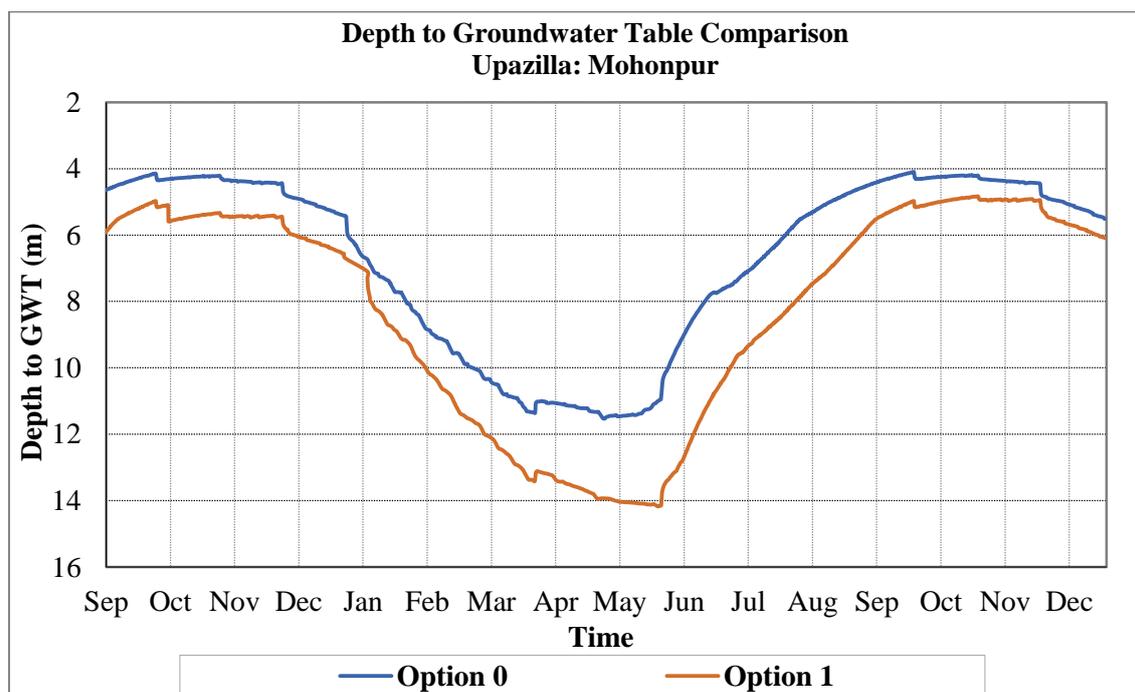


Figure 8-5: Groundwater Level Comparison; Option I & Option 0 for Mohonpur of Rajshahi District

8.2.4.2 Impact on Depth to Groundwater Tables

To investigate the impact of increased abstraction on the study area, spatial distribution of impact maps (Difference of Base condition & Option I) of maximum and minimum depth to groundwater tables were prepared for 1st May and 1st November as shown in Figure 8-6 for the 3 districts of the project. It is observed from Figure 8-6 that in most of the areas, the groundwater table drops down by about 1.0 m to 3.0 m compared to the groundwater table in Base condition. It is also observed that groundwater table drops down by about 3.0 m to 9.5 m in some pockets of the areas of Barind region as shown in Figure 8-6. However, groundwater tables under Option I returns to its original position during the peak time of the monsoon in major part of the areas except the part of Tanore, Godagari and Bagmara upazilas of Rajshahi district, Sapahar, Porsha and Niamatpur upazilas of Naogaon district and Nachol and Gomostapur upazilas of Chapainawabganj district as shown in Figure 8-6.

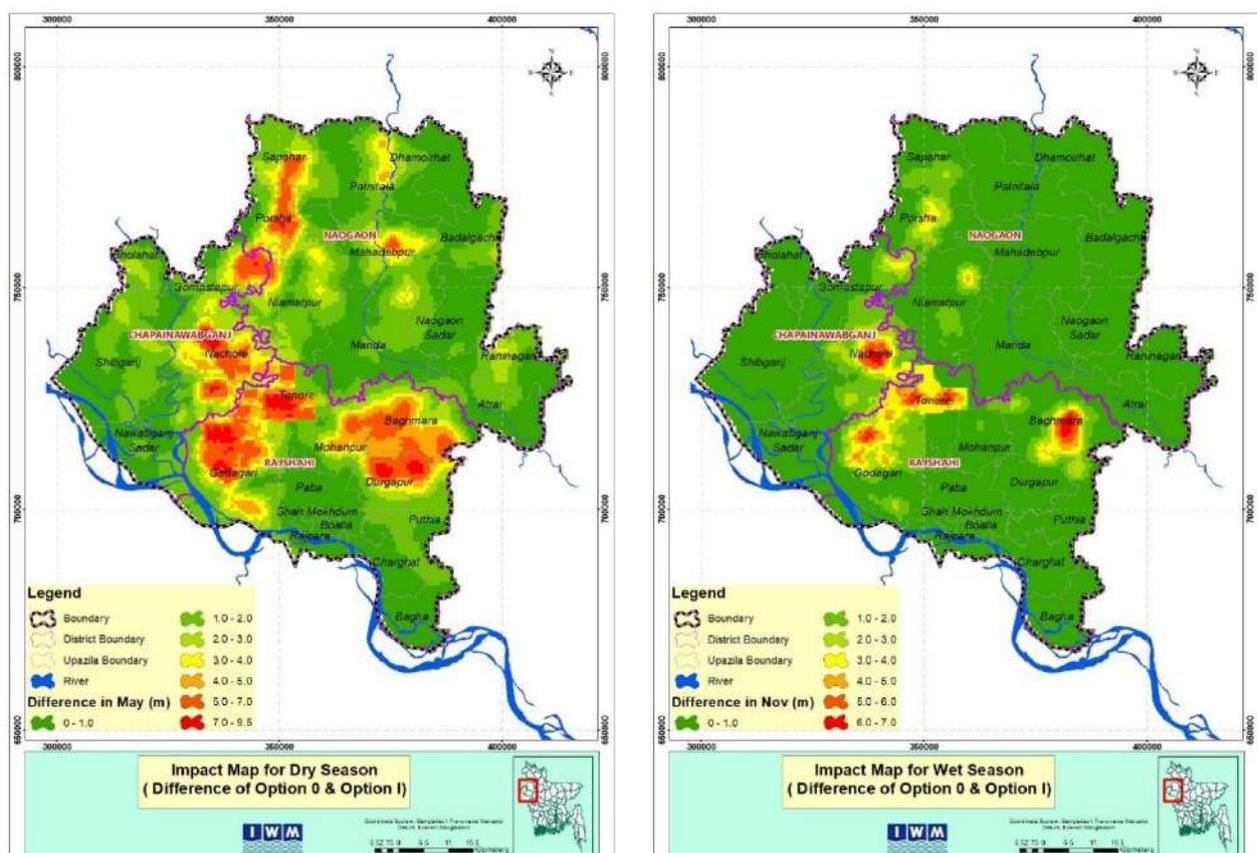


Figure 8-6: Impact Map (Base Condition – Option I) of Maximum Depth to Groundwater Table for the Dry Season (Left) and Minimum Depth to Groundwater Table for the Wet Season (Right)

8.2.5 Option II: Future Option with Extreme Dry Year

Option II was designed to evaluate the impact of severe drought on groundwater. Model simulation was carried out for extreme dry year conditions (1997, which is 1: 100 years extreme dry year) for this option. Hydrographs of simulated groundwater tables of Option II were compared with simulated groundwater tables of Options I and Options 0 at some pre-selected locations.

8.2.5.1 Hydrograph Analysis

Sample plots of hydrographs are shown in Figure 8-7. Option II causes a greater decline in groundwater level in the dry season than Option I and Option 0. This situation occurred because in extreme dry year the amount of rainfall is much less than that of the rainfall in Option I and Option 0. The groundwater level is slightly lower than its original position in monsoon which indicates that continued groundwater use, despite the occurrence of extreme dry years, can lead to groundwater mining. In such scenarios, management measures would be required to ensure long-term sustainability. Recurrence of such climatic conditions over the years may lead to a slow decline in long-term average groundwater tables.

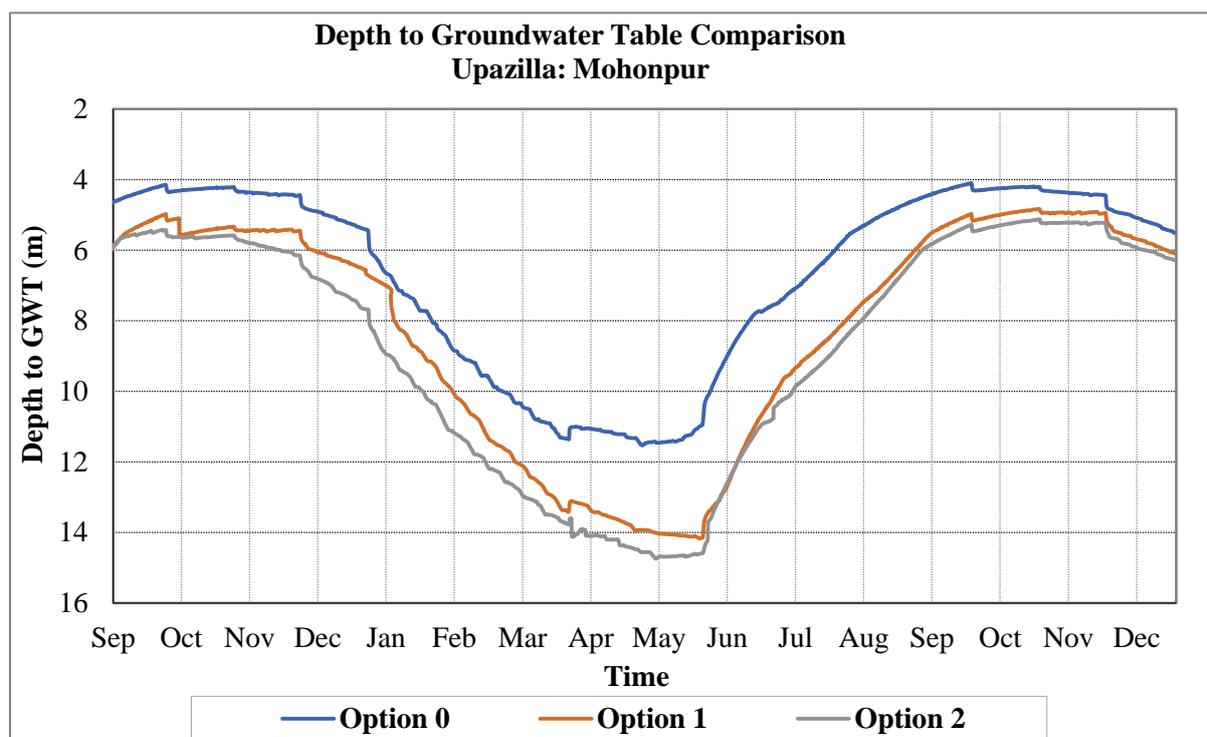


Figure 8-7: Comparison of Hydrographs of Option II with Options I and 0 for Mohonpur of Rajshahi District

8.2.5.2 Impact on Depth to Groundwater Tables

To investigate the impact of increased abstraction on the study area for Option II, spatial impact maps (Difference of Option 0 & Option II) of maximum and minimum depth to groundwater tables were prepared for 1st May and 1st November as shown in Figure 8-8 for the 3 districts of project area. It is noticeable from Figure 8-8 that in most of the areas, the groundwater table drops down about 1.0 m to 4.0 m compared to the groundwater table of Option 0. It is also observed that groundwater table drops down by about 4.0 m to 10.0 m in some pocket's areas of Barind region as shown in Figure 8-8.

assessment made in the paper Karim et. al. 2021, was based on IPCC’s 5th assessment report (AR5) for two emission scenarios RCP 4.5 and RCP 8.5 (Representative Concentration Pathways). In the IPCC’s 5th assessment report (AR5) the scenarios are called Representative Concentration Pathways (RCPs). Study analysis has been done based on available data of IPCC’s 5th assessment (AR5) though IPCC’s 6th assessment has been released recently. The RCPs describe 4 different scenarios based on different assumptions about population, economic growth, energy consumption and sources and land use over this century. There are four RCPs (Representative Concentration Pathway) scenarios which are based on multi-gas emission scenarios, namely RCP2.6, RCP4.5, RCP6, and RCP8.5, are labelled after a possible range of radiative forcing values in the year 2100 relative to pre-industrial values (+2.6, +4.5, +6.0, and +8.5 W/m², respectively). Rainfall and PET were projected in the paper based on scaling factors derived from GCM results. Scaling factors and subsequent rainfall and PET time series were derived for a period over 2046–2075 for the RCP4.5 and RCP8.5 emission scenarios. The scaling factor (SF) is estimated as $SF = X_f/X_b$, where X_f and X_b are the GCM simulation for the future and baseline periods respectively. The scaling factor is then used to produce a future climate time series by multiplying baseline observed climate data with SF. Simulations and scaling factors for rainfall and PET for these scenarios are given in Table 8-4.

Table 8-4: Five Climate Change Simulations – Names, Scaling Factors, Rainfall and PET Factors

Simulation Id	Scaling Factors for 2060	Rainfall	PET
1	Average PET and low rainfall	0.983	1.029
2	Average PET and high rainfall	1.220	1.039
3	Average PET and average rainfall	1.118	1.034
4	Low PET and average rainfall	1.096	0.991
5	High PET and average rainfall	1.019	1.075

Source: Karim et al, 2021

Using the scaling factors as shown in Table 8-4, the base model (Option 0) has been simulated to analyze and compare the climate change impact under each of the 5 climate scenarios listed in Table 8-4.

8.3.1 Hydrographs

Simulated hydrographs for these are shown in Figure 8-9 to Figure 8-11.

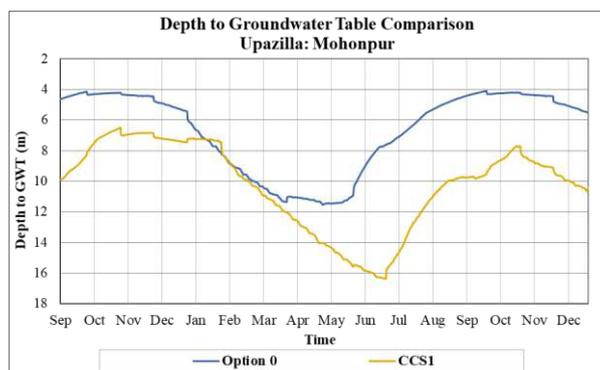


Figure 8-9: Comparison of Hydrographs of Options 0 under Climate Change (CC) Simulation 1

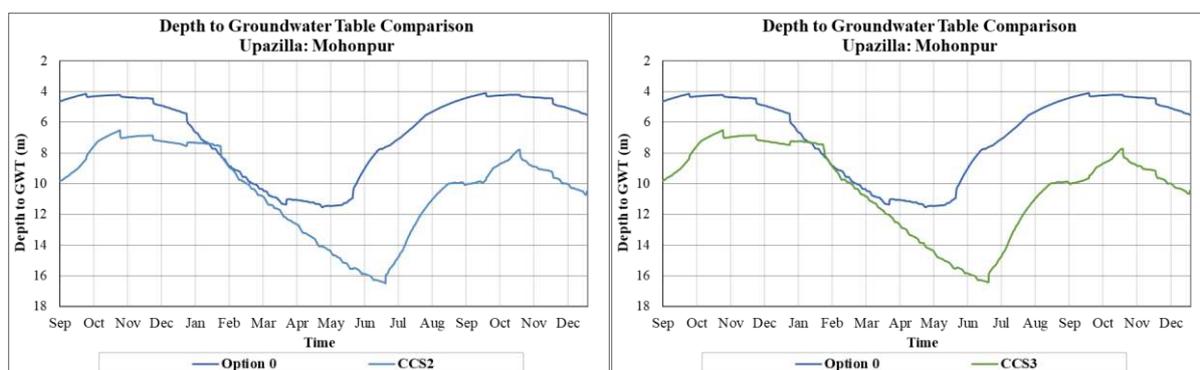


Figure 8-10: Comparison of Hydrographs of Options 0 under Climate Change (CC) Simulation 2 (Left) and Simulation 3 (Right)

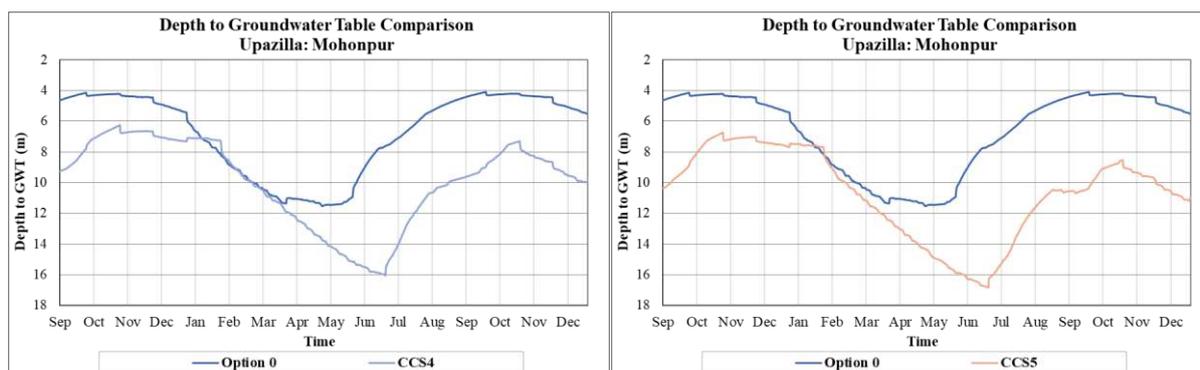


Figure 8-11: Comparison of Hydrographs of Options 0 under Climate Change (CC) Simulation 4 (Left) and Simulation 5 (Right)

Comparison of hydrographs in Figure 8-9 to Figure 8-11 reveals groundwater level drops down by about 2.5 to 3.5 m compared to the groundwater level for base condition during irrigation period for the climate scenarios compared to the baseline condition considered in Options. The climate change scenarios also reveal that the peak of drawdown due to irrigation in dry season shifts from mid-May to mid-June. Changes in groundwater level across different climate scenarios are not significant in the annual time scale considered in the analysis. Climate change's impact on groundwater levels may occur due to changes in amount, distribution and/or duration of rainfall. The most important simulated effect is that the groundwater table fails to regain its original position in monsoon and in post monsoon. This indicates that the

groundwater table may drop up to 6 m due to the impact of climate change, although these are subject to uncertainties in the predicted rainfall. Considering these situations, the proper monitoring of groundwater level should be continued, and initiatives should be taken accordingly. Overall, these simulations indicate that groundwater levels will be immediately responsive to changes in rainfall and ET patterns.

9 PROSPECT OF FUTURE SURFACE WATER DEVELOPMENT

9.1 River System

Surface water model simulation has been carried out including all major rivers of the study area. The following major rivers also have been included in the model to assess surface water availability for future developments.

- Ganges
- Atrai
- Sib-barnai
- Mohananda

Ganges River

The river enters into Bangladesh in Chapainawabganj District at 18.0 km below Farrakha Barrage and then flows as common border for about 106 km. A major diversion of the Ganges takes place from Farakka Barrage. This diverts flows away from Bangladesh. Although the flow is diverted, this river can represent the major source of dry period irrigation water supply in high barind areas.

Atrai River

The Atrai river flows from north to south. At Manda, Sib-Barnai River bifurcated from Atrai. The bifurcated point had been closed by embankment by the local people.

Sib-Barnai River

The river flows from north to south. The river almost dries up during dry season, except in the depression area along the river.

Mohananda River

The Mohananda river flows into the western part of the project area. After flowing 79.0 km, it meets the Ganges River. The river system has been shown in Figure 9-1.

9.2 Surface Water Availability

For the purpose of assessing surface water resources, discharge data were analyzed to estimate the flow event for different return periods. In selecting design event, most weight was given for 80% dependable flow. Frequency analysis for monthly minimum flow data up to 2012 for some selected locations in the major rivers have been carried out using the California method. For the California method, monthly minimum values from the yearly series data are selected for ranking, after that a frequency analysis is carried out. Table 9-1 shows the dry period 80% dependable flow in different rivers of the study area. It is observed from Table 9-1 that some

resources are available in Atrai and Mohananda while very limited resource is available in Sib-Barnai River.

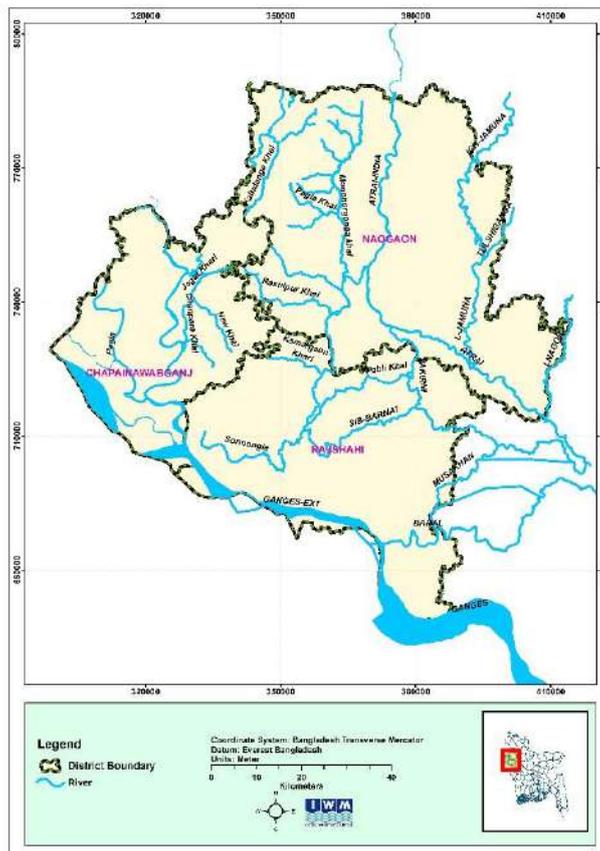


Figure 9-1: Schematized River System in Barind Area

Table 9-1: 80% Dependable Flow during Dry Period in Different Rivers

River	80% Dependable Flows (m ³ /s)					
	November	December	January	February	March	April
Atrai River						
1. Chainage 4.84 km at Mohadevpur	23.91	10.65	8.63	7.73	5.46	--
2. Chainage 54.29 km at Atrai Rail Bridge	39.69	20.08	10.39	7.22	--	--
Sib-Barnai River						
1. Chainage 61.152 km at Nawhata	8.80	2.16	--	--	--	--
Mohananda River						
1. Chainage 49.45 km at Chapainawabganj	81.59	58.02	29.36	17.78	6.50	3.29

9.3 Application of Surface Water -Groundwater Interaction Model

There is a possibility of increasing groundwater recharge by conservation of water in rivers and kharies throughout the year. Accordingly, a simulation has been carried out considering 1 retention structure at Sib-Barnai River to conserve surface water in this river. Total length of Sib-Barnai is about 140.0 km and located in Bagmara, Manda and Mohonpur Upazila. The main purpose of this simulation is to determine the impact of surface water conservation on groundwater recharge. The location and dimension of retention structure have been given in Table 9-2.

Table 9-2: Location of Retention Structure in Sib-Barnai River

SI No	River / Khari	Chainage (km)	Dimension
1.	Sib-Barnai River	40.00	Length =37.0m Ponding level = 11.0 m Bottom Level = 9.8 m

In this simulation, it is observed that water level is increased from existing situation on 1st January up to 40.0 km from u/s of retention structure (Figure 9-2).

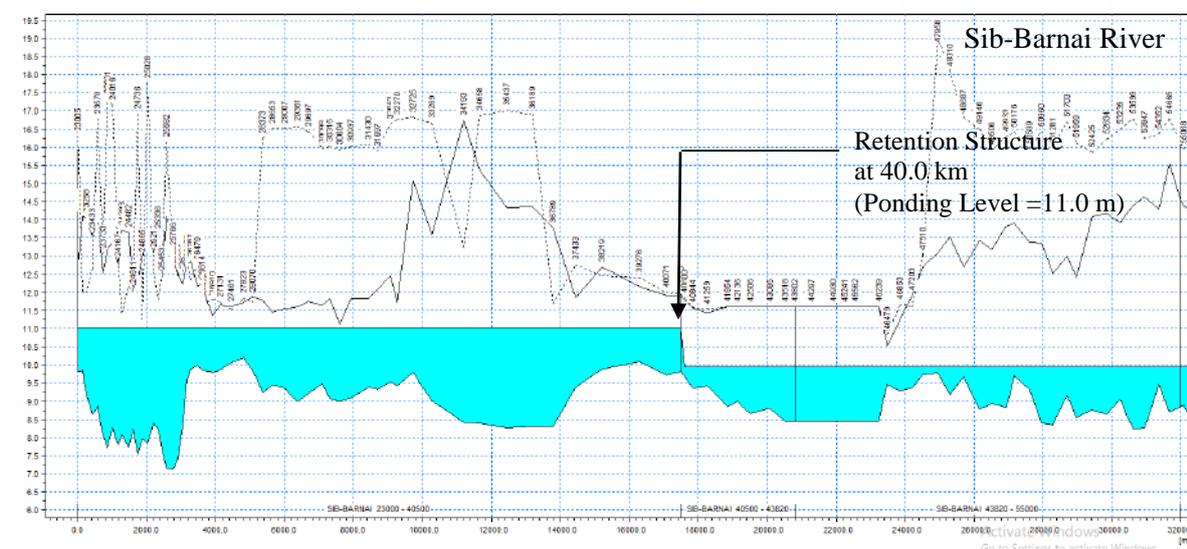


Figure 9-2: Surface Water Profile for Sib-Barnai River, Considering Retention Structure

In order to see the impact of conservation of surface water by construction of retention structure, spatial distribution of impact map of depths to groundwater tables on 1st January has been prepared (Figure 9-3). It has been found from the map that groundwater tables increase by 0.05 m to 0.35 m. It is due to the increase of groundwater recharges from October to January. The impact area is about 137 km² in the adjacent area of Sib-Barnai River during dry period. During monsoon period, sufficient water can be conserved by the retention structure and supplement irrigation is possible using this water which can reduce the pressure on groundwater withdrawal. However, the volume of conserved water and volume of recharge will vary from river to river at different places.

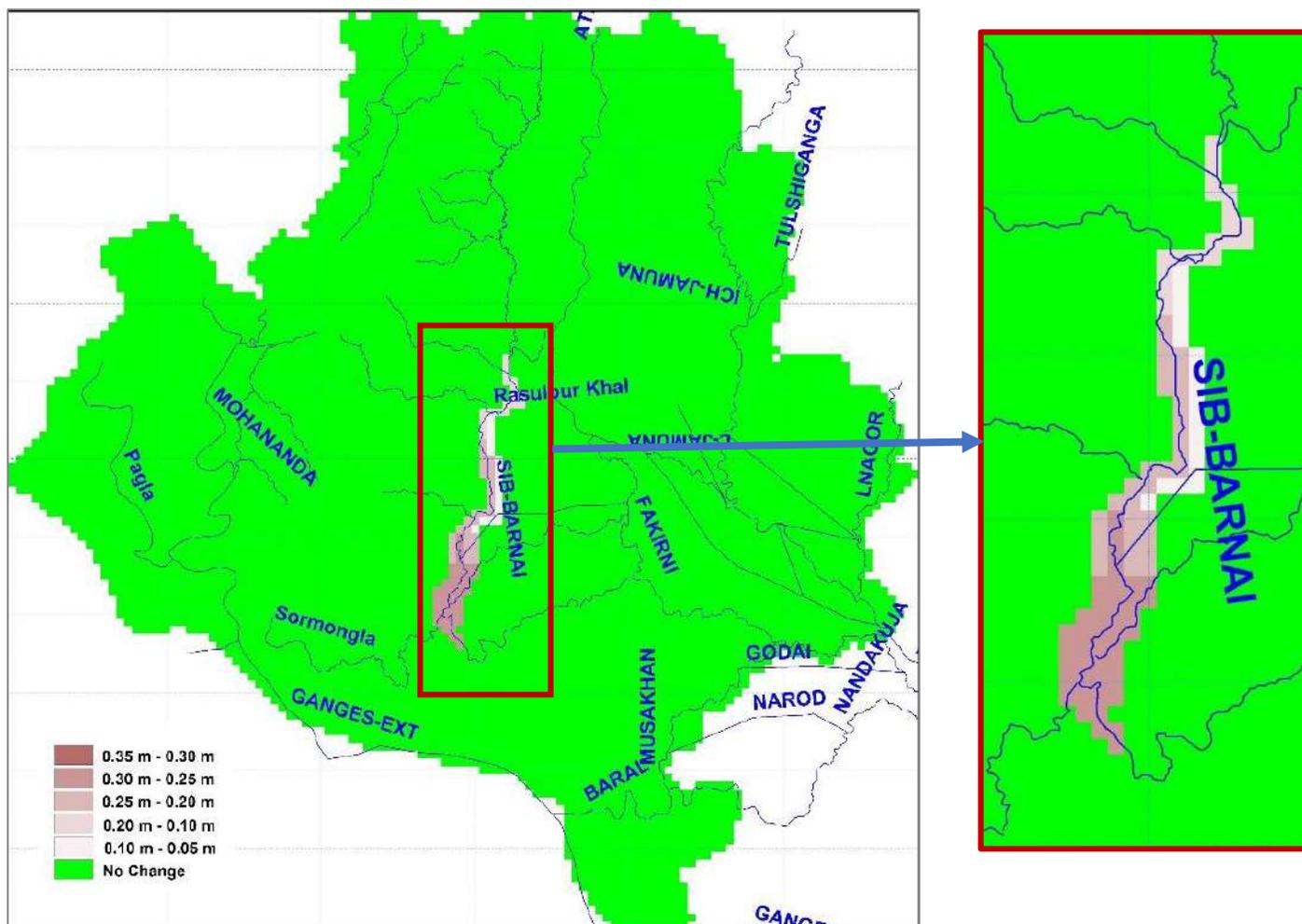
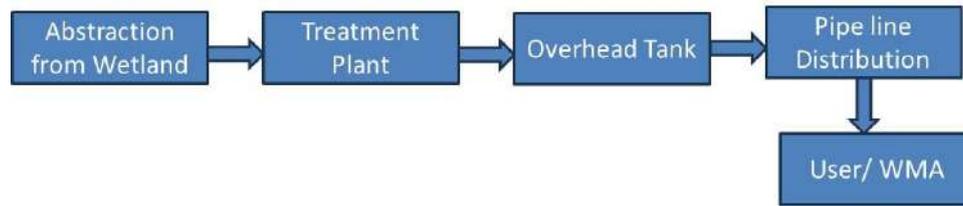


Figure 9-3: Impact Map due to Conservation of Water in Sib-Barnai River

9.4 Supplemental Domestic Water Supply

For immediate response to supplement the domestic water supply in the high stress area, a business model can be applied as follows:



The above business model can be applied on a pilot basis for the very high-water stress area as mentioned below:

District	Upazila	Union	Name of Beel	Area (ha)	Stored volume of water (Mm ³)	Domestic Demand (Mm ³)
Rajshahi	Tanore Pourashava	Talanda, Badhair, Tanore Pourashava	Beel Kumari	208	4.17	1.67
Naogaon	Sapahar	Aihai, Siranti	Jobai Beel	44	0.88	0.93
Chapainawabganj	Nachol	Fatehpur	Hugla Damas Beel	179	2.48	0.64

Existing potential wetlands may be re-excavated which cover an area of about 143 Km² and can store an amount of 286 Mm³ of water. Perennial Water Bodies in the study area is shown in Figure 9-4.

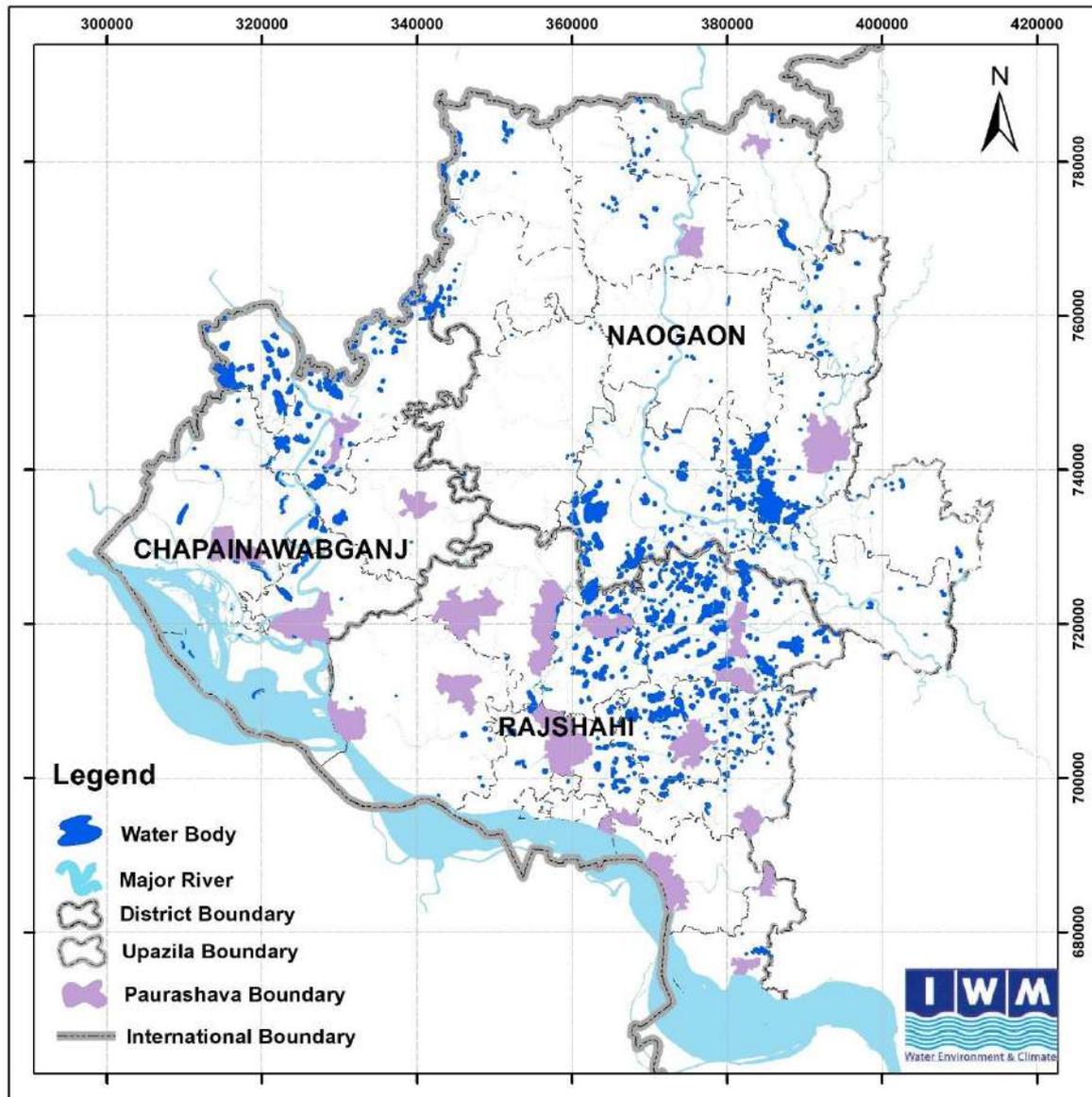


Figure 9-4: Perennial Water Bodies in the Study Area

In addition, a total 8200 ponds (>100 decimal) have been identified which can be re-excavated and can store 120 Mm³ of water.

Moreover, potential beels in the study area can be re-excavated as given below:

- Potential beels lies in Bagmara, Durgapur, Paba, Puthia and Tanore upazilas under Rajshahi district can be re-excavated to deeper extents and can be developed as potentials for surface water retention and preservation for irrigation year-round, fish culture and household purposes which will reduce the quantity of groundwater abstraction.
- The potential beels lies in Atrai, Raninagar, Manda, Naogaon Sadar, Sapahar, Porsha and Niamatpur upazilas under Naogaon district can be developed as potentials for surface water retention and preservation for irrigation year-round, fish culture and

household purposes. Damudahar Beel and Dak Beel at Aihai union, Kayamar Beel at Pathari union, Baksha Beel, Puroil Beel, Mahil Beel, Jaba Beel at Goala union, beels at Nithpur union, Chhatra Beel of Niamatpur, Bisha, Kalikapur, Maniari and Panchupur of Atrai, Masho and Chuary Beel of Raninagar, Bharso and Tentulia beel of Manda, Sekherpur, Dubalhati and Hashaighari beel of Naogaon Sadar can be considered for this purpose.

- The potential beels at Bholahat, Gomostapur and Nachol upazilas of Chapainawabganj district can be re-excavated to enlarge the water retention capacity both by volume as well as using the surface water for irrigation, fish culture and household purposes for major part of the year, which will reduce the dependency on groundwater. Bhatia Beel, Sonajal Beel and Amgachi Beel of Bholahat; beels at Radhanagar union of Gomostapur; Tali Beel and Anil Beel of Nachol upazilas can be re-excavated.

10 GROUNDWATER RESOURCE ASSESSMENT, SAFE YIELD AND WATER STRESS AREA

10.1 Assessment of Groundwater Resources

Reliable assessment of groundwater resources is essential for effective water resource management and safeguarding of the environment. Accordingly, groundwater resource of the study area has been assessed based on actual recharge. In addition, the safe yield level of groundwater for the study area has been estimated for future planning and developments. Details have been given below.

10.2 Recharge Characteristics

Recharge means the replenishment of groundwater storage that is depleted by withdrawal of groundwater with tube wells and by natural processes. The sources of groundwater replenishment of the study area are deep percolation of rainwater and irrigated water from the crop fields, seepage from the rivers, khals, ponds and other water bodies, and horizontal flow of groundwater from the surrounding areas. Recharge to groundwater depends on different physical and climatic conditions as well as hydraulic properties related to soil, aquifer and water. Recharge to groundwater begins with the rainfall from late May and continues up to October while recharge from irrigated crop field occurs from December to the end of March.

The aquifer becomes full normally in the months of August/September, but excess rains are available to recharge till October, if there is room for recharge. By creating additional storing space, the magnitude of annual replenishment of groundwater may be increased but it depends on the availability of water and the percolation rate of soil. Direct percolation occurs during the rains from naturally submerged fields and un-submerged lands. Excess rainwater is also stored within the bund that surrounds the paddy field and in the depressed areas. This water is also available for recharging the groundwater after meeting the demand of evapo-transpiration. The long-term average of annual replenishment of groundwater may be considered for groundwater abstraction. Groundwater storage reduces due to withdrawal for irrigation, domestic and other uses and outflow to rivers, canals, ditches, ponds and other water bodies. The loss of groundwater due to evaporation from water table and transpiration by plants is also attributed to depletion of groundwater storage.

10.3 Assessment of Safe Yield

The amount of water that can safely be abstracted from an aquifer system where annual withdrawal does not exceed the annual rate of recharge in that aquifer system is termed as safe withdrawal. Professionals and researchers used the term safe yield in place of safe withdrawal.

The safe yield concept has originated with prime attention to environment and unwanted declining of water table. At first this concept was based on capacity of aquifer and its size and reduction without defining its spatial aspects. Lee (1915) was first who define the safe yield as

maximum quantity of water that could be withdrawn from ground water system without producing the unwanted results to aquifer.

Soon after him Meinzer (1923) has defined safe yield as

rate of maximum output of aquifer to human beings.

It seems that Meinzer has discussed only the economic aspects of groundwater system. After that Conkling (1946) and Banks (1953) discussed the water quality and water rights concept. Further addition was made by Todd (1959) in safe yield concept as

“it is amount of water that can be withdrawn annually without producing undesired results”.

Although the definition of safe yield is still in use ignoring other relevancy to groundwater system but still yield quantification required to improve it further. Another ambiguity linked with maximum and minimum limits of safe yield is still unstipulated (Calo wet al. 2010 and Mukherji 2008).

Professionals and researchers also used the term sustainable yield in place of safe yield. The sustainable concept is developed in the early 1980s with centered idea of limited availability of resources and how to regenerate for coming generations. Proper definition of safe yield was given by Brundtland Commission (1987) which was also known as world commission on environment and development that is to meet the needs without compromising the needs of future generations. Then United Nation (1992) has put forward the concept of sustainability. This idea is based on integration of environmental and development apprehensions. Further it is highlighted in recent World Summit that sustainability is a concept which deals with resources quantification. The water resources sustainability is different as compared to other natural resources. It is also crucial to define water sustainability, because it is vitally linked with the existence of human beings and according to some estimation more than 0.783 billion people will not have safe drinking water by 2050 (Gleick 2001). Like the concept of safe yield, sustainable yield is also expressed in broader extent which make somewhat ambiguous due to applied constraints. Holistic view of sustainable yield may be valuable to some environmental and economic aspects but in water resources it is defined within the confined framework which is not elaborating water resources in detail due to broader spectrum (Sophocleous 1998; Alley et al. 1999; Sophocleous 2000). Although it is tried to explain sustainable yield in similar lines of safe yield concept, it is still ambiguous due to dynamic groundwater system and its development. The major challenge of this era is to define sustainability due to its versatile scope (UNESCO 1999; Loucks 2000). Some ambiguities attached with sustainability concept due to its philosophical framework (Norton and Toman 1995). For example, the use of resources will differ from ecologist to economist due to their perspectives of ecosystem existence and profit generation or else. And also, economists will think about the non-declining trend of his capital stock and will seek the relation between strong and weak sustainability of his resources.

Safe yield can be determined from the estimated potential recharge of the target aquifer. Potential recharge is the actual recharge plus rejected recharge. Generally, in our country recharging to groundwater continues for 100-180 days starting from late May and continues up to October when aquifer becomes full in average hydrologic condition. During October there is still some rainfall, which goes straightway as runoff because aquifer is full. Excess rainfall for the month of October could have been recharged to groundwater if there were room for recharge. Sometimes the water table attains this highest elevation before September. After that there is no room to recharge groundwater, but excess rainfall is available, which is mainly lost by surface runoff. This water is termed as rejected recharge. Steps for generally estimating safe yield using modelling techniques are described below.

1. A groundwater-surface water (GW-SW) model for the study area is developed for an average year condition.
2. Model simulation is done by starting an artificially low groundwater table (estimated from long-term groundwater level hydrographs) to ascertain that all the available recharge from rainfall will enter the saturated zone where soil properties are the only controlling factor against recharge.
3. A low groundwater table is determined from long-term groundwater level hydrographs in such a way that groundwater returns to its original position during the peak time of the monsoon.
4. A successive simulation method is conducted for simulation to visualize whether the groundwater table regains its original position for a number of pre-defined locations. A sample plot of simulation is shown in Figure 10-1 and Figure 10-2 for two locations.
5. Using the values of the water balance components obtained from model simulation potential recharge is estimated.

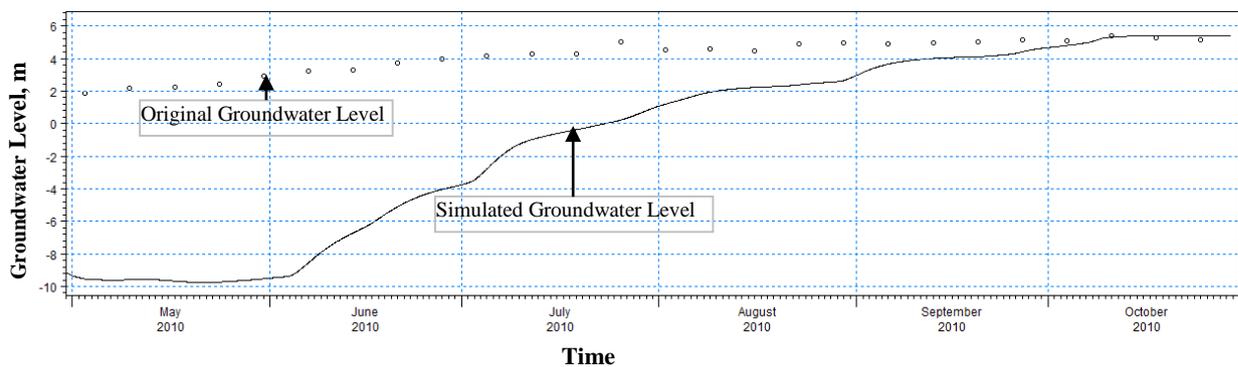


Figure 10-1: Checking of Groundwater Level for Potential Recharge at Location 1

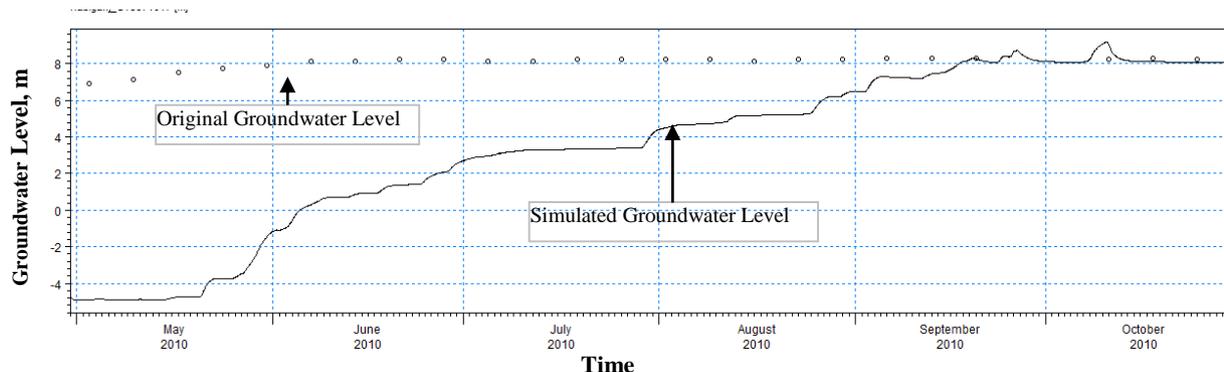


Figure 10-2: Checking of Groundwater Level for Potential Recharge at Location 2

This concept is applicable when groundwater table (GWT) is steady i.e. no declining GWT (season recharge is sufficient for the dry season losses and abstractions, Type-4). But from the analysis of GWT trend for the study area, it has been found that the trend of GWT in most of the areas are declining (falls under Type 1, 2 or 3). For this reason, yearly actual recharge of the study area has been estimated from yearly water balance result instead of potential recharge to find out safe yield. Assessment of actual recharge is described below.

In order to assess the actual recharge total water balance of each union for the study area for the year 2017 (average annual year) has been made considering all the physical processes in saturated and unsaturated zones and rivers systems in an integrated way. In general, water balance includes the hydrological components which come as inflow to or outflow from the system. The difference between inflow and outflow is the net storage change within the system.

A sample calculation of actual recharge from water balance for Ganeshpur union under Manda upazila of Naogaon district is given below. Actual recharge for the remaining unions has been given in Table 12-1.

Estimation of Actual Recharge for Ganeshpur Union

Water balance of the study area describing inflow and outflow for the period of January 01, 2017 to December 31, 2017 is graphically shown in Figure 10-3 while the same in tabular form is given in Table 10-1. It appears from the Table 10-1 that in unsaturated zone (UZ) a total of 2242 mm of water enters into the system mainly from rainfall and irrigation applied to the field from both groundwater and surface water sources while a total of 2168 mm of water goes out of the system mainly as evapotranspiration (ET), deep percolation from UZ to SZ and overland flow to river. The percentage of ET is about 46.34% of applied water (rainfall and irrigation application). The net flow from the UZ amounting to a total of 780 mm enters into the SZ. In the saturated zone, a total of 846 mm of water enters into the system mainly from UZ and 809 mm goes out mainly as groundwater abstraction and drain flow to boundary, resulting to a positive change of storage of 36 mm. It appears from the water balance of river/aquifer interaction system that river receives a total of 271 mm of water mainly from overland flow to river and base flow, while it has a little contribution to aquifer. Thus, throughout the year, river

system gains a significant amount of water. The net or actual recharge for the simulation period is 410 mm, calculated from the net recharge /discharge figures given in the Table 10-1.

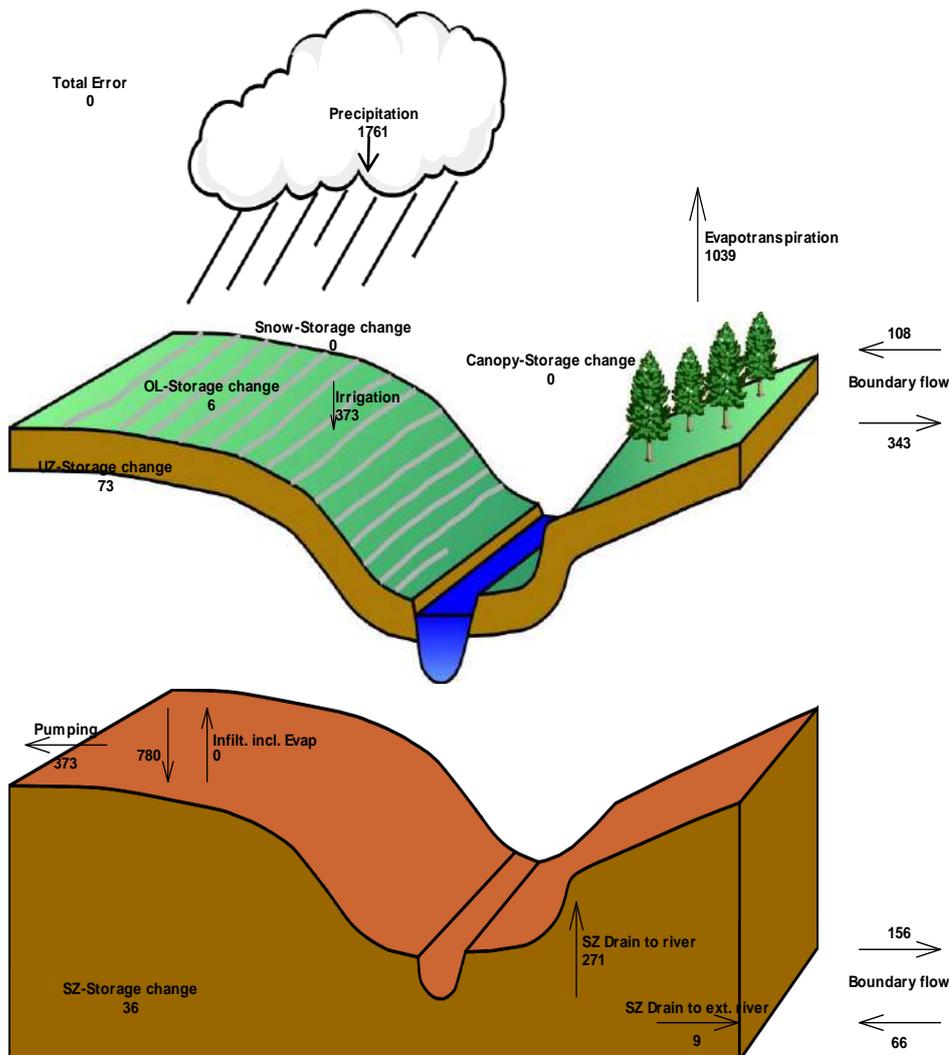


Figure 10-3: Water Balance (in mm) for the Period of 01st January 2017 to 31st December 2017

Table 10-1: Water Balance for the Period 01st January 2017 to 31st December 2017

Sl. No.	Components	Unsaturated Zone(UZ)		Saturated Zone (SZ)		River System		GW Recharge/Discharge	
		Inflow (mm)	Outflow (mm)	Inflow (mm)	Outflow (mm)	Inflow (mm)	Outflow (mm)	Recharge (mm)	Discharge (mm)
1	Rainfall	1761	—	—	—	—	—	—	—
2	Evapotranspiration(ET)	—	1039	—	—	—	—	—	—
3	Abstraction	—	—	—	373	—	—	—	—
4	Irrigation	373	—	—	—	—	—	—	—
5	Capillary rise & ET from SZ to UZ	0	—	—	0	—	—	—	—
6	Deep Percolation from UZ to SZ	—	780	780	—	—	—	780	0
7	Boundary Flow	108	343	66	156	—	—	0	90
8	Base Flow	—	—	0	0	0	0	0	0
9	Overland flow to river	—	0	—	—	0	—	—	—
10	Drain flow to river	—	—	0	271	271	0	0	271
11	OL storage Change	0	6	—	—	—	—	—	—
12	Drain SZ/Boundary	—	—	0	9	—	—	0	9
Total		2242	2168	846	809	271	0	780	370
Net Balance=Inflow-Outflow								410	
Explanation		Inflow/Outflow of SZ		Change in Storage		River/Aquifer Interaction		Net Recharge /Discharge	

According to the NWMP guideline and other literature review, 75% of the actual recharge can be taken as safe yield for development consideration. It is due to the fact that various uncertainties inherent in different assumptions for the estimation of actual recharge. Estimated actual recharge is shown in Figure 10-4 to Figure 10-6 whereas it has given in a tabular form in Table 12-1.

The estimated union wise actual recharge ranges from 160-708 mm for Rajshahi District, 193-727 mm for Chapainawabganj district and 116-780 mm for Naogaon District have been found.

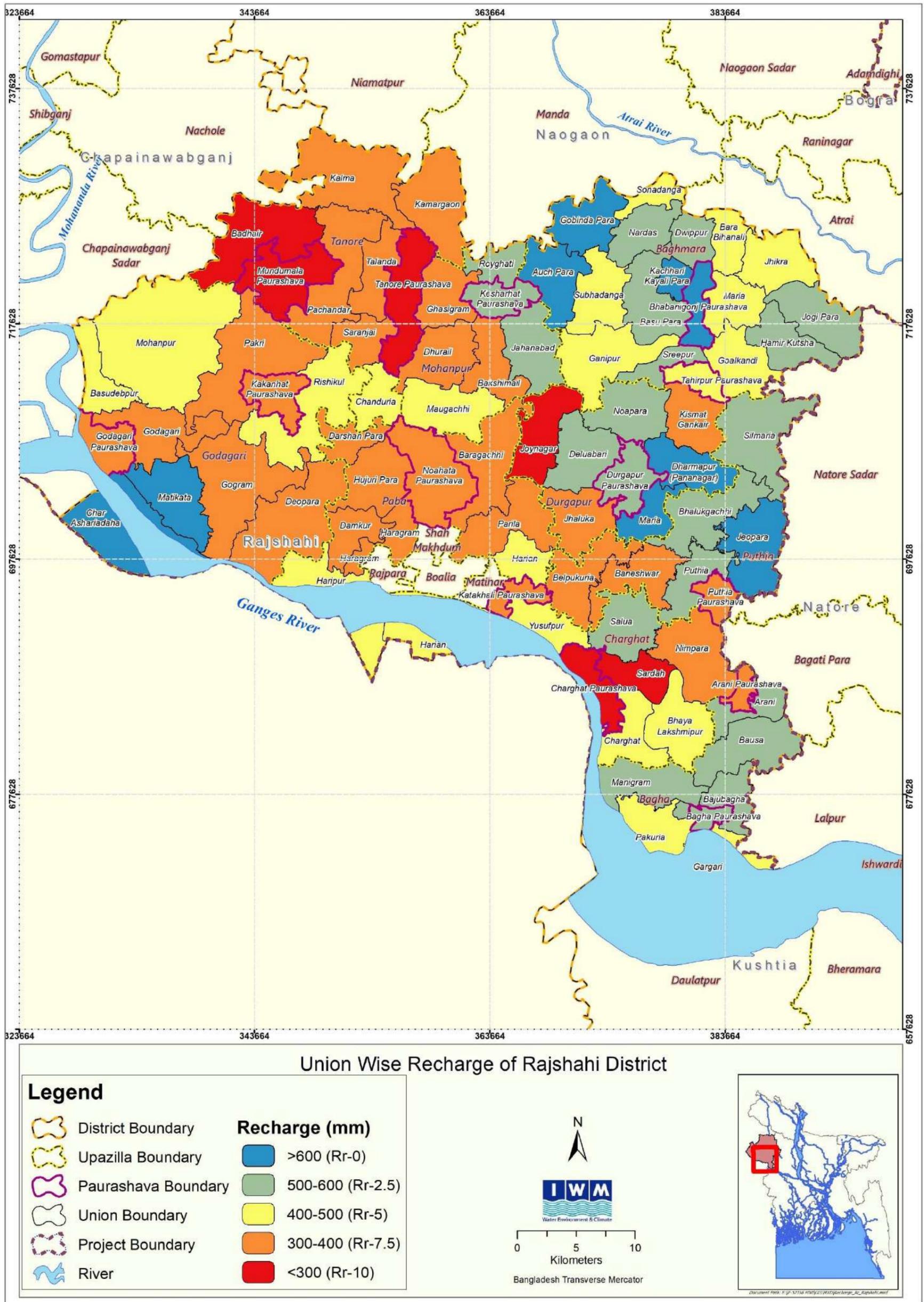


Figure 10-4: Union Wise Recharge Area of Rajshahi District

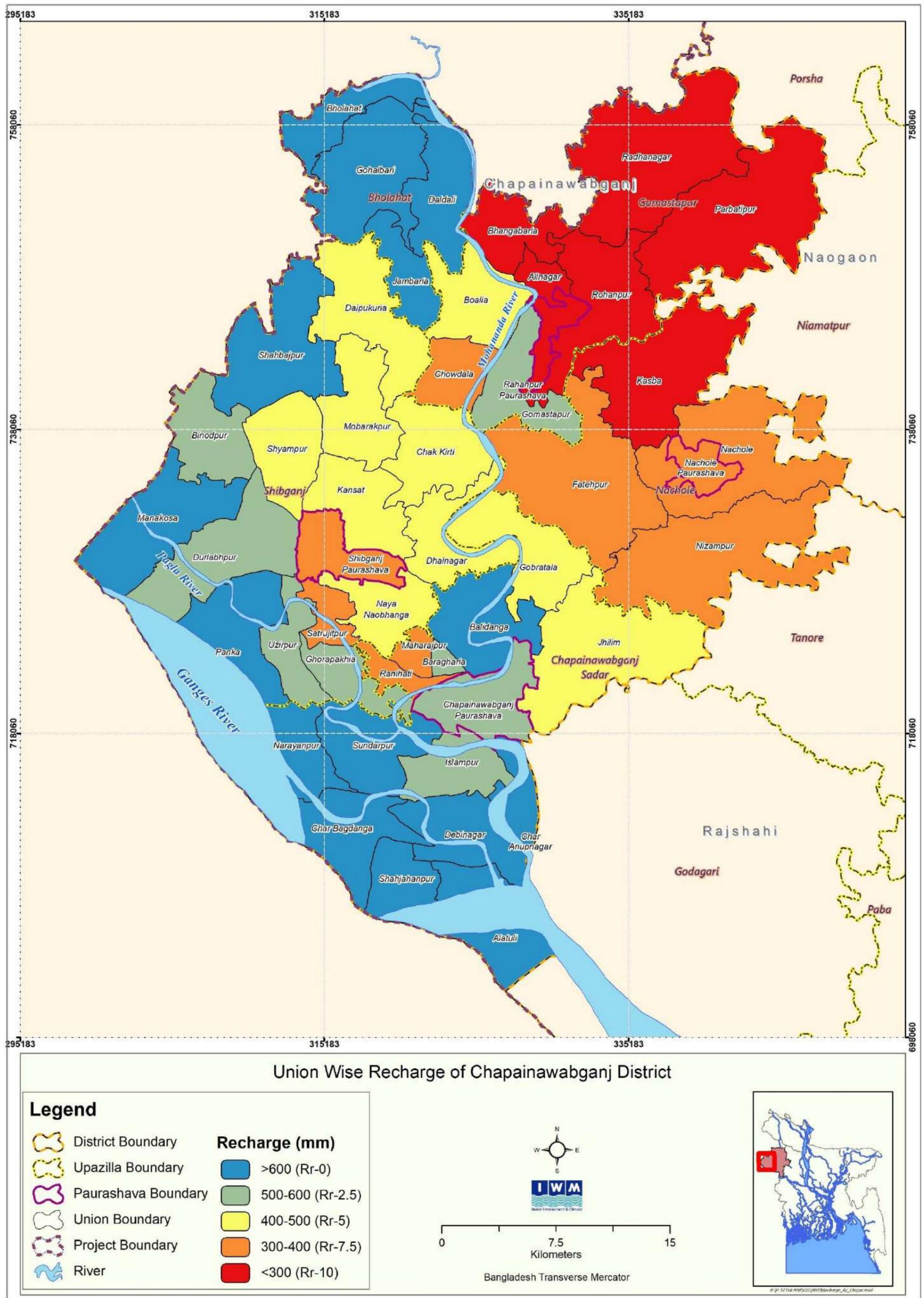


Figure 10-5: Union Wise Recharge Area of Chapainawabganj District

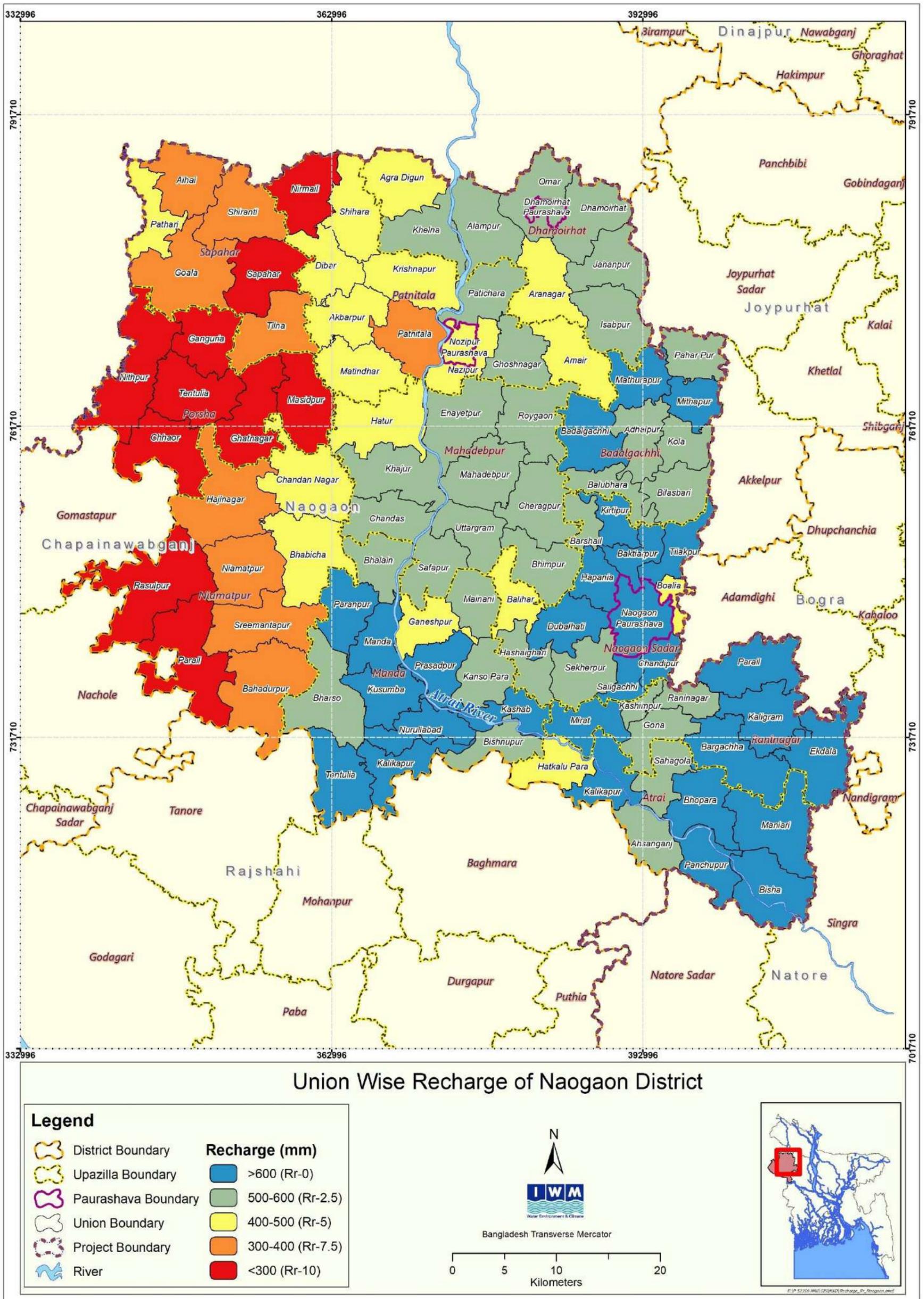


Figure 10-6: Union Wise Recharge Area of Naogaon District

10.4 Water Stress Area Identification

To Identify Water Stress Area for the study area a mapping technique has been used. The technique has been approved by the Panel of Expert (PoE) committee. The following parameters have been considered while analyzing the water stress of the study area:

[D]-Depth to Water Table, [R]-Recharge, [A]-Aquifer Thickness, [U]-Media of Unsaturated Zone, [H]-Hydraulic conductivity of the Aquifer, [Q]-Groundwater Quality, [E]-Environmental Issues, [L]-Trend of Groundwater Level, assigned based on expert judgment.

Water Stress Area Index at any cell or polygon on the map has been determined as:

$$\text{Water Stress Index (WSI)} = D_r D_w + R_r R_w + A_r A_w + U_r U_w + H_r H_w + Q_r Q_w + E_r E_w + L_r L_w$$

The method has been named DRAHQEL according to the used parameters.

The description of the parameters is given below:

[D]-Depth to Water Table: Depth to water table determines the thickness of material through which infiltrated water must travel before reaching the aquifer-saturated zone. Depth to water consequently impacts on degree of physical and chemical attenuation, and degradation processes. In general, the aquifer potential protection increases with depth to water.

The minimum range for depth to water table has been considered less than 3 m. As, when the water table is within 3m then there is no stress or very low water stress. Considering the suction limit (7 m) for hand tubewell and Tara pump tubewell, the next ranges are set as 7 m and 20 m. The water table depth greater than 30 m has been considered as very high-water stress.

[R]-Actual Recharge: The actual recharge is the amount of water from precipitation and artificial sources available to migrate down to the groundwater. Recharged water is, therefore, a significant carrier for percolating and transporting contaminants within the vadose zone to the saturated zone. It carries solid and liquid contaminants to the water table and also increases the water table. In addition, it controls the volume of water available for dispersion and dilution of the contaminant in the Vadose and saturated zones. In general, the greater the recharge, the greater the potential for groundwater pollution and increase in groundwater resources.

The range of actual recharge greater than 600 mm has been considered zero stress or very low water stress and less than 300 mm has been considered as very high-water stress. The other ranges of actual recharge are 400 mm and 500 mm.

[A]-Aquifer Thickness: An aquifer is an underground layer of water-bearing, permeable rock, rock fractures, or unconsolidated materials. The greater the thickness of aquifer the more possibility of groundwater availability.

An aquifer thickness greater than 30 m is considered as good aquifer and less than 4 m is considered as very low potential aquifer.

[U]-Media of Unsaturated Zone: The media of unsaturated zone influence on aquifer recharge potential is essentially similar to that of soil cover, depending on its permeability and on the attenuation characteristics of the media.

The media of unsaturated zone covering with medium to coarse sand has high potential for groundwater recharge. On the other hand, the media of unsaturated zone covering with clay/silty clay has very low potential for groundwater recharge. The media with silt, very fine sand and fine sand have low potential for groundwater recharge respectively.

[H]-Hydraulic conductivity of the Aquifer: Aquifer hydraulic conductivity is the ability of the aquifer formation to transmit water. It depends on the intrinsic permeability of the material and on the degree of saturation. This critical factor controls the migration and dispersion of water from the injection/abstraction point within the saturated zone.

An aquifer with greater than 30 m/day hydraulic conductivity has high potential to transmit water and less than 5 m/day has very low potential. The other ranges of aquifer hydraulic conductivity are 20 m/day and 10 m/day.

[Q]-Groundwater Quality: The quality of groundwater influences the vulnerability and stress on the aquifer.

The concentration of Manganese and Iron in groundwater has been considered for groundwater quality assessment for the study area (Barind region). For the other parts of Bangladesh, the groundwater quality may be assessed with other parameters. The concentration of Iron less than 1 mg/l has been considered as very low stress area and greater than 2 mg/l concentration has been considered as high stress area. The other ranges of Iron concentration are 1.25 mg/l and 1.5 mg/l.

The concentration of Manganese less than 1 mg/l has been considered as very low stress area and greater than 5 mg/l has been considered as high stress area. The other ranges of Manganese concentration are 2 mg/l and 3.5 mg/l. From the two parameters of Iron and Manganese, the high stress parameter has been considered for WSI calculation.

[E]-Environmental Issues: The environmental issues due to withdrawal of groundwater influences water stress of the area.

The water table within suction limit (7 m) and if water is available in pond and wetlands has been considered as very low water stress areas. On the other hand, drying out of pond and wetlands where drinking water is hard to reach has been considered as very high stress areas. If the water table is beyond suction limit and water is available in pond and wetlands has been considered as moderate stress areas.

[L]-Trend of Groundwater Level: Trend of groundwater level influences aquifer storage and resource condition of the specific area.

The declining slope of groundwater level less than 0.01 m/year has been considered as very low stress and greater than 0.3 m/year has been considered as very high stress area.

Weight: Represents the relative importance of each parameter in its ability to affect pollution transport to and within the aquifer. The weight is from 1-5. The weight for DRAHQEL parameters has been given in Table 10-2.

Table 10-2: Weight for DRAHQEL Parameters

Feature	Weight
Depth to Water Table	3
Actual Recharge	4
Aquifer Thickness	2
Media of Unsaturated Zone	4
Hydraulic Conductivity	3
Groundwater Quality	3
Environmental Issues	2
Groundwater Level Trend	4

Range: Each DRAHQEL factor has been divided into either ranges or significant media types which have an impact on water stress.

Rating: Determine the relative significance of parameter with respect to water stress parameter. The ratings are from 0 to 10.

To assess the Water Stress Area Index (WSI) within hydrogeological settings, numerical ranking has been used on the DRAHQEL parameters. There are 3 significant parts- Weights, Ranges, and Ratings. Weight and Ratings for DRAHQEL parameters are given in Table 10-2 and Table 10-3 assigned based on expert judgment. The value of weightage of different parameters have been taken as 1-5 and ratings of different parameters have been taken as 0-10. Summation of the product of weight and rating for each parameter give the final Water Stress Area Index (WSI). A water stress area map has been prepared by using the obtained final WSI value. The higher the WSI value, the higher the stress area. According to WSI values study area has been divided into five zones- Very high-water stress area (WSI >160), high water stress area (WSI 140-160), Moderate water stress area (WSI 120-140), Low water stress area (WSI 100-120) and very low water stress area (WSI <100).

Table 10-3: Ratings for DRAHQEL Parameters for Barind Region

Depth to Groundwater Table (m)		Actual Recharge (mm)		Aquifer Thickness (m)		Media of UZ Zone		Aquifer Hydraulic Conductivity (m/day)		Groundwater Quality				Environmental Issues		Groundwater Level Trend Declining Slope (Last 10 years) (m/yr)	
Range	Dr	Range	Rr	Range	Ar	Range	Ur	Range	Hr	Range (Fe)	Qr	Range (Mn)	Qr	Range	Er	Range	Lr
< 3	0	>600	0	>30	0	Medium to Coarse Sand	0	>30	0	<1	0	<1	0	WT within suction limit and water is available in pond and wetlands	0	<0.01	0
3-7	2.5	500-600	2.5	15-30	2.5	Fine Sand	2.5	20-30	2.5	1-1.25	2.5	1-2	2.5	WT beyond suction limit, but water is available in pond and wetlands	5	0.01-0.05	2.5
7-20	5	400-500	5	7-15	5	Very Fine Sand	5	10-20	5	1.25-1.5	5	2.0-3.5	5	Drying out of pond/wetlands & Hard to reach for drinking water	10	0.05-0.1	5
20-30	7.5	300-400	7.5	4-7	7.5	Silt	7.5	5-10	7.5	1.5-2	7.5	3.5-5	7.5			0.1-0.3	7.5
> 30	10	<300	10	<4	10	Clay/ Silty Clay	10	<5	10	>2	10	>5	10			>0.3	10

10.5 Union Wise Water Stress Area Identification

Union wise water stress areas have been identified for the study area. WSI value for each union has been calculated using DRAHQEL method. WSI is the summation of the product of weight and rating of 8 parameters of DRAHQEL method. Weightage for the 8 parameters have been fixed by the PoE committee. Ratings for 8 parameters have been identified based on the range of the parameters for the specific unions. To find out the rating of the unions, 8 maps have been prepared based on the range of 8 parameters. Figure 10-7 to Figure 10-10 showing different maps based on range of different parameters of DRAHQEL method for the unions of Tanore Upazila.

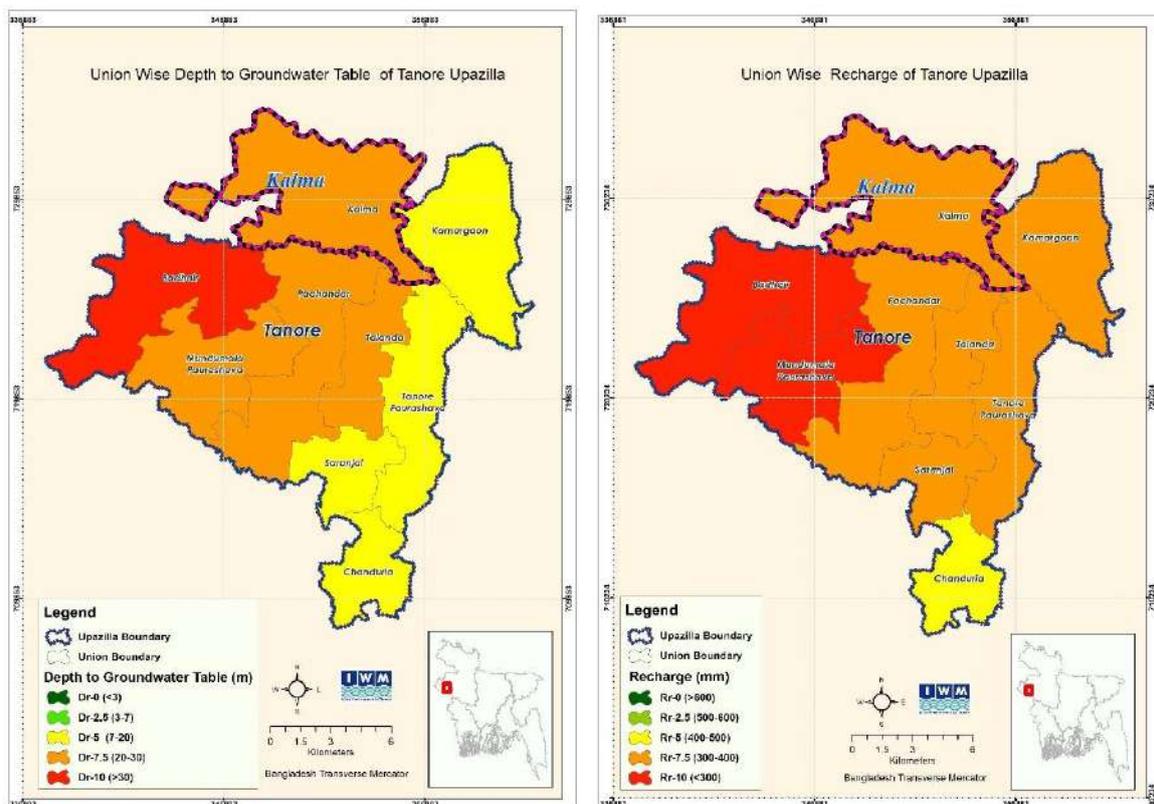


Figure 10-7: Union Wise Depth to Groundwater Table (Left) and Recharge (Right) Map of Tanore Upazila

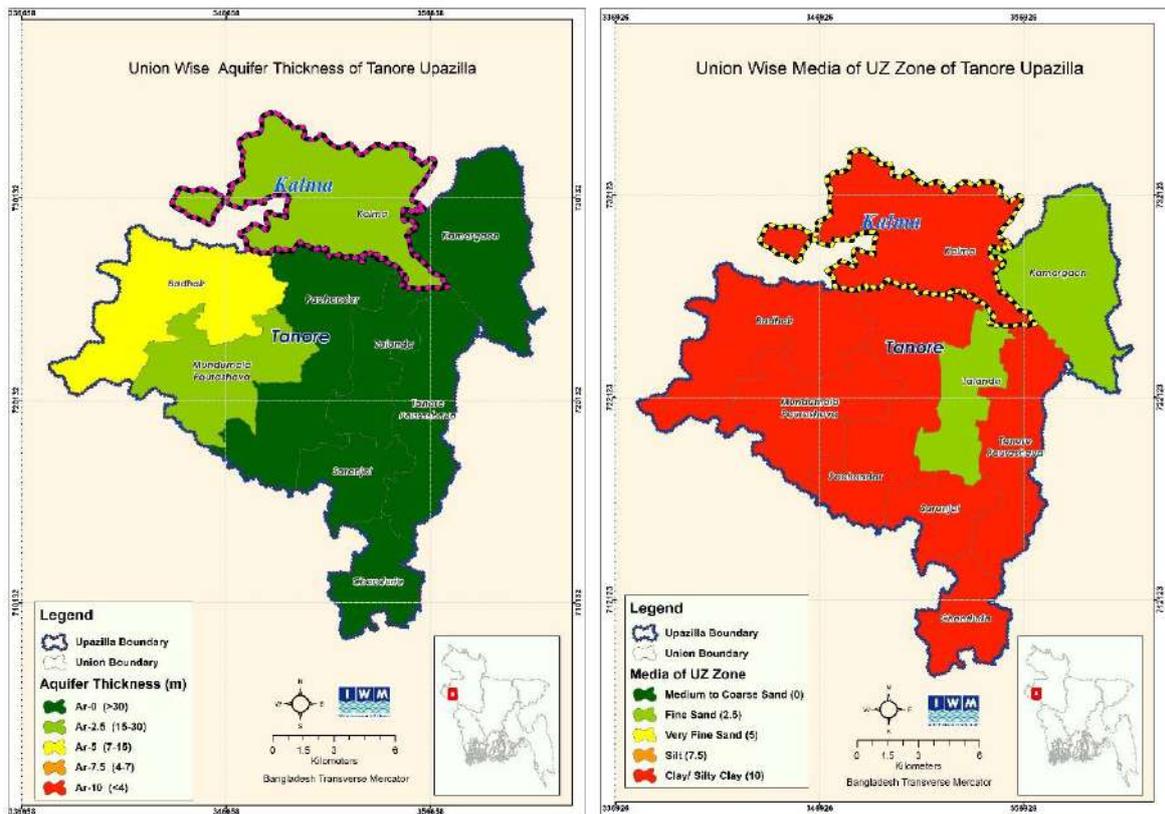


Figure 10-8: Union Wise Aquifer Thickness (Left) and Media of UZ Zone (Right) Map of Tanore Upazila

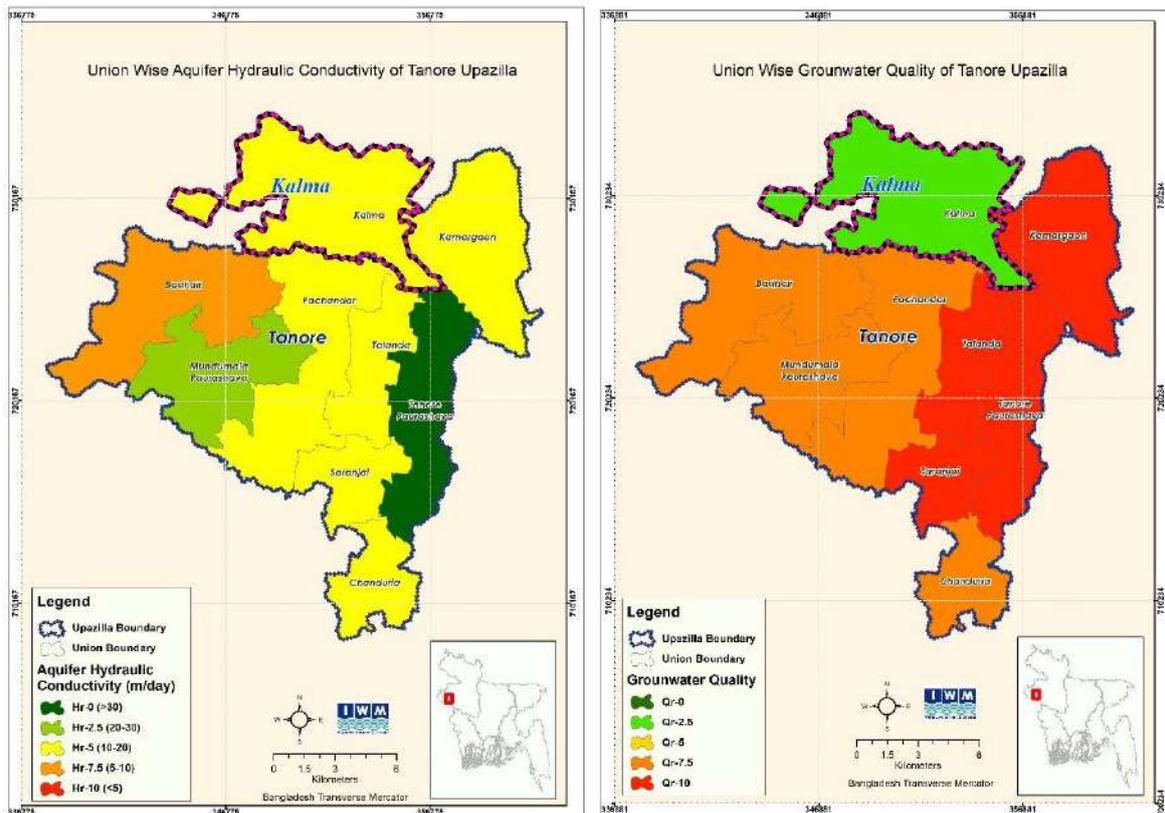


Figure 10-9: Union Wise Aquifer Hydraulic Conductivity (Left) and Groundwater Quality (Right) Map of Tanore Upazila

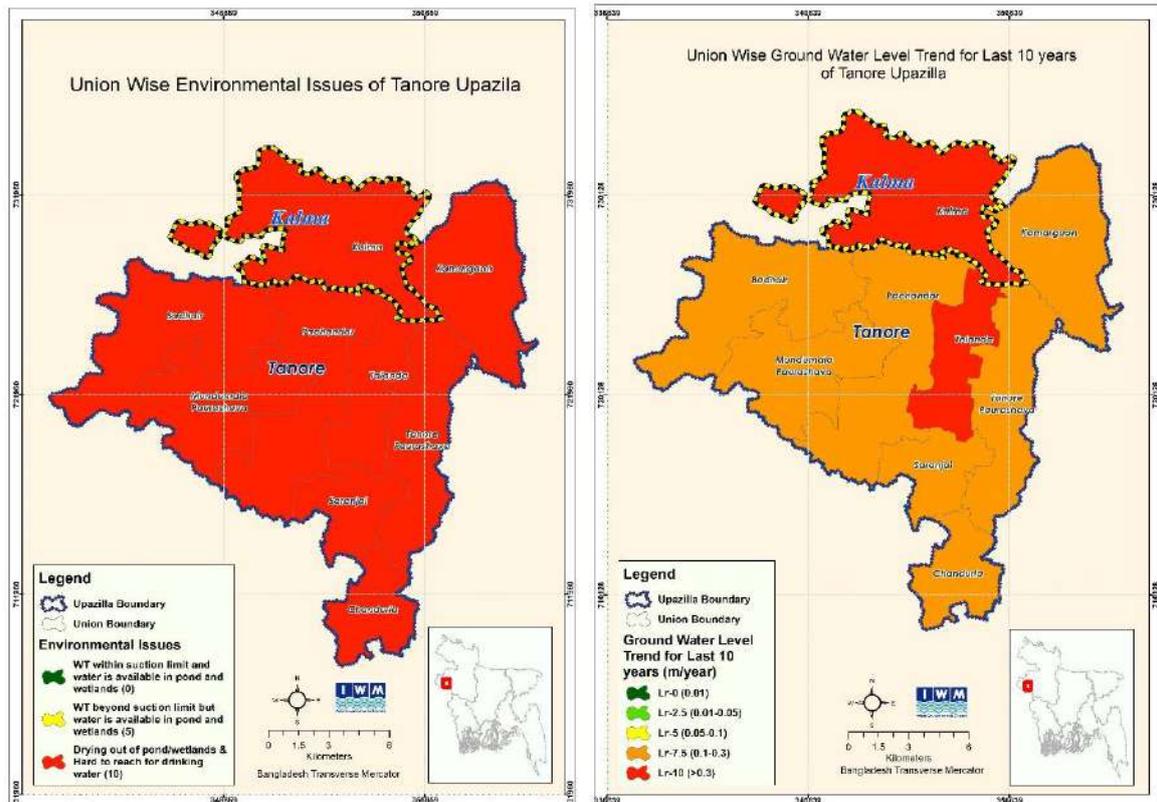


Figure 10-10: Union Wise Environmental Issue (Left) and Groundwater Level Trend (Right) Map of Tanore Upazila

Identified weightage and ratings for the 8 parameters for Kalma union of Tanore Upazila is given in Table 10-4 below:

Table 10-4: Identified Weightage and Ratings for Different Parameters for Kalma Union

Feature	Weight	Rating
Depth to Water Table (D)	3	7.5
Actual Recharge (R)	4	7.5
Aquifer Thickness (A)	2	2.5
Media of Unsaturated Zone (U)	4	10
Hydraulic Conductivity (H)	3	5
Groundwater Quality (Q)	3	2.5
Environmental Issues (E)	2	10
Groundwater Level Trend (L)	4	10

Water Stress Index (WSI) for Kalma Union

$$\begin{aligned}
 &= D_r D_w + R_r R_w + A_r A_w + U_r U_w + H_r H_w + Q_r Q_w + E_r E_w + L_r L_w \\
 &= 7.5*3 + 7.5*4 + 2.5*2 + 10*4 + 5*3 + 2.5*3 + 10*2 + 10*4 \\
 &= 180 > 160
 \end{aligned}$$

As the water stress index (WSI) value is greater than 160, the Kalma union has been identified as a very high-water stress area.

A similar procedure has been used for the other unions to identify water stress areas. Identified water stress area for Rajshahi, Chapainawabganj and Naogaon districts are shown in Figure 10-11 to Figure 10-13. Upazila wise number of water stressed unions are given in Table 10-5 to Table 10-7 whereas union wise detail calculations of WSI to identify water stress areas are given in Appendix-J, Volume IV. Water stress area map for different upazilas of the study area is given in Appendix-K, Volume IV.

Table 10-5: Upazila Wise Number of Water Stressed Union for Rajshahi District

Sl No.	Upazila	Number of Unions					% of Very High Stress Union
		Very High Stress	High Stress	Moderate Stress	Low Stress	Very Low Stress	
1	Bagha	0	2	4	0	0	0
2	Bagmara	0	1	8	4	3	0
3	Charghat	0	1	4	1	0	0
4	Durgapur	0	3	2	2	0	0
5	Godagari	3	3	3	0	0	33.33
6	Mohonpur	1	4	1	0	0	16.66
7	Paba	3	1	4	0	0	37.5
8	Puthia	0	0	4	1	1	0
9	Tanore	6	1	0	0	0	85.71

Table 10-6: Upazila Wise Number of Water Stressed Union for Chapainawabganj District

Sl No.	Upazila	Number of Unions					% of Very High Stress Union
		Very High Stress	High Stress	Moderate Stress	Low Stress	Very Low Stress	
1	Bholahat	0	0	4	0	0	0
2	Chapainawabganj Sadar	1	3	2	0	8	7.14
3	Gomostapur	5	3	0	0	0	62.5
4	Nachol	4	0	0	0	0	100
5	Shibganj	0	4	8	0	3	0

Table 10-7: Upazila Wise Number of Water Stressed Union for Naogaon District

Sl No.	Upazila	Number of Unions					% of Very High Stress Union
		Very High Stress	High Stress	Moderate Stress	Low Stress	Very Low Stress	
1	Atrai	0	1	2	0	5	0
2	Badalgachi	0	0	0	2	6	0
3	Dhamoirhat	0	0	1	3	4	0
4	Manda	0	3	5	5	1	0

Sl No.	Upazila	Number of Unions					
		Very High Stress	High Stress	Moderate Stress	Low Stress	Very Low Stress	% of Very High Stress Union
5	Mohadevpur	0	1	0	8	1	0
6	Naogaon Sadar	0	2	7	3	0	16
7	Niamatpur	6	1	1	0	0	75
8	Patnitala	7	2	2	0	0	63.63
9	Porsha	6	0	0	0	0	100
10	Raninagar	0	3	4	1	0	0
11	Sapahar	5	1	0	0	0	83.33

Water stress area map has been prepared using the obtained final WSI value which is shown in Figure 10-11 to Figure 10-13.

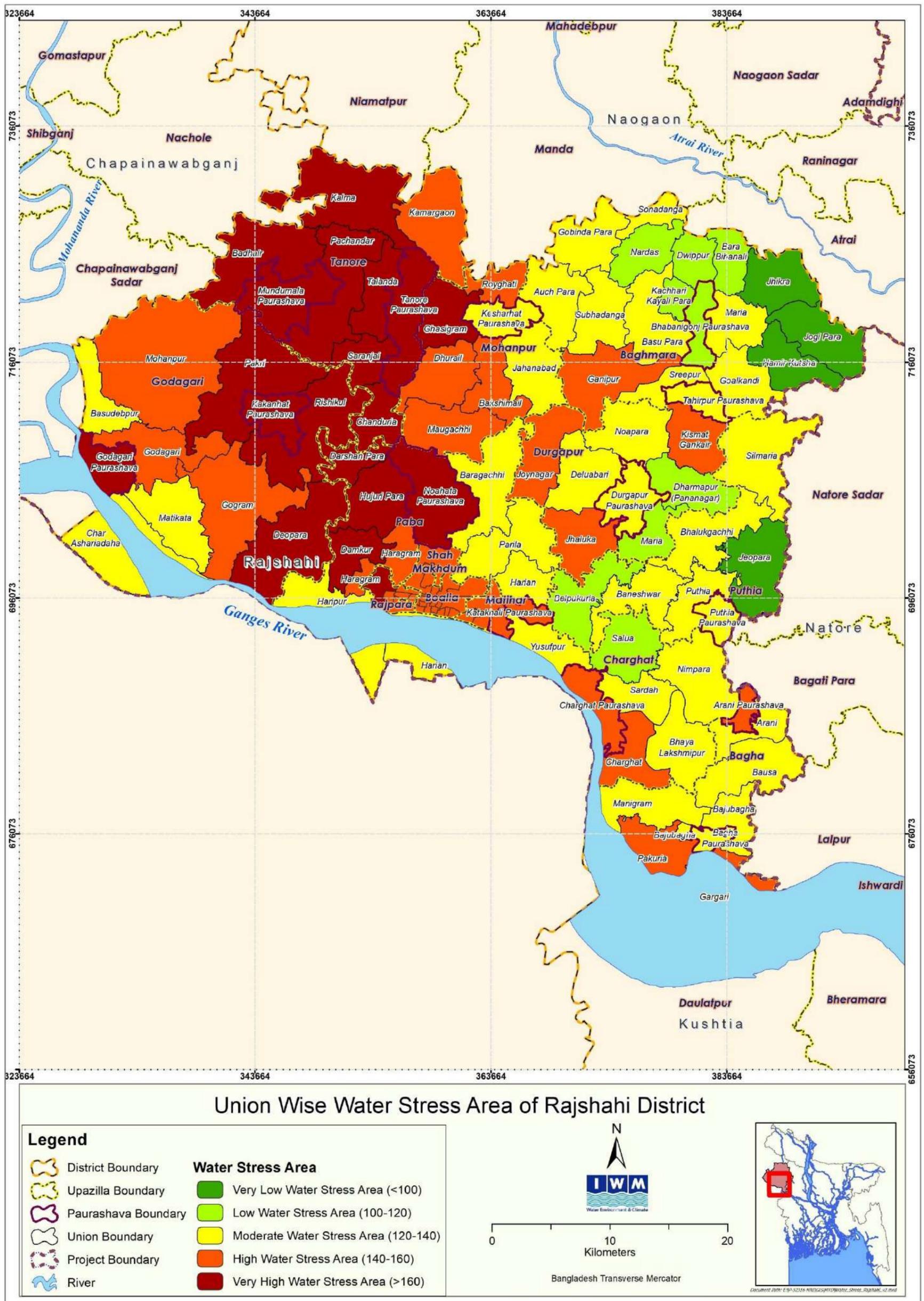


Figure 10-11: Union Wise Water Stress Area for Rajshahi District

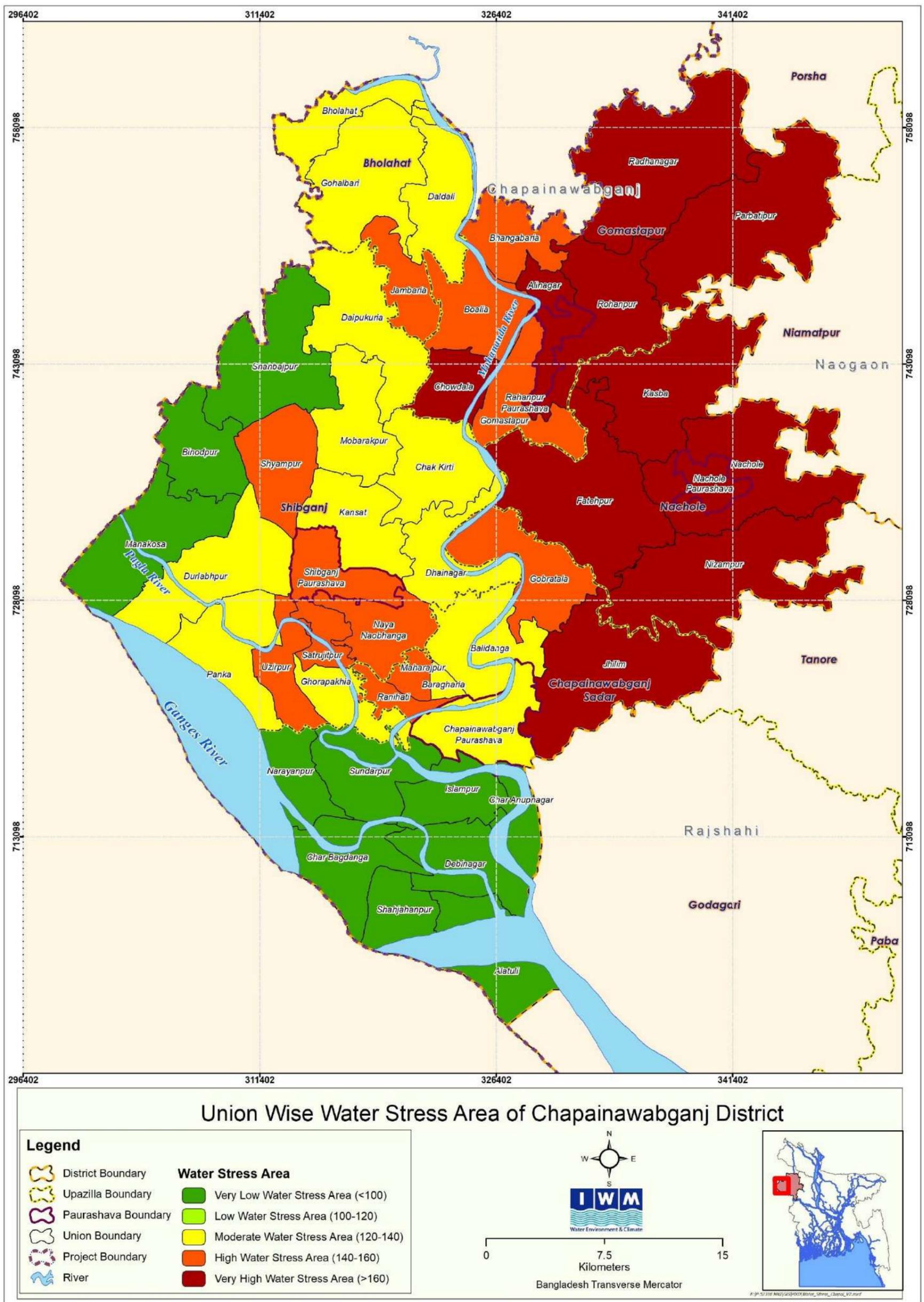


Figure 10-12: Union Wise Water Stress Area for Chapainawabganj District

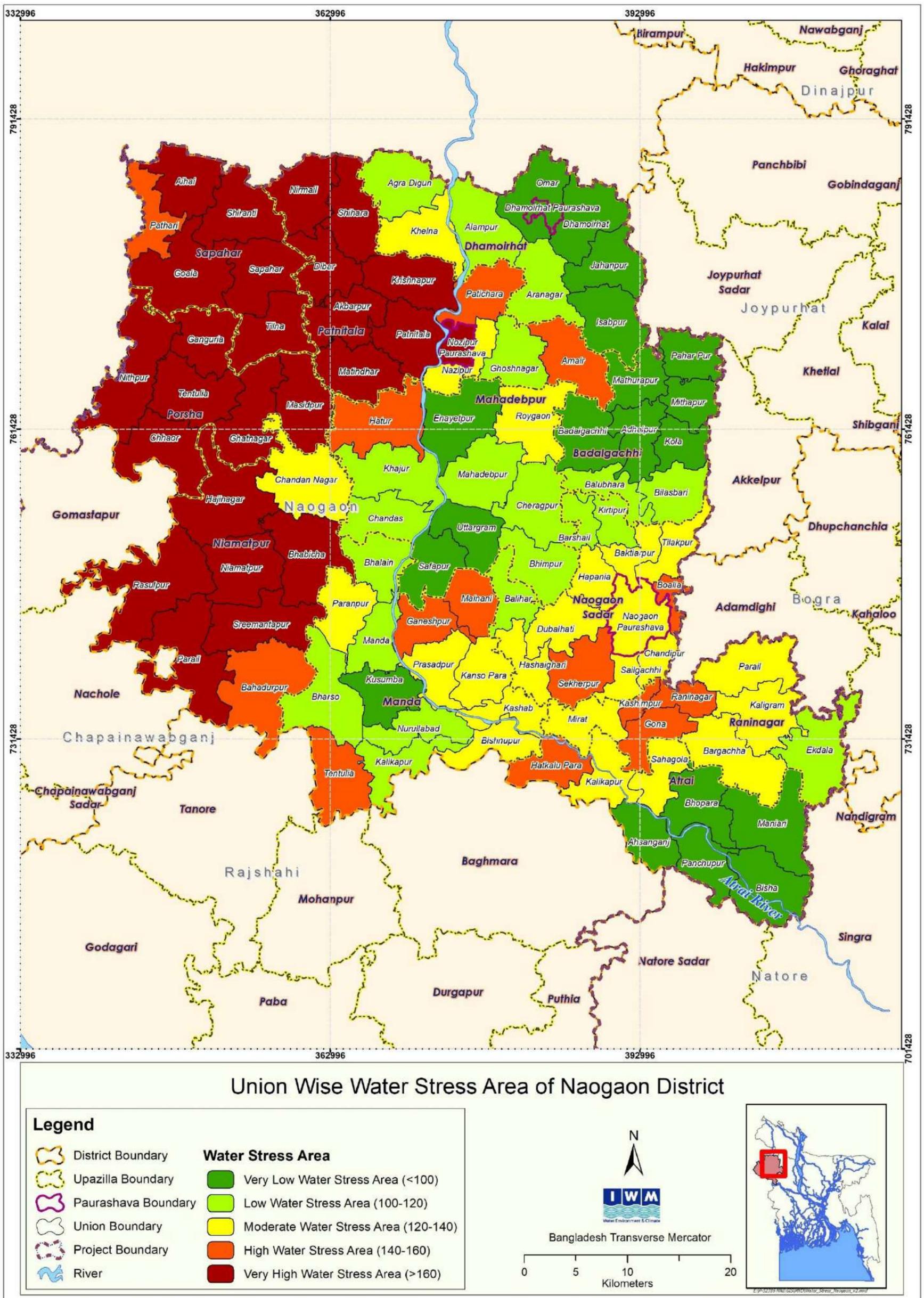


Figure 10-13: Union Wise Water Stress Area for Naogaon District

For the study area, identified district wise number of water stressed unions is shown the Table 10-8.

Table 10-8: District Wise Number of Water Stressed Unions

District	Number of Unions				
	Very High Stress	High Stress	Moderate Stress	Low Stress	Very Low Stress
Rajshahi	13	16	30	8	4
Chapainawabganj	10	10	14	-	11
Naogaon	24	14	22	22	17
Total	47	40	66	30	32

From the identification of water stress area, it has been found that 3 unions of Godagari upazila, 1 union of Mohonpur upazila, 3 unions of Paba upazila and 6 unions of Tanore upazila under Rajshahi district; 1 union of Chapainawabganj Sadar upazila, 5 unions of Gomostapur upazila, 4 unions of Nachol upazila under Chapainawabganj district and 6 unions of Niamatpur upazila, 7 unions of Patnitala upazila, 6 unions of Porsha upazila, 5 unions of Sapahar upazila under Naogaon district falls in the very high water stress area.

It also has been found that 2 unions of Bagha upazila, 1 union of Bagmara upazila, 1 union of Charghat upazila, 3 unions of Durgapur upazila, 3 unions of Godagari upazila, 4 unions of Mohonpur upazila, 1 union of Paba upazila, 1 union of Tanore upazila under Rajshahi district falls in the high water stress area. In Chapainawabganj district, 3 unions of Chapainawabganj Sadar upazila, 3 unions of Gomostapur upazila, 4 unions of Shibganj upazila lies with high water stress area. In Naogaon district, 1 union of Atrai, 3 unions of Manda upazila, 1 union of Mohadevpur upazila, 2 unions of Naogaon Sadar upazila, 1 union of Niamatpur upazila, 2 unions of Patnitala upazila, 3 unions of Raninagar upazila, 1 union of Sapahar upazila falls in the high water stress area.

11 NATIONAL WORKSHOP

11.1 National Level Workshop on Draft Final Report

The final workshop on Draft Final Report (DFR) was held at Pan Pacific Sonargaon, Dhaka as shown in Figure 11-1. The workshop was attended by the participants from Planning Commission, Ministry of Water Resources, BWDB, DBHWD, BUET, SDC, SRC, DASCOH, DPHE, BADC, BMDA and other organizations. The Honorable Minister of State, Ministry of Water Resources were present at the workshop. The study objectives, methodologies, findings and recommendations have been presented in the workshop. After a thread bore discussions, some comments and suggestions have been recommended on the DFR. The Final Report has been updated and prepared incorporating the recommendations and suggestions of the workshop.



Figure 11-1: National Workshop at Pan Pacific Sonargaon, Dhaka

12 SUMMARY OF FINDINGS AND RECOMMENDATIONS

12.1 Findings

Major Findings from Hydrogeological Investigations:

The Rajshahi district mostly falls under the two physiographic units: Barind Tract and Ganges Flood plain.

- Tanore and Godagari upazilas fall under the unit of Barind Tract where a thin aquifer exists in the shallow depth except some eastern part of Tanore and Godagari upazila. The thickness of the aquifer varies from 3 to 12 m and depth to groundwater table varies from 23 to 34 m. In Badhair union of Tanore upazila, only one aquifer exists up to a drilling depth of 426m. A thick aquifer presents in Soranjai, Pachandor, Talando and Kamargaon unions in the eastern part of Tanore and Godagari upazila where the aquifer thickness varies from 27 to 72 m. In the area depth to groundwater table has declined down to a depth of 25-27 m.
- Rajshahi City Corporation, Puthia, Bagha, Paba, Charghat and Bagmara and part of Mohonpur upazilas fall under the unit of Ganges River Floodplain where multi-aquifers exist. The depth to groundwater table ranges from 3 to 21 m except for some parts of Rajshahi City Corporation, Mohonpur and Bagmara upazilas.
- In Mohonpur, Tanore and Godagari area, the declining trend of water level is very alarming, suggesting no further abstraction of groundwater. Mundumala pourashava and Badhair union fall under critical conditions in terms of subsurface lithology and declining trend of groundwater level, suggesting that special attention will be required before further development is considered.

The Chapainawabganj district mostly falls under three physiographic units: Ganges River Floodplain, Teesta Floodplain and Barind Tract.

- Nachol, eastern part of Chapainawabganj Sadar and Gomostapur upazilas fall under the unit of Barind Tract where a thin aquifer exists in the shallow depth throughout the area except a part of Nachol pourashava. The thickness of that aquifer varies from 6 to 18 m which is the only drinking water source for these areas up to the drilling depth of 432 m. The depth to groundwater table varies from 30 to 32 m which has already dropped down beyond the suction limit (7 m) may and creates a very alarming situation for the area.
- Due to existence of thin aquifer, the groundwater table condition of Nachol, Kosba, Fatehpur, Jhilim, Parbatipur, Rohanpur and Radhanagar unions are very alarming where the depth to groundwater table varies from 27 to 35 m which has also dropped down beyond the suction limit (7 m).

- On the other hand, Bholahat, western part of Gomostapur, western part of Chapainawabganj and Shibganj upazila falls under the unit of Ganges River Floodplain and Teesta Floodplain where a thick aquifer exists except the Shibganj pourashava area, where thickness of aquifer varies from 18 to 60 m.
- At Shibganj pourashava area, the existence of two aquifers have been found upto the drilling depth of 265 m. The depth to groundwater table condition of Shibganj, Monakasha, Chakkirti, Mobarakpur, Ranihati, Bholahat and Shahabajpur unions are relatively good where groundwater table ranges from 4 to 12 m.

The Naogaon district mostly falls under three physiographic units: Teesta Floodplain, Lower Atrai Basin and Barind Tract.

- Porsha, Sapahar, Niamatpur and some parts of Patnitala and Dhamoirhat upazila fall under the unit of Barind Tract where only one aquifer exists. The depth to groundwater table of the aquifer varies from 18 to 36 m.
- Even in some areas of Porsha and Sapahar upazilas such as Chaor, Ganguria and Tetulia union, no suitable aquifer is found up to the drilling depth of 300 m.
- On the other hand, Naogaon Sadar, Atrai, Raninagar, Mohadevpur, Manda, Badalgachi and some Part of Patnitala and Dhamoirhat falls under the unit of Teesta Floodplain and Lower Atrai Basin where a thick aquifer exists.

Major Findings from Water Quality Sampling and Analysis:

- Conditions that are neutral to mildly acidic are indicated by pH values ranges from 6.27 to 7.39. Temperature of groundwater samples vary from 23 to 28.1 °C. But Ec values range from 186 to 1190 $\mu\text{S}/\text{cm}$, TDS values from 82 to 580 mg/l and salinity values from 0.13 to 0.95 ppt.
- The range of calcium values is 1 to 140 mg/l. Concentration of 14 samples exceed the recommended Bangladesh Drinking Water Standards. Higher values were identified in some places in Bagha, Charghat, Shibganj Upazila and Shah Makhdum thana.
- Magnesium, Sodium, Chloride, Sulfate, Phosphate and Fluoride concentration are found with in limit of Bangladesh Drinking Water Standards 1997 guideline limit.
- Potassium concentration ranges from 1 to 5 mg/l except in Tetulia union of Manda upazila where it reaches 50 mg/l.
- The concentration of bicarbonate ranges from 167 to 671 mg/l. Out of 50 samples, 49 samples show higher concentration which exceeds Bangladesh irrigation standard limit, just one sample at Uttargram union under Mohadevpur upazila have within the standard limit.

- The range of nitrate concentration is 0.33 to 10.95 mg/l. Out of 50 samples, 2 samples at Chatrajitpur and Matikata union under Shibganj and Godagari upazila respectively, have higher concentration that are greater than the Bangladesh drinking standards.
- Less than 0.03 to 2.5 mg/l of manganese is the range for concentrations. Chargaht, Raninagar, Gomostapur upazila and Shah Makhdum thana had the highest concentration. The Bangladesh Drinking Water Standards 1997 recommended level for Manganese is exceeded in 38 samples (out of 50 samples). As a result, manganese exposure poses a possible risk in the studied region.
- The range of iron concentrations varies from 0.60 to 12.90 mg/l. The Bangladesh Standard ranges between 0.3mg/l to 1.0mg/l. The area with the highest iron content, Kashimpur union under Raninagar upazila, has a concentration of 12.90 mg/l level. Considering the Bangladesh Drinking Water Standards, 38 samples show concentrations above standard limit.
- Arsenic concentration varies from less than 0.001 to 0.047 mg/l except Ranihati union under Chapainawabganj upazila where the concentration of As is 0.07 mg/l which exceeds the Bangladesh drinking water regulations limit.
- According to the data collected under this study and the report of BGS 2001, the arsenic concentration has been found as beyond the drinking water limit (BD standard) at Durlabpur, Monakasha unions of Shibganj upazila and Ranihati union of Chapainawabganj sadar upazila in Chapainawabganj district, Jewpara union of Puthia upazila, Baksimoil union of Mohonpur upazila, Haripur and Hujuripara unions of Paba upazila in Rajshahi district and Nurullabad and Manda unions of Manda upazila in Naogaon district.

Major Findings from Groundwater Level Trend Analysis:

- From the trend analysis of groundwater level data at 122 locations, it has been found that 46 nos. fall under Type 1 (these wells have strongly declining levels in both minimum groundwater depths and maximum groundwater depths), 48 nos. fall under Type 2 (groundwater trends where the dry season minimum groundwater depth is declining and the wet season induced recharge top-up appears insufficient to fully restore groundwater levels), 24 nos. fall under Type 3 (groundwater trends where the maximum depth is declining but there is no decline in the minimum depth) and only 4 nos. fall under Type 4 (both minimum depth and maximum depth show no trend) indicating occurrence of insufficient recharge to compensate abstractions in most part of the study areas which is very alarming.

Major Findings from Mathematical Modelling:

- From scenario analysis of extreme dry condition (100-Yr return period event), it reveals that the groundwater table drops down about 1.0 m to 4.0 m compared to the groundwater table of base condition.
- It is also observed that groundwater table drops down by about 4.0 m to 10.0 m in some pocket's areas of Barind region.
- Climate change's impact on groundwater levels shows that the groundwater table fails to regain its original position in monsoon and post monsoon.
- From analysis it has been found that the groundwater table may drop down up to 6 m from base condition due to the impact of climate change, although these are subject to uncertainties in the predicted rainfall.
- Overall, these simulations indicate that groundwater levels will be immediately responsive to changes in rainfall and ET patterns.

Major Findings from Surface Water Resource Assessment:

- From the assessment of surface water resources, it has been found that surface water development is possible during dry period using abstraction from the Atrai and Mohananda River as resources are available in these rivers.
- The possibility of increasing groundwater recharge by conservation of water in rivers and kharies have been analyzed for a selected area using modelling techniques. From the spatial distribution of impact map of depth to groundwater table, it has been found that groundwater tables increase by 0.05 m to 0.35 m with an impact area of about 137 km² due to conservation of water in Sib-Barnai River during dry period.
- It has been found that existing potential wetlands may be re-excavated which cover an area of about 143 Km². and can store an amount of 286 Mm³ of water.
- A total 8200 ponds (>100 decimal) have been identified which can be re-excavated and can store 120 Mm³ of water.
- Potential beels identified in Bagmara, Durgapur, Paba, Puthia and Tanore upazilas under Rajshahi district, Atrai, Raninagar, Manda, Naogaon Sadar, Sapahar, Porsha and Niamatpur upazilas under Naogaon district, and Bholahat, Gomostapur and Nachol upazilas under Chapainawabganj district, can be re-excavated to deeper extents and can be developed as potentials for surface water retention and preservation for irrigation year-round, fish culture and household purposes which will reduce the quantity of groundwater abstraction.

Major Findings from Safe yield and Water Stress Area Identifications:

- 75% of actual recharge has been taken as safe yield level for the study areas. The estimated union wise actual recharge ranges from 160-708 mm for Rajshahi District, 193-727 mm for Chapainawabganj district and 116-780 mm for Naogaon District.
- According to WSI values, the study area has been classified into five zones- Very high-water stress area (WSI >160), high water stress area (WSI 140-160), Moderate water stress area (WSI 120-140), Low water stress area (WSI 100-120) and very low water stress area (WSI <100).
- 3 unions of Godagari upazila, 1 union of Mohonpur upazila, 3 unions of Paba upazila and 6 unions of Tanore upazila under Rajshahi district; 1 union of Chapainawabganj Sadar upazila, 5 unions of Gomostapur upazila, 4 unions of Nachol upazila under Chapainawabganj district and 6 unions of Niamatpur upazila, 7 unions of Patnitala upazila, 6 unions of Porsha upazila, 5 unions of Sapahar upazila under Naogaon district falls in the very high-water stress area.
- 2 unions of Bagha upazila, 1 union of Bagmara upazila, 1 union of Charchhat upazila, 3 unions of Durgapur upazila, 3 unions of Godagari upazila, 4 unions of Mohonpur upazila, 1 union of Paba upazila, 1 union of Tanore upazila under Rajshahi district falls in the high-water stress area. In Chapainawabganj district, 3 unions of Chapainawabganj Sadar upazila, 3 unions of Gomostapur upazila, 4 unions of Shibganj upazila lies with high water stress area. In Naogaon district, 1 union of Atrai, 3 unions of Manda upazila, 1 union of Mohadevpur upazila, 2 unions of Naogaon Sadar upazila, 1 union of Niamatpur upazila, 2 unions of Patnitala upazila, 3 unions of Raninagar upazila, 1 union of Sapahar upazila falls in the high water stress area.
- The summary of District wise number of unions according to different types of water stress area are given below:

District	Number of Unions				
	Very High Stress	High Stress	Moderate Stress	Low Stress	Very Low Stress
Rajshahi	13	16	30	8	4
Chapainawabganj	10	10	14	-	11
Naogaon	24	14	22	22	17
Total	47	40	66	30	32

The summary of hydrogeological investigation and model findings has been illustrated in Table 12-1.

Table 12-1: Summary of Hydrogeological Investigation and Mathematical Modelling Results

SI No	District	Upazila	Union	Area (km ²)	Present Water Demand (MCM)	Top Layer Thickness (m)	Thickness of 1 st Aquifer (m)	Transmissivity (m ² /d)	Storage Coefficient	Depth to Top of 2 nd Aquifer (m)	Thickness of 2 nd Aquifer (m)	Depth to GWT (m)		Present Abstraction (mm)	Actual Recharge (mm)	Safe Yield (mm)	Status of GW	
												Minimum	Maximum					
1	Rajshahi	Bagha	Arani	11.17	7.50	16-18	39-62	2599-3191	0.001835-0.006428	-	-	3.43	9.64	671	436-546	300-410	Moderate Stress	
2			Bajubagha	14.25	9.84	15-21	35-47	2479-5003	0.000501-0.001603	-	-	3.65	9.55	691	423-529	291-397	Moderate Stress	
3			Bausa	30.59	21.01	15-18	42-67	2937-4129	0.000917-0.003145	-	-	4.05	9.75	687	428-535	294-401	Moderate Stress	
4			Gargari	43.90	26.59	17-20	31-43	2890-4647	0.000657-0.001406	-	-	3.77	9.65	606	380-475	261-356	High Stress	
5			Manigram	32.26	20.46	12-18	36-42	2226-4050	0.000685-0.001319	-	-	3.89	9.49	634	451-564	310-423	Moderate Stress	
6			Pakuria	29.78	19.53	12-27	33-39	2310-4003	0.000889-0.001318	-	-	3.69	9.8	656	360-451	248-338	High Stress	
7		Bagmara	Auch Para	27.36	11.77	12-30	29-36	3369-4577	0.000177-0.002194	-	-	6.32	13.67	430	541-677	372-508	Moderate Stress	
8			Bara Bihanali	15.43	6.99	0-11	6-90	2406-2644	0.002317-0.007893	-	-	3.21	11.7	453	380-475	261-356	Low Stress	
9			Basu Para	28.78	12.22	9-15	18-47	2658-3287	0.000791-0.004295	36-39	12-24	1.87	9.45	425	444-555	305-416	Moderate Stress	
10			Dwippur	13.74	5.44	3-14	15-43	2462-2723	0.002132-0.007476	-	-	2.94	15.07	396	447-559	307-419	Low Stress	
11			Ganipur	36.23	17.12	3-15	6-21	2701-4119	0.000729-0.002327	15-40	18-40	2.27	9.44	473	336-421	232-316	High Stress	
12			Goalkandi	24.06	10.95	12	67	2278-2610	0.00068-0.001464	115	21	3.07	12.54	455	399-499	274-374	Moderate Stress	
13			Gobinda Para	27.00	12.06	18-27	9-43	2363-3547	0.000053-0.00288	32	28	5.73	12.06	447	488-611	336-458	Moderate Stress	
14			Hamir Kutsha	21.90	9.47	8-12	37-62	2344-2621	0.000799-0.003463	52-104	22-32	2.97	10.11	432	445-557	306-418	Very Low Stress	
15			Jhikra	24.94	10.50	5-9	22-50	2491-2801	0.002387-0.005085	-	-	3.56	11.57	421	360-450	248-338	Very Low Stress	
16			Jogi Para	28.42	11.96	7-10	35-57	2477-2763	0.001652-0.003711	-	-	3.19	10.46	421	434-543	299-407	Very Low Stress	
17			Kachari Koali Para	5.77	2.44	10-12	37-47	2676-2842	0.0011-0.003425	-	-	1.12	11.29	424	493-617	339-463	Low Stress	
18			Maria	18.41	8.36	3-12	7-42	2357-2693	0.00093-0.002844	-	-	2.6	10.55	454	384-481	265-361	Moderate Stress	
19			Nardas	23.85	10.13	9-15	18-45	2155-3260	0.001592-0.014622	33-36	22-24	7.48	12.44	425	443-554	305-416	Low Stress	
20			Sonadanga	24.42	10.43	9-23	5-45	2176-2641	0.001442-0.014105	-	-	4.49	11.56	427	383-479	263-359	Moderate Stress	
21			Sreepur	10.49	4.51	12-15	39-42	2425-3354	0.000741-0.001354	54	15	1.96	8.75	430	442-553	304-415	Moderate Stress	
22			Subhadanga	11.29	5.02	12-24	35-48	2958-4038	0.000523-0.002887	-	-	4.16	10.76	445	394-493	271-370	Moderate Stress	
23			Charghat	Bhaya Lakshmipur	26.87	15.74	13-19	32-47	2268-3124	0.000792-0.004706	-	-	3.7	9.41	586	368-461	254-346	Moderate Stress
24				Charghat	20.55	12.09	6-21	30-54	1679-2543	0.000455-0.001889	-	-	3.98	9.03	588	380-476	262-357	High Stress
25				Nimpara	36.97	22.59	12-18	36-46	2259-2769	0.002991-0.013315	-	-	3.36	10	611	316-395	217-296	Moderate Stress
26				Salua	25.82	16.32	15	37	1120-2605	0.000795-0.006206	-	-	3.95	10.55	632	435-544	299-408	Low Stress
27		Sardah		16.97	10.54	0-22	18-42	916-2466	0.000551-0.004861	24-71	27-67	4.45	9.55	621	373-466	280-350	Moderate Stress	
28		Yusufpur		18.59	10.77	13-19	32-55	1043-2979	0.000689-0.001516	-	-	3.75	9	579	355-444	244-333	Moderate Stress	
29		Durgapur	Deluabari	27.51	19.81	9-13	22-53	2921-4665	0.000082-0.001257	-	-	3.15	14.7	720	410-513	282-385	Moderate Stress	
30			Dharmapur	21.29	14.69	6-12	39-46	2414-3225	0.000077-0.003116	-	-	2.47	11.17	690	547-684	376-513	Low Stress	
31			Jhaluka	24.11	18.39	8-15	17-57	2817-4638	0.000137-0.001938	-	-	3.44	12.13	763	383-479	287-356	High Stress	
32			Joynagar	29.78	21.87	12-13	42-48	3741-4668	0.000929-0.001273	-	-	3.77	13.95	734	366-458	275-344	High Stress	
33			Kismat Gankair	24.17	18.55	3-9	45-53	2619-2980	0.001093-0.002222	-	-	2.73	9.44	767	380-475	285-356	High Stress	
34			Maria	15.72	11.51	3-12	24-26	2676-3002	0.000408-0.002825	36-42	18-39	2.81	11.09	732	566-708	389-531	Low Stress	
35		Noapara	30.09	21.61	9-12	44-57	2848-3776	0.000713-0.001461	-	-	2.73	10.79	718	415-519	285-389	Moderate Stress		
36		Godagari	Basudebpur	18.85	12.99	0-34	3-37	909-2250	0.020231-0.100385	30-32	25-26	4.04	10.29	689	374-468	257-351	Moderate Stress	
37			Char Ashariadaha	32.58	21.59	13-23	18-21	2361-2765	0.01336-0.095706	-	-	9.81	14.86	663	485-607	334-455	Moderate Stress	
38			Dewpara	50.86	33.95	3-18	18-57	643-2999	0.000671-0.011811	87-131	21-25	20.23	24.89	668	319-399	219-299	Very High Stress	
39			Godagari	47.78	33.12	0-51	7-40	2088-2771	0.025073-0.108311	30-88	9-24	25.1	34.89	693	317-397	218-298	High Stress	
40			Gogram	59.03	37.10	11-18	10-37	1228-3324	0.000952-0.029682	27	72	4.83	11.65	628	244-305	168-229	High Stress	
41			Matikata	42.30	26.54	21	18	2371-2838	0.014551-0.07323	-	-	12.15	17.26	627	484-605	333-454	Moderate Stress	
42			Mohonpur	87.70	60.81	2-98	25-167	777-3360	0.0078-0.054201	-	-	24.69	26.97	693	372-466	256-350	High Stress	
43		Pakri	47.32	31.68	3-33	6-31	2737-4927	0.001669-0.025446	39	51	26.85	30.21	669	240-300	165-225	Very High Stress		

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												Minimum	Maximum					
44	Rajshahi	Godagari	Rishikul	55.32	36.54	3-21	6-61	2050-5299	0.001083-0.011919	15-40	6-45	5.52	11	661	336-421	232-316	Very High Stress	
45		Mohonpur	Baksimoil	22.15	16.49	9-14	7-53	4277-4770	0.000746-0.002343	-	-	8.41	15.92	744	311-389	214-292	High Stress	
46			Dhurail	27.68	20.25	1-26	11-74	4560-6279	0.001284-0.00683	-	-	11.33	17.6	732	252-315	173-236	High Stress	
47			Ghasigram	23.43	15.25	6-34	15-54	4332-5618	0.000428-0.003479	37-45	15-21	8.44	16.55	651	264-330	182-248	Very High Stress	
48			Jahanabad	29.65	20.13	9-15	12-43	3826-4501	0.000509-0.001361	-	-	6.4	14.22	679	405-507	279-380	Moderate Stress	
49			Maugachhi	31.32	21.25	10-17	32-54	3775-5462	0.001301-0.004377	-	-	9.37	17	678	356-445	245-334	High Stress	
50			Royghati	13.25	9.33	6-21	42-54	3165-4678	0.000018-0.000967	-	-	10.37	21.49	704	445-557	306-418	High Stress	
51			Paba	Baragachhi	38.45	28.37	12-15	45-54	3544-4355	0.000553-0.001584	-	-	5.76	14.2	738	316-396	217-297	Moderate Stress
52		Damkur		17.98	12.18	6-25	31-58	848-3092	0.000711-0.002749	-	-	4.62	6.72	677	273-342	188-256	Very High Stress	
53		Darshan Para		14.19	8.98	6-30	24-48	2610-4523	0.001209-0.002246	48-91	12-31	9.53	15.67	633	289-362	199-271	Very High Stress	
54		Haragram		17.23	10.98	6-27	33-58	2306-3601	0.000643-0.001003	-	-	6.27	12.5	637	257-322	177-241	High Stress	
55		Harian		9.56	7.32	12-18	37-56	2029-3697	0.000918-0.001671	-	-	4.7	12.9	766	353-442	243-331	Moderate Stress	
56		Haripur		50.49	32.63	14-26	24-47	1440-3067	0.000815-0.007464	-	-	5.16	12.35	646	378-473	260-354	Moderate Stress	
57		Hujuri Para		27.49	19.16	21	36	851-3965	0.000417-0.001768	-	-	8.04	14.1	697	265-332	182-249	Very High Stress	
58		Parila		32.35	25.50	18	42	3287-4644	0.000453-0.001638	-	-	2.95	13.4	788	304-381	209-285	Moderate Stress	
59		Puthia	Baneshwar	25.74	18.94	15-21	48-82	1520-2788	0.001339-0.007289	-	-	3.48	9.47	736	241-302	166-226	Moderate Stress	
60			Belpukuria	28.16	17.91	11-12	32-70	1459-3309	0.001177-0.002989	-	-	3.82	10	636	249-312	171-234	Low Stress	
61			Bhalukgachhi	33.90	26.47	12-21	45-70	2154-2818	0.001717-0.003807	-	-	1.81	8.1	781	443-554	304-415	Moderate Stress	
62			Jewpara	33.46	23.69	12-19	35-60	2091-2713	0.003122-0.00539	-	-	3.35	11.4	708	541-677	372-507	Very Low Stress	
63			Puthia	15.72	12.09	9-24	63-73	2328-2814	0.001773-0.012844	-	-	3.05	9.03	769	455-569	312-426	Moderate Stress	
64			Silmaria	42.14	36.66	12-13	57-68	2330-2719	0.001215-0.003315	-	-	2.71	9.25	870	476-595	327-446	Moderate Stress	
65		Tanore	Badhair	43.51	20.95	9-37	6-67	1828-4367	0.001278-0.011714	82-208	12-64	32.01	34.72	481	187-234	128-175	Very High Stress	
66			Chanduria	16.60	9.39	8-15	12-61	4084-5827	0.001952-0.005343	-	-	11.68	17.87	566	330-413	227-309	Very High Stress	
67			Kalma	51.63	28.36	21	9	1363-4187	0.000357-0.005343	-	-	23.56	27.04	549	300-376	206-282	Very High Stress	
68			Kamargaon	37.89	21.34	5	73	1409-4627	0.000382-0.002792	118	21	15.73	18.08	563	279-349	191-261	High Stress	
69			Pachandar	45.77	25.06	6-15	42-60	2526-6445	0.000591-0.002751	-	-	23.7	24.96	548	280-350	192-262	Very High Stress	
70			Saranjai	16.88	9.96	0-13	47-76	3993-6387	0.001869-0.007176	-	-	22.26	23.51	590	309-387	212-290	Very High Stress	
71			Talanda	26.48	14.92	6-15	33-76	3094-7437	0.000012-0.003635	-	-	21.83	22.65	563	312-391	215-293	Very High Stress	
72		Chapainawabganj	Bholahat	Bholahat	22.00	14.22	15	97	1312-1739	0.00615-0.016248	-	-	8.21	10.82	646	494-618	340-464	Moderate Stress
73				Daldali	32.17	20.81	12-15	33-97	1139-2002	0.002203-0.013706	-	-	8.1	27	647	546-683	376-512	Moderate Stress
74				Gohalbari	50.87	30.13	14-18	41-97	1293-2097	0.000672-0.016693	-	-	7.8	9.29	592	504-630	347-473	Moderate Stress
75	Jambaria			18.48	11.11	15-18	41-55	1001-1763	0.002927-0.004916	-	-	6.42	10.13	601	506-633	348-475	Moderate Stress	
76	Chapainawabganj Sadar		Alatuli	36.60	26.19	20-26	16-19	2268-2528	0.066285-0.178101	-	-	8	13.08	716	581-727	400-545	Very Low Stress	
77			Balidanga	40.62	29.12	11-36	3-34	515-1051	0.000926-0.015878	-	-	9.25	11.96	717	548-686	377-515	Moderate Stress	
78			Baragharia	7.25	5.28	15-26	27-41	996-1123	0.011793-0.017164	-	-	6.63	10.2	728	430-538	296-404	Moderate Stress	
79			Char Anupnagar	22.63	15.66	19-30	17-28	1032-2402	0.028544-0.15039	-	-	7.32	10.79	692	520-650	358-488	Very Low Stress	
80			Char Bagdanga	34.93	24.13	16-22	19-31	1621-2467	0.049154-0.170808	-	-	12.08	16.17	691	527-659	362-494	Very Low Stress	
81			Debinagar	34.26	25.17	19-23	17-26	1749-2524	0.091481-0.177668	-	-	3.2	12.97	735	490-613	337-460	Very Low Stress	
82			Gobratala	35.32	24.89	12-28	5-20	722-923	0.002124-0.007077	-	-	6	8.5	705	366-458	252-344	High Stress	
83			Islampur	22.97	16.41	20-28	21-32	1154-1988	0.035544-0.116017	-	-	6.53	11.73	714	452-565	311-424	Very Low Stress	
84			Jhilim	60.53	44.51	36-42	8-12	484-2424	0.000149-0.021031	-	-	32.2	36.95	735	331-414	228-311	Very High Stress	
85			Maharajpur	8.96	6.51	13-21	31-55	1060-1211	0.015115-0.021595	-	-	6.08	10.01	727	254-318	175-239	High Stress	
86			Narayanpur	43.62	29.66	16-20	26-39	1452-1741	0.02504-0.080257	-	-	5.5	10.3	680	521-652	359-489	Very Low Stress	
87			Ranihati	9.81	7.59	12	60	1014-1281	0.015653-0.029333	-	-	6.11	11.03	774	241-302	166-227	High Stress	
88			Shahjahanpur	30.40	22.42	19-21	18-23	2137-2526	0.124641-0.177848	-	-	3.2	10.71	738	546-683	376-512	Very Low Stress	
89	Sundarpur	31.05	23.97	14-22	25-47	1272-1926	0.027771-0.107431	-	-	3.7	10.22	772	525-657	361-493	Very Low Stress			

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												Minimum	Maximum					
90	Chapainawabganj	Gomostapur	Alinagar	15.59	9.54	13-20	22-67	684-1014	0.003038-0.006655	83-118	22-36	10.94	13.44	612	208-261	144-196	Very High Stress	
91			Bhangabaria	19.80	11.94	12-23	28-67	837-1485	0.003662-0.007737	-	-	10.84	12.71	603	236-296	163-222	High Stress	
92			Boalia	30.11	19.25	0	106	513-1541	0.001251-0.00471	-	-	9.2	11.16	639	320-400	220-300	High Stress	
93			Chowdala	18.59	11.16	17-19	21-59	401-942	0.000658-0.002681	-	-	7.18	10.5	600	254-318	175-239	Very High Stress	
94			Gomostapur	28.11	16.06	9-26	11-82	311-822	0.000297-0.003204	-	-	13.95	16.05	571	463-579	318-434	High Stress	
95			Parbatipur	75.82	45.85	57-280	6-61	412-1079	0.008494-0.037138	-	-	39	46.87	605	193-242	133-182	Very High Stress	
96			Radhanagar	81.12	46.31	27	6	89-971	0.007271-0.016421	42	15	26.3	35.75	571	196-246	135-185	Very High Stress	
97			Rohanpur	34.43	22.53	9-28	6-27	452-944	0.000761-0.00925	60	79	23.8	30.55	654	216-270	149-203	Very High Stress	
98			Nachol	Fatehpur	73.97	38.54	27	9.15	536-981	0.00037-0.00752	-	-	26.9	28.35	521	248-311	171-233	Very High Stress
99		Kasba		61.44	33.17	27	9.15	517-901	0.001369-0.013442	-	-	31.81	32.74	540	221-277	152-208	Very High Stress	
100		Nachol		61.45	30.44	14-23	18-40	423-1867	0.002624-0.008101	-	-	32.9	36.72	495	288-361	199-271	Very High Stress	
101		Nezampur		74.83	38.52	21-95	24	692-3040	0.001489-0.008857	-	-	31.02	40.51	515	295-369	203-277	Very High Stress	
102		Shibganj	Binodpur	29.31	14.20	7-16	34-77	2321-3278	0.00313-0.011097	61-94	32-53	6.01	10.11	484	476-596	328-447	Very Low Stress	
103			Chakkirti	34.02	15.74	33	6	524-884	0.000321-0.007864	-	-	4.29	11.3	463	369-462	254-347	Moderate Stress	
104			Daipukuria	43.01	21.26	15-20	20-58	616-2791	0.000968-0.004841	50-63	23-32	4.5	9.5	494	376-470	259-353	Moderate Stress	
105			Dhainagar	27.59	12.03	23	12	659-939	0.00083-0.007997	-	-	7.24	9.3	436	336-420	231-315	Moderate Stress	
106			Durlabhpur	51.74	22.11	9-25	10-59	485-4648	0.000701-0.041167	20-82	12-44	3.13	6.0	427	466-583	321-437	Moderate Stress	
107			Ghorapakhia	22.20	8.75	12-19	26-60	1185-1477	0.015876-0.040884	-	-	5.24	9.87	394	416-520	286-390	Moderate Stress	
108			Kansat	30.91	13.86	24	15	437-1382	0.000595-0.03125	82	30	5.17	8.06	448	388-485	267-364	Moderate Stress	
109			Mobarakpur	50.98	22.07	21	18	524-1985	0.000322-0.009296	-	-	3.98	12.45	433	386-483	266-362	Moderate Stress	
110			Monakasha	30.80	14.52	6	42	2128-4594	0.001032-0.014831	-	-	2.86	9.1	471	508-635	349-476	Very Low Stress	
111			Naya Naobhanga	22.33	11.80	13-21	13-57	829-1174	0.00642-0.019109	45-50	3-15	5.72	9.51	528	340-425	234-319	High Stress	
112			Panka	50.25	21.00	16-20	21-34	1529-2652	0.012258-0.028715	56-62	25-31	5.5	7.1	418	537-672	370-504	Moderate Stress	
113			Satrujitpur	10.38	5.04	14-21	20-47	957-1447	0.012717-0.018286	-	-	5.5	11.2	486	298-373	205-280	High Stress	
114			Shahbajpur	52.67	26.17	0	73	1253-3409	0.000075-0.007318	-	-	5.61	9.04	497	492-615	338-461	Very Low Stress	
115			Shyampur	19.13	9.92	15-24	12-41	592-2619	0.004017-0.037827	41-64	24-41	5.67	9.58	519	369-462	254-347	High Stress	
116			Uzirpur	14.36	7.02	15-21	20-43	1276-1792	0.016471-0.02879	-	-	5.28	8.8	489	405-507	279-380	High Stress	
117			Naogaon	Atrai	Ahsanganj	49.73	31.29	8-9	47-71	2614-3021	0.001692-0.00361	55-95	8-25	3.21	10.65	629	435-544	299-408
118		Bhopara			36.28	23.81	9-15	42-74	2868-3271	0.000521-0.004587	-	-	3.24	10.95	656	557-697	383-522	Very Low Stress
119		Bisha			42.66	28.33	9-10	50-56	2807-2962	0.002626-0.005751	61-80	3-15	3.80	10.45	664	529-662	364-496	Very Low Stress
120		Hatkalu Para			26.13	17.42	8-12	26-47	2070-2636	0.004464-0.016108	-	-	4.06	12.16	667	359-449	246-336	High Stress
121		Kalikapur			28.44	18.16	7-9	43-54	2488-3020	0.002069-0.006566	-	-	4.6	13.44	639	484-606	333-454	Moderate Stress
122		Maniari			49.04	32.98	9-10	46-55	2871-3347	0.003428-0.011635	-	-	5.2	10.86	673	552-690	379-517	Very Low Stress
123		Panchupur			28.77	18.50	9-10	54-76	2769-2952	0.002309-0.004834	68-98	6-9	2.80	9.55	643	532-665	365-498	Very Low Stress
124		Sahagola			23.36	15.20	6-18	40-58	2754-3453	0.000247-0.002296	-	-	3.00	10.22	651	457-572	314-429	Moderate Stress
125	Badalgachi	Adhaipur		27.71	19.08	3-9	24-35	3942-7535	0.000169-0.004271	25-30	28-37	5.48	8.99	689	422-528	290-396	Very Low Stress	
126		Badalgachi		39.70	28.18	3-8	24-40	3702-7634	0.000015-0.010155	-	-	6.85	12.58	710	538-673	370-504	Very Low Stress	
127		Balubhara		21.67	14.79	6-12	27-40	4008-7021	0.00114-0.007587	21-28	9-32	5.40	9.01	683	461-577	317-432	Low Stress	
128		Bilasbari		31.12	21.00	8-13	34-40	3715-5713	0.003628-0.00823	-	-	4.65	8.2	675	432-540	297-405	Low Stress	
129		Kola		21.84	15.19	7-10	32-37	4678-5900	0.002532-0.005041	25-28	28-31	5.55	9.05	696	401-502	276-376	Very Low Stress	
130		Mathurapur		27.39	18.99	5-7	28-36	2588-4621	0.000218-0.003018	-	-	3.75	8.6	693	521-652	358-489	Very Low Stress	
131		Mithapur		21.61	14.93	7-9	30-37	4095-4921	0.002637-0.004348	-	-	5.29	8.97	691	494-618	339-463	Very Low Stress	
132		Paharpur		22.94	16.31	6-8	29-32	3623-4344	0.002663-0.00403	-	-	5.06	8.85	711	477-597	328-447	Very Low Stress	
133	Dhamoirhat	Agra Digun		35.93	28.02	4-6	3-75	1696-2360	0.028469-0.104554	-	-	10.65	11.73	780	336-421	231-315	Low Stress	
134		Alampur		40.81	31.14	6	45	1472-2420	0.001522-0.02729	-	-	6.3	10.99	763	400-501	275-375	Low Stress	
135		Aranagar		38.49	28.67	3-6	15-16	2227-3406	0.000081-0.011244	18-19	21-30	8.09	14.27	745	387-484	266-363	Low Stress	

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												Minimum	Maximum				
136	Naogaon	Dhamoirhat	Dhamoirhat	34.96	25.92	4-8	21-40	2382-3051	0.000791-0.010269	23-41	10-28	2.95	7.60	741	410-513	282-384	Very Low Stress
137			Isabpur	37.57	28.41	5-6	28-32	2922-3576	0.000906-0.008006	28-31	21-27	7.2	9.5	756	417-522	287-391	Very Low Stress
138			Jahanpur	34.57	25.83	0-7	30-33	2643-3455	0.00358-0.009116	-	-	5.5	8.99	747	401-502	276-376	Very Low Stress
139			Khelna	35.75	27.06	5-6	40-49	1382-2308	0.003038-0.135103	-	-	8.94	10.57	757	411-514	282-385	Moderate Stress
140			Omar	31.56	23.37	6-15	36-42	2233-2735	0.000026-0.013246	-	-	8.41	9.57	740	432-541	297-405	Very Low Stress
141		Manda	Bhalain	30.69	22.67	9-12	28-36	2933-4446	0.013444-0.019047	-	-	4.1	10.3	739	467-584	321-438	Low Stress
142			Bharso	52.06	37.38	6	15	2425-3243	0.000955-0.01336	27	32	10.3	13.22	718	472-590	324-442	Low Stress
143			Bishnupur	28.47	20.75	18	14	1298-2496	0.000751-0.03774	37	24	4.75	11.38	729	452-566	311-424	Moderate Stress
144			Ganeshpur	26.23	19.22	12-18	20-48	2240-4023	0.011082-0.028659	-	-	7.31	10.28	733	327-409	224-306	High Stress
145			Kalikapur	28.53	20.58	24	5	2271-3604	0.000887-0.0116	30	31	1.7	7.75	721	484-606	333-454	Low Stress
146			Kanso Para	21.99	16.44	15-24	11-50	580-2450	0.019933-0.056124	27-34	21-31	6.4	10.87	748	410-513	282-384	Moderate Stress
147			Koshob	15.96	12.05	15	9	628-2337	0.01669-0.055165	29	28	5.29	11.26	755	536-670	368-502	Moderate Stress
148			Kusumba	28.79	21.44	9-12	15-61	2626-3108	0.002851-0.013735	34	40	9.24	14.58	745	518-648	356-486	Very Low Stress
149			Mainani	25.65	18.58	6-20	25-48	2341-5170	0.010278-0.027688	-	-	7.12	9.65	724	418-523	287-392	High Stress
150			Manda	21.48	16.22	8-18	24-47	2784-3338	0.008928-0.015409	-	-	8.63	11.87	755	488-610	335-457	Low Stress
151			Nurullabad	28.89	20.97	11-20	11-54	2042-3134	0.001444-0.019649	-	-	5.1	14.84	726	481-602	331-451	Low Stress
152			Paranpur	26.96	19.98	6-14	24-56	2689-3363	0.01084-0.016475	28	13	6.82	10.76	741	487-609	334-456	Moderate Stress
153			Prasadpur	22.69	16.71	6-20	10-50	2035-3109	0.010819-0.028462	33-36	18-30	7.05	10.95	736	498-623	342-467	Moderate Stress
154			Tentulia	38.74	28.81	21	3	2958-4366	0.0002-0.003048	31	30	8.76	14.22	744	498-623	342-467	High Stress
155			Mohadevpur	Bhimpur	33.49	22.63	0-18	20-48	3703-7447	0.000768-0.009504	-	-	6.91	10.28	676	447-559	307-419
156		Chandas		31.67	21.92	0-10	28-40	3018-5532	0.008041-0.01991	-	-	4.4	9.63	692	435-544	299-408	Low Stress
157		Cheragpur		41.73	27.65	5-15	15-54	5033-7011	0.004598-0.008246	27-30	28-32	7.09	9.93	663	420-525	288-393	Low Stress
158		Enayetpur		46.17	29.52	9	12	1784-4994	0.000172-0.014605	27	21	10.08	11.25	639	428-536	294-402	Very Low Stress
159		Hatur		51.86	34.74	7-9	20-37	2397-4011	0.004412-0.022396	-	-	11.07	12.3	670	352-440	242-330	High Stress
160		Khajur		44.40	29.91	3-8	27-41	3037-5925	0.004687-0.022324	25-29	20-25	10.95	11.83	674	448-560	308-420	Low Stress
161		Mohadevpur		40.46	27.47	0-9	30-47	3310-7249	0.004598-0.010175	-	-	4.93	9.26	679	416-520	286-390	Low Stress
162		Roygaon		41.63	28.08	0-8	27-43	3243-6334	0.004821-0.015749	25-30	19-26	5.95	9.2	674	404-505	277-378	Low Stress
163		Safapur		33.99	22.92	7-26	10-51	3333-6309	0.008456-0.01645	-	-	7.07	11.09	674	428-535	294-401	Low Stress
164		Uttargram		30.12	20.44	9	64	4857-7349	0.007624-0.011428	-	-	7.36	9.46	679	432-540	297-405	Low Stress
165		Naogaon Sadar	Baktiarpur	17.35	11.97	7-14	19-40	2006-7667	0.005014-0.014979	-	-	6.23	10.15	690	497-622	342-466	Moderate Stress
166			Balihar	23.53	16.95	0-13	34-50	2360-5630	0.00736-0.027645	-	-	6.97	10.15	720	380-476	261-357	Low Stress
167			Barshail	14.83	10.33	7-13	13-43	5606-8178	0.004087-0.005529	-	-	5.67	9.4	697	438-548	301-411	Low Stress
168			Boalia	7.54	5.23	6-12	11-49	1844-5400	0.000102-0.01566	-	-	5.67	10.42	694	368-460	253-345	High Stress
169			Chandipur	14.90	10.19	6	46	1508-4399	0.000901-0.003067	-	-	5.15	11.15	684	506-633	348-474	Moderate Stress
170			Dubalhati	29.75	12.66	12	48	1787-4077	0.003753-0.034372	-	-	4.35	11.93	426	536-670	368-502	Moderate Stress
171			Hapania	18.69	15.92	7-11	34-46	3336-8226	0.000926-0.006082	-	-	7.55	11.35	852	564-706	388-529	Moderate Stress
172	Hashaighari		23.95	15.21	8-15	22-65	605-3395	0.010823-0.055659	-	-	5.95	11.08	635	445-557	306-417	Moderate Stress	
173	Kirtipur		18.11	14.87	7-11	30-37	3667-7310	0.004069-0.009091	-	-	4.6	8.6	821	539-674	370-505	Low Stress	
174	Sailgachhi		12.69	10.95	6-10	39-47	1995-2853	0.002099-0.007447	-	-	5.17	12.08	863	532-666	366-499	Moderate Stress	
175	Sekherpur		34.18	26.97	6-15	42-51	1980-3058	0.003982-0.0258	-	-	5.35	12.8	789	472-591	325-443	High Stress	
176	Tilakpur	23.17	18.19	5-15	40-46	1778-4326	0.005546-0.016001	-	-	5.67	9.6	785	545-682	375-511	Moderate Stress		
177	Niamatpur	Bahadurpur	56.45	31.15	3-7	52-62	1079-2619	0.00054-0.011111	-	-	17.22	18.96	552	266-333	183-249	High Stress	
178		Bhabicha	52.97	28.31	9	27	1104-3557	0.013322-0.056501	-	-	19.65	22.42	534	372-466	256-349	Very High Stress	
179		Chandan Nagar	51.87	28.75	7-19	28-46	1412-3542	0.017202-0.049211	-	-	10.81	13.25	554	340-425	233-318	Moderate Stress	
180		Hajinagar	61.93	33.88	9-12	34-42	707-2258	0.029701-0.070172	-	-	18.25	20.4	547	285-357	196-267	Very High Stress	
181		Niamatpur	44.38	24.19	12-18	9-24	731-3085	0.006028-0.061413	-	-	17.55	20.95	545	271-339	186-254	Very High Stress	

SI No	District	Upazila	Union	Area (km ²)	Present Water Demand (MCM)	Top Layer Thickness (m)	Thickness of 1 st Aquifer (m)	Transmissivity (m ² /d)	Storage Coefficient	Depth to Top of 2 nd Aquifer (m)	Thickness of 2 nd Aquifer (m)	Depth to GWT (m)		Present Abstraction (mm)	Actual Recharge (mm)	Safe Yield (mm)	Status of GW			
												Minimum	Maximum							
182	Naogaon	Niamatpur	Parail	58.14	32.41	9-20	6-37	544-2265	0.003163-0.014553	-	-	23.66	24.52	557	186-233	128-174	Very High Stress			
183			Rasulpur	75.59	42.21	17-22	7-33	710-1282	0.006183-0.04262	-	-	20.42	21.76	558	190-238	130-178	Very High Stress			
184			Sreemantapur	47.81	25.92	9-22	18-24	527-3292	0.004083-0.01526	-	-	14.98	17.09	542	269-337	185-252	Very High Stress			
185		Patnitala	Akbarpur	Akbarpur	34.12	21.79	12	35	2107-5964	0.002183-0.079915	-	-	13.8	14.3	639	364-456	250-342	Very High Stress		
186				Amair	34.06	21.30	5-7	27-33	2673-4580	0.000376-0.011014	28-31	20-32	7.87	10.11	625	396-496	272-372	High Stress		
187				Dibar	31.50	20.26	61	6	1422-4248	0.026538-0.135246	73	12	13.18	13.82	643	354-443	243-332	Very High Stress		
188				Ghoshnagar	30.36	20.28	0-8	23-33	1967-5032	0.009076-0.015277	30-32	19-22	9.48	10.7	668	403-504	277-378	Moderate Stress		
189				Krishnapur	41.43	25.13	6	33	1368-2508	0.00619-0.137423	79	12	12	14.08	607	396-495	272-371	Very High Stress		
190				Matindhar	35.28	22.88	6-9	9-21	2300-5851	0.00317-0.019241	21-34	10-31	12.36	13.30	649	351-439	241-329	Very High Stress		
191				Nazipur	20.06	13.03	6-9	19-31	1603-2637	0.004354-0.014901	29-43	16-20	9.49	10.83	650	339-424	233-318	Moderate Stress		
192				Nirmail	12.52	8.38	152	148	1711-2453	0.055911-0.108547	-	-	11.45	12.82	669	184-230	126-172	Very High Stress		
193				Patichara	31.74	20.27	3-8	20-35	1503-2659	0.001989-0.011345	22-53	16-22	7.5	9.8	639	426-533	293-399	High Stress		
194				Patnitala	35.05	22.92	6-9	22-37	1265-2940	0.000089-0.03412	30-73	13-22	10.04	11.2	654	284-355	195-266	Very High Stress		
195				Shihara	37.05	22.56	40-64	6-9	1218-2273	0.065004-0.150701	64	9	11.1	12.9	609	354-443	243-332	Very High Stress		
196				Porsha	Chhaor	Chhaor	43.07	21.31	115	6	176-1990	0.010847-0.052603	-	-	13.71	16.58	495	124-156	85-117	Very High Stress
197						Ganguria	41.23	19.73	298	0	2038-3751	0.022822-0.030161	-	-	11.74	16.51	479	116-145	79-108	Very High Stress
198						Ghatnagar	50.63	25.90	12-103	30-45	1458-5128	0.009746-0.046163	-	-	20.31	36.92	512	168-211	116-158	Very High Stress
199						Moshidpur	36.03	18.90	6-9	9-55	2867-5938	0.002411-0.026764	18-38	16-32	15.68	16.37	525	233-292	160-219	Very High Stress
200		Nitpur	58.41			28.34	14-108	12-24	304-2365	0.011045-0.029013	25-121	12-21	6.15	12.74	485	204-255	140-191	Very High Stress		
201		Tetulia	42.51	21.84	57-115	3-27	1026-3470	0.020047-0.03045	78-180	6-12	11.64	14.53	514	163-204	112-153	Very High Stress				
202		Raninagar	Bargachha	Bargachha	44.56	36.78	6-9	45-48	2632-3324	0.001744-0.010262	-	-	4.41	20.29	825	571-714	392-535	Moderate Stress		
203				Ekdala	24.95	21.76	6	48	3077-3677	0.007785-0.017863	-	-	7.95	10.97	872	624-780	429-585	Low Stress		
204				Gona	39.60	26.41	6-7	47-55	2221-3113	0.000812-0.003601	-	-	3.97	10.74	667	454-568	312-426	High Stress		
205				Kaligram	10.03	8.65	6-12	42-48	2800-3573	0.003952-0.015787	-	-	3.23	9.28	862	512-641	352-480	Moderate Stress		
206				Kashimpur	27.67	22.72	12-13	47-50	1473-2494	0.001572-0.003273	-	-	4.69	11.39	821	440-551	303-413	High Stress		
207				Mirat	49.50	24.17	7-12	23-49	1940-2576	0.002214-0.023699	-	-	4.66	11.87	488	494-618	339-463	Moderate Stress		
208				Parail	15.79	12.40	3-6	48-51	2527-3516	0.003067-0.009454	-	-	4.68	9.99	785	568-711	391-533	Moderate Stress		
209				Raninagar	46.22	35.38	6	48	1780-2300	0.002413-0.01678	-	-	4.37	10.37	766	459-574	316-431	High Stress		
210		Sapahar	Aihai	Aihai	38.03	22.60	15-24	29-45	2113-2703	0.0343-0.045821	-	-	12.16	15.12	594	315-394	216-295	Very High Stress		
211				Goala	57.91	34.08	3-42	22-36	1963-3281	0.02699-0.045575	-	-	10.61	16.72	588	240-300	165-225	Very High Stress		
212	Pathari			28.60	16.02	10-12	5-41	1997-2498	0.029324-0.039088	-	-	10.75	15.74	560	360-451	248-338	High Stress			
213	Sapahar			39.21	22.58	57-198	36	2321-4209	0.022625-0.081152	-	-	18.30	29.25	576	222-278	152-208	Very High Stress			
214	Shiranti			40.51	23.86	27-51	3-24	2332-2872	0.037822-0.07002	64-103	3-9	14.57	35.60	589	313-392	215-294	Very High Stress			
215	Tilna			40.34	24.16	15-18	36-42	3381-5991	0.001918-0.03973	-	-	7.95	26.80	599	306-383	210-287	Very High Stress			

12.2 Recommendations

Following recommendations have been made for the study area:

- Present groundwater abstraction in Tanore and Godagari upazilas of Rajshahi district, Niamatpur, Porsha and Sapahar upazilas of Naogaon district and Nachol and Gomostapur upazilas of Chapainawabganj district is quite alarming. Therefore, these upazilas should be brought under restricted/limited abstraction areas.
- In the high water stress area, no additional abstraction should be allowed as it exceeds the safe yield limit and should be kept the static water level in present condition. Deficiency of water demand in the high water stress area should be filled up by supplying water from less water stress areas if possible.
- Potential beels that are identified at Bagmara, Durgapur, Paba, Puthia and Tanore upazilas under Rajshahi district, Atrai, Raninagar, Manda, Naogaon Sadar, Sapahar, Porsha and Niamatpur upazilas under Naogaon district and Bholahat, Gomostapur and Nachol upazilas of Chapainawabganj district, should be re-excavated to deeper extents and should be developed as potentials for surface water retention and preservation for irrigation year-round, fish culture, birds habitats and household purposes to reduce groundwater abstraction in dry season.
- Use of surface water should be increased to reduce pressure on groundwater. Drinking water can be provided in the water stress areas after storing surface water during the monsoon season by constructing reservoirs and necessary infrastructures (pipelines, water treatment plants, overhead tanks, etc.).
- As a pilot project, fresh water can be provided by conserving surface water through re-excavation of 3 beels. The potential beels are: Beel Kumari of Tanore Upazila under Rajshahi District, Jobai Beel of Sapahar Upazila under Naogaon District and Hugla Damas Beel of Nachol Upazila under Chapainawabganj District.
- In high water stress areas, at least one pond should be used for drinking water, one pond for bathing and domestic purposes and others for fish farming. In this case, sign boards should be provided in the reserved ponds based on usage.
- A total 8200 ponds (>100 decimal) have been identified in the study areas which should be re-excavated to a deeper extent for extensive use in fish farming and household purposes.
- Crop diversification is prescribed as cultivation of crops with less water requirement should be introduced instead of HYV Boro rice to improve the water management. In this regard, awareness campaigns should be organized for crop diversification.
- The monitoring wells installed under this project for the observation of groundwater level data should be kept under continuous monitoring as this is one of the hotspots

identified in Delta Plan 2100. An IoT-based automation along with telemetry system should be developed to regularly monitor the groundwater level changes.

- The study areas are geologically diverse and complex, and the composition and structure of regional aquifers are highly variable. The model developed under this study should be updated with continuous field monitoring data which will reduce the uncertainty of the model.

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