A COMPARATIVE ASSESSMENT OF GROUNDWATER RESOURCE AND RECHARGE POTENTIAL IN BARIND AREA USING MODFLOW AND MIKE SHE MODELS

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of
MASTER OF SCIENCE IN WATER RESOURCES ENGINEERING

by
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July 2008
I do hereby declare that this thesis work A Comparative Assessment of Groundwater Resource and Recharge Potential in Barind Area Using MODFLOW and MIKE SHE Models has been done by me. Neither of this thesis nor any part of it has been submitted elsewhere for the award of any degree or diploma.

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<td>BADC</td>
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<td>BARC</td>
<td>Bangladesh Agricultural Research Council</td>
</tr>
<tr>
<td>BBS</td>
<td>Bangladesh Bureau of Statistics</td>
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<tr>
<td>BMDA</td>
<td>Barind Multipurpose Development Authority</td>
</tr>
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<td>BRDB</td>
<td>Bangladesh Rural Development Board</td>
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<tr>
<td>BRRI</td>
<td>Bangladesh Rice Research Institute</td>
</tr>
<tr>
<td>BS</td>
<td>Block Supervisor</td>
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<tr>
<td>BTM</td>
<td>Bangladesh Transverse Mercator</td>
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<tr>
<td>BUET</td>
<td>Bangladesh University of Engineering &amp; Technology</td>
</tr>
<tr>
<td>BWDB</td>
<td>Bangladesh Water Development Board</td>
</tr>
<tr>
<td>CWR</td>
<td>Crop Water Requirement</td>
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<tr>
<td>DAE</td>
<td>Department of Agricultural Extension</td>
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<tr>
<td>DEM</td>
<td>Digital Elevation Model</td>
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<tr>
<td>DoE</td>
<td>Department of Environment</td>
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<tr>
<td>DTW</td>
<td>Deep Tubewell</td>
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<tr>
<td>EPWAPDA</td>
<td>East Pakistan Water and Power Development Authority</td>
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<tr>
<td>ETo</td>
<td>Potential Evapotranspiration</td>
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<tr>
<td>FAO</td>
<td>Food and Agricultural Organization</td>
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<td>FAP</td>
<td>Flood Action Plan</td>
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<td>FIWR</td>
<td>Field Irrigation Water Requirement</td>
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<td>FYP</td>
<td>Five Year Plan</td>
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<td>GW</td>
<td>Groundwater</td>
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<td>GWH</td>
<td>Groundwater Hydrology</td>
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<td>GWL</td>
<td>Groundwater Level</td>
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<td>GIS</td>
<td>Geographical Information System</td>
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<td>GoB</td>
<td>Government of Bangladesh</td>
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<tr>
<td>HTW</td>
<td>Hand Tubewell</td>
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<tr>
<td>HYV</td>
<td>High Yielding Variety</td>
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<tr>
<td>IECO</td>
<td>International Engineering Company</td>
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<td>IWM</td>
<td>Institute of Water Modelling</td>
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<tr>
<td>IDA</td>
<td>International Development Agency</td>
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<tr>
<td>LGED</td>
<td>Local Government Engineering Department</td>
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<tr>
<td>LLP</td>
<td>Low Lift Pump</td>
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<tr>
<td>MIKE-SHE</td>
<td>Modelling Software of DHI for Groundwater Flow Simulation</td>
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<td>MoWR</td>
<td>Ministry of Water Resources</td>
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<td>MPO</td>
<td>Master Plan Organization</td>
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<tr>
<td>MWSWs</td>
<td>Municipal Water Supply Wells</td>
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<td>NMIC</td>
<td>National Minor Irrigation Census</td>
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<td>NWMP</td>
<td>National Water Management Plan</td>
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<td>NWPo</td>
<td>National Water Policy</td>
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<td>PRSP</td>
<td>Poverty Reduction Strategy Paper</td>
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<td>PWD</td>
<td>Public Works Datum</td>
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<td>SIWR</td>
<td>Scheme Irrigation Water Requirement</td>
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<td>SRDI</td>
<td>Soil Resources Development Institute</td>
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<td>STW</td>
<td>Shallow Tubewell</td>
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<td>SWR</td>
<td>Scheme Water Requirement</td>
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<td>WARPO</td>
<td>Water Resources Planning Organization</td>
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Fatema Akram
ABSTRACT

MIKE SHE and MODFLOW are used to simulate the regional groundwater flow in the High Barind of northwest Bangladesh. The study area is the driest part of Bangladesh and has an upper thick and compacted clay layer of Pleistocene deposits. The low permeability of this clay layer limits its recharge to the aquifers. The geology of the area encloses two aquifers which are interconnected in many places. The aquifers are very thin locally. Heavy abstraction of groundwater is taking place for agricultural, industrial and drinking purposes. The study area faces problems like: almost no rain from November to April, limited scope for surface water storage, inadequate knowledge related to existing hydrogeology, etc.

The models have been applied for the simulation of the groundwater flow for a period 1997-2005 over an area of about 2236 km$^2$. The area has been divided into 186 rows and 85 columns in layers of five distinct vertical deposits. Considering lithological variations and groundwater flow capacity, total 5 hydro-stratigraphic units have been demarcated within the studied depth in the study area (Clay Top, Upper Aquifer, Clay Middle, Lower Aquifer and Clay Bottom). At the outset MIKE SHE has been calibrated for 1997 to 2003 and validated for January 2004 to December 2005 against the observed groundwater levels at different locations. There is reasonable match between the computed and observed levels. Overland leakage coefficient is one of the major calibration parameters as unsaturated zone of the study area is thick. Soil properties like soil moisture tension/content relationship, unsaturated hydraulic conductivity and maximum bypass ratio of net rainfall are also important parameters for calibration. From the calibrated output, recharge values are extracted and used as input to the MODFLOW. During simulation of the MODFLOW the other input data and parameters are kept same to examine the results both from MIKE SHE and MODFLOW. The main difference between the two models is that MIKE SHE includes unsaturated zone, so it calculates infiltration, actual evapotranspiration and recharge from their physical laws. On the other hand MODFLOW deals with saturated zone only. From model result it is apparent that if recharge is calculated properly from other source, then MODFLOW will give good result. So in the case of groundwater flow study where
irrigation is not present, MODFLOW can be used. Otherwise MIKE SHE will be more appropriate.

Due to the occurrence of thin aquifers the study area shows a lower transmissivity locally. The study area being a ridge-shaped terrain, however, shows an outward flow of its groundwater all through the year to its surrounding low-relief areas. The recharge from rain starts in May and continues up to the end of October-November. It is found that for 1997-2005 the average recharge within the study area is about 443 mm, varying in the range of 308 mm in Sapahar Upazila to 607 mm in Chapai-Nawabganj Upazila. Simulation shows that recharge occurs mainly due to rainfall, while the contribution of irrigation (in the winter) is very negligible. Upazila-wise groundwater resources have been assessed based on safe-yield criteria, where groundwater table would be replenished every year. MIKE SHE result shows that the available groundwater resource (before irrigation starts) varies in the range of 180 mm in Tanore Upazila to 913 mm in Nawabganj Sadar Upazila. Usable resource has been assumed as 90% of the available resource as there are some natural losses set-out the study area during irrigation season. For the study area, potential recharge has been estimated considering water balance of the period from May 2001 to October 2001 (as water table attains the lowest and highest elevation in May and October, respectively). The potential recharge of the present study varies from 395 mm in Porsha Upazila to 621 mm in Nawabganj Upazila. For every year and every upazila, plots on cumulative recharge against cumulative rainfall have been drawn and found that the plots are following some exponential relations. With the increment of rainfall, recharge increases gradually in the initial stage and comparatively faster in the later stage.

Some upazilas are withdrawing more water than the maximum capacity of recharge (i.e., potential recharge). In many cases water table goes beyond suction limit, which leads shallow tube wells to inoperable condition. The adverse effect of over exploitation of groundwater may be overcome by placing shallow tube wells with appropriate spacing. There is a possibility of fault location near Tanore Upazila, which should be investigated further.
CHAPTER 1
INTRODUCTION

1.1 General

Ground water is an integral part of the water cycle. The cycle starts with precipitation falling on the surface. Runoff from precipitation goes directly into lakes and streams. Some of the water which seeps into the ground is used by plants for transpiration. The remaining water drains down through the soil to the saturated zone, where water fills all the spaces between soil particles and rocks, called ground water.

Groundwater is a vital source of water throughout the world because of its availability and general good quality. Ground water is often taken for granted, but recent circumstances indicate that ground water is seriously vulnerable to depletion in some places. Because of this threat, it is important to understand the processes that make ground water available for use. As the number of groundwater investigations increase, it is important to understand how to develop comprehensive quantified conceptual models and appreciate the basis of analytical solutions or numerical methods of modelling groundwater flow. Groundwater Hydrology: Conceptual and Computational Models describe advances in both conceptual and numerical modelling. It gives insights into the interpretation of field information, the development of conceptual models, the use of computational models based on analytical and numerical techniques, the assessment of the adequacy of models, and the use of computational models for predictive purposes. It focuses on the study of groundwater flow problems and a thorough analysis of real practical field case studies.

The sustainable use and management of groundwater is now a great challenge for the national water agencies of Bangladesh. A number of studies have been done to assess the groundwater resources and to estimate the groundwater recharge in different areas of Bangladesh. Recently groundwater modeling has been an effective way to perform these jobs in many countries of the world. U.S. Geological Survey
(USGS) originated software MODFLOW is being extensively used worldwide to carry out research in the field of groundwater resource management. MIKE SHE, emerged from SHE developed by a consortium of three European organisations, has already been used in Bangladesh for a long time.

There is a number of groundwater flow models exist. MIKE SHE, MODFLOW and FEFLOW are worth of mention. MIKE SHE software has been used in Bangladesh for a long time. Now the use of MODFLOW is spreading rapidly. Institutions are interested on using both software and try to compare the results for management decisions. The study area lies within the Barind area. Two softwares, MIKE SHE and MODFLOW have been chosen for this study to develop the groundwater model and to compare the results for better understanding and decision making. The present study focuses more intensively on the high Barind area with 500 by 500 m cell size.

Drought is the major problem of the project area. The area is the driest part of Bangladesh; normally there is no rain from November to April. The Mean monthly average rainfall from November to April varies only from 12 mm to 20 mm, although the annual rainfall varies from a minimum of 1000 mm to a maximum of 2000 mm. In the driest months, most of the ponds and tanks have become derelict creating shortage of water for both domestic uses and use by the livestock population. Dry season irrigation in the project area is mainly done from the groundwater. The deep tubewell irrigation in the Barind area faces problem during peak demand due to decline in groundwater table and power shortage. Permanent decline of groundwater table is observed from field data due to over-abstraction of groundwater. The operation of few thousand DTWs by BMDA for irrigation during dry periods also creates problems for operation of shallow tubewells, hand tubewells and dug wells. The study area faces drought even in the monsoon period also.

Surface water is available at near the outfall of the Mohananda river into the Ganges and in the Ganges river. Pumping of surface water to the project area from the Ganges, Mohanada and other rivers will augment both surface and groundwater. However, available water in the rivers could not be utilized to irrigate high Barind areas for non-availability of storage reservoir and due to topography, it requires large pumping plant. Moreover the water levels of the rivers in some reaches go
down beyond the suction limit of low lift pumps becoming the problems of pumping from river.

The existing problems in the project area are summarized below;
- Rainfall scarcity from November to April.
- Very limited scope of conserving large volume of water in wet months for irrigation.
- Available water in the rivers could not be utilized to irrigate High Barind areas for non-availability of storage reservoir and require large pumping plant with second lift.
- Existing data and information indicate that potential aquifers for large scale groundwater development do not exist within the drilled depth of about 80 m in places in High Barind area and is problem for dry season cultivation.
- Inadequate power supply is another problem for the smooth operation of DTWs.

Considering the above mentioned problems, a study is necessary to solve or minimize the problems. Therefore, the present study is embraced with the problems of the region and may be able to give some recommendations for future study.

1.2 Objectives of the study

The study will explore the use of two popular models (e.g., MIKE SHE and MODFLOW) for assessing groundwater resource and recharge potential for a difficult area like Barind. Each model has its own advantages over the other. As such it is intended to identify the suitability of the model for simulating the groundwater resource of the study area.

The specific objectives of the present study are as follows:

- To setup the MIKE SHE and MODFLOW models to simulate the groundwater resource of the study area.
- To determine the recharge potential from MIKE SHE model and subsequently to use it in MODFLOW to confirm its validity in simulating the groundwater resource.
1.3 Structure of the Report

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

**Chapter-1:** focuses on the project background, brief description of the existing problems and bottlenecks, justification of the study and study objectives,

**Chapter-2:** presents the brief summary of the previous studies related to this study.

**Chapter-3:** gives the physical setting of the study that includes description of the study area; it’s geo-morphological and hydrogeological setting, drainage and river system, agricultural and irrigation conditions.

**Chapter-4:** presents the general approach and methodology that has been applied during the modelling works. It deals with data requirement, data collection from secondary sources, data analysis and processing for model input. It provides the various activities of modelling study that includes development of model, calibration validation of model and comparison of two models.

**Chapter-5:** reflects the result and analysis of the modelling works, water balance, potential recharge and groundwater resource assessment.

**Chapter-6:** presents the conclusions and recommendations that have been found during the study.

Appendices of the report include the following;

**Appendix-A** : Double Mass Curve

**Appendix-B** : Geological Cross Section

**Appendix-C** : Simulated GWL Hydrograph Using MIKE SHE

**Appendix-D** : Simulated GWL Hydrograph Using MODFLOW

**Appendix-E** : Upazila-wise Water Balance Components
CHAPTER 2
LITERATURE REVIEW

2.1 Introduction
Groundwater is the water in the saturated zone of earth materials under pressure greater than atmospheric, i.e., positive pressure. Water enters to the groundwater through infiltration or percolation. Again, seepage from surface water bodies also causes groundwater recharge (Lerner, 1990). Discharge to rivers or lakes causes depletion of groundwater storage in addition to pumping of groundwater for irrigation. The groundwater environment is hidden. The withdrawal and replenishment of groundwater is slow, complex phenomena and necessitates carefully investigation.

Modelling and simulation are popular instruments to manage groundwater resource. The efficiency of the groundwater models is mostly dependent on the quality of input data. This chapter will discuss about some selected previous studies.

2.2 Working Principles of MIKE SHE and MODFLOW

MIKE SHE
MIKE SHE is a fully distributed, physically-based hydrologic model that can simulate water movement over and under the Earth's surface. Danish Hydraulic Institute (DHI) has developed the software MIKE SHE, is a dynamic, user-friendly modeling tool that can simulate the entire land phase of the hydrologic cycle. MIKE SHE includes both simple and advanced process descriptions to maximize computational efficiency. It can easily link the regional and local scale models. The seamless link to ArcView shape files for all distributed parameters saves time and effort. MIKE SHE can be used for the analysis, planning and management of a wide range of water resources and environmental problems related to surface water and groundwater.
Five basic modules of MIKE SHE water movement are: Overland Flow (OL), Channel/River Flow (OC), Evapotranspiration (ET), Unsaturated Flow (UZ) and Saturated/Groundwater Flow (SZ).

MODFLOW

US Geological Survey originated software Visual MODFLOW is an easy-to-use modeling environment for practical applications in three-dimensional groundwater flow and contaminant transport simulations. It is a finite difference model, which solves a system of equations describing the major flow and related processes in the hydrological system.

Against five modules of MIKE SHE water movement, MODFLOW deals with Channel Flow and Saturated Flow only.

2.3 Comparison between MIKE SHE and MODFLOW

The MIKE SHE can be used to simulate all of the processes in the land phase of the hydrologic cycle, including overland flow, channel flow, groundwater flow in the unsaturated zone and saturated groundwater flow. MODFLOW, on the other hand, is restricted to simulating flow only in the saturated groundwater zone. In MIKE SHE, the saturated zone is only one component of an integrated groundwater/surface water model. The saturated zone interacts with all of the other components - overland flow, unsaturated flow, channel flow, and evapotranspiration. For comparison, MODFLOW only simulates the saturated flow. All of the other components are either ignored (e.g. overland flow) or are simple boundary conditions for the saturated zone (e.g. evapotranspiration). Although many of the processes simulated in MIKE SHE are used in a similar way when simulating groundwater flow with MODFLOW.

For example, MODFLOW includes recharge as an upper boundary condition to the groundwater model, where recharge is defined as the amount of water reaching the groundwater table after accounting for evapotranspiration, surface runoff and changing storage in the unsaturated zone. It is usually done by applying a constant
or varying fraction (rule-of-thumb) to the measured precipitation data. In most cases, the model results are very sensitive to this fraction and since there is little data, it assumes a starting value and uses this as a calibration parameter. Thus the amount of recharge is adjusted during the calibration process until the measured groundwater levels match the calculated values.

On the other hand, there are very few differences between the MIKE SHE Saturated Zone numerical engine and MODFLOW. In fact, they share the same PCG solver. The differences that are present are limited to differences in the discretization and to the way some of the boundary conditions are defined.

Setting up the saturated zone hydraulic model involves defining the geological model, the vertical numerical discretization, the initial conditions, and the boundary conditions. In the MIKE SHE, the geological model and the vertical discretization are essentially independent, while the initial conditions are defined as a property of the numerical layer. Similarly, subsurface boundary conditions are defined based on the numerical layers, while surface boundary conditions such as wells, drains and rivers (using MIKE 11) are defined independently of the subsurface numerical layers. The use of grid independent geology and boundary conditions provides a great deal of flexibility in the development of the saturated zone model, thus the same geological model and many of the boundary conditions can be re-used for different model discretizations and different model areas. In MODFLOW, the River boundary condition is used to simulate the influence of a surface water body on the groundwater flow. Surface water bodies such as rivers, streams, lakes and swamps may either contribute water to the groundwater system, or act as groundwater discharge zones depending on the gradient between the surface water body and the groundwater system. The MODFLOW River Package simulates the surface water / groundwater interaction via a seepage layer separating the surface water body from the groundwater system. The rest of the components of saturated zone hydraulic model are set up as similar as MIKE SHE.
MODFLOW and MIKE SHE treat internal inactive zones quite differently. In MIKE SHE, the internal inactive zones are simply treated as cells with a very low hydraulic conductivity, whereas, MODFLOW ignores them in the solution. Thus, when question comes to the interpolation in MIKE SHE, the interpolation does not know about the inactive zone and interpolates through the inactive zone - there are simply no data points in the inactive zones.

While MODFLOW and MIKE SHE both solves the same physical problem using the finite-difference method there are some significant differences between the two models. Studying manuals of MIKE SHE and MODFLOW, some distinct differences of them are presented below:

<table>
<thead>
<tr>
<th></th>
<th>MODFLOW (by USGS)</th>
<th>MIKE SHE (by DHI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid</td>
<td>Uses variable finite difference grid</td>
<td>Uses square grid</td>
</tr>
<tr>
<td>Spatial distribution of data</td>
<td>A confined aquifer can be specified using a transmissivity value and aquitards can be specified using a leakage value. In both cases there is no need for specifying the top and bottom of aquifer and/or aquitard and system geometry is eliminated from the input data</td>
<td>In MIKE SHE each model layer is characterized by horizontal (isotropic) and vertical hydraulic conductivity and a top and bottom elevation.</td>
</tr>
<tr>
<td></td>
<td>MODFLOW allows the user to take anisotropy into account for the horizontal hydraulic conductivity by specifying a ratio between the horizontal hydraulic conductivity in the x and y directions per layer of the grid</td>
<td>MIKE SHE assumes horizontal hydraulic conductivity to be isotropic.</td>
</tr>
<tr>
<td></td>
<td>MODFLOW uses the leakage (L/T) between layers. This implies that for a N layer model there are N-1 leakage values in the MODFLOW input.</td>
<td>MIKE SHE requires input for the vertical hydraulic conductivity (L/T) for each layer.</td>
</tr>
<tr>
<td></td>
<td>MODFLOW uses time varying drain levels</td>
<td>In MIKE SHE drain levels cannot change with time</td>
</tr>
<tr>
<td></td>
<td>MODFLOW uses time varying riverbed hydraulic conductivity</td>
<td>In MIKE SHE riverbed hydraulic conductivity cannot vary with time</td>
</tr>
<tr>
<td>Data &amp; Parameter Requirements</td>
<td>Frame: Horizontal discretization, Topography, Boundary type</td>
<td>Frame: Horizontal discretization, Topography, Distribution</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Codes for rainfall and meteorological stations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Interception:</strong> Should be used DUFLOW or other rainfall runoff model</td>
</tr>
<tr>
<td><strong>Evapotranspiration:</strong> Maximum ET rate, Elevation of ET surface, ET extinction depth</td>
</tr>
<tr>
<td><strong>Overland and Channel Flow:</strong> Hydraulic conductivity of riverbed, Head in the river, Elevation of river bottom</td>
</tr>
<tr>
<td>Manning’s roughness coefficient, Slope and width of stream channel</td>
</tr>
<tr>
<td><strong>Seasonal Water Courses/Drains:</strong> Drain hydraulic conductivity, Elevation</td>
</tr>
<tr>
<td><strong>Unsaturated Zone Modelling:</strong> Not Included</td>
</tr>
<tr>
<td><strong>Interception:</strong> Canopy drainage parameters, canopy storage capacity, ground cover indices, Leaf Area Index, Interception capacity coefficient, Rainfall rate</td>
</tr>
<tr>
<td><strong>Evapotranspiration:</strong> Canopy resistance, aerodynamic resistance, Ground Cover Indices, Ratio between actual and potential evapotranspiration as a function of soil moisture tension, Root distribution with depth, Empirical constants describing the ratio between actual and potential evapotranspiration as a function of soil moisture, Leaf Area Index, root depth, root distribution coefficient, Meteorological data</td>
</tr>
<tr>
<td><strong>Overland and Channel Flow:</strong> Strickler roughness coefficient (similar to Manning’s M) for overland and river flows, Detention storage capacity on ground surface, Coefficient of discharges for weir formulae, Specified levels and flows at boundaries, Man-controlled discharges, Topography of overland flow plane and river cross sections, Riverbed lining thickness, riverbed lining</td>
</tr>
</tbody>
</table>
**Saturated Zone Modeling:**
Storage coefficients, Saturated hydraulic conductivities, Effective porosity, Location of abstraction and recharge wells, Pumping and recharge rates

**Seasonal Water Courses/Drains:**
Included in Drainage

**Unsaturated Zone Modelling:**
- Soil moisture tension/content relationship, Unsaturated hydraulic conductivity as a function of soil moisture content, Maximum bypass ratio of net rainfall,
- Distribution codes for soil profiles, Distribution codes for soil types in soil profiles, Vertical node discretization in UZ

**Reservoirs:**
- Land surface elevation, Riverbed hydraulic conductivity, Thickness of riverbed

**Horizontal Flow Barrier:**
- Barrier direction, Hydraulic conductivity / thickness of barrier

**Interbed Storage:**
- Pre-consolidation head, Elastic storage factor, Inelastic storage factor, Starting compaction

**Saturated Zone Modeling:**
- Storage coefficients, Saturated hydraulic conductivities, Drainage depth, Time constant for drainage routing, Specified flows, Gradients and heads at boundaries, Location of abstraction and recharge wells, Pumping and recharge rates, Vertical node discretization in SZ

**Reservoirs:**
- Not included

**Horizontal Flow Barrier:**
- Not included

**Interbed Storage:**
- Lance can be included

<table>
<thead>
<tr>
<th>Density</th>
<th>Water density can vary from cell to cell. Density depended head is</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Not included</td>
</tr>
<tr>
<td>Feature</td>
<td>MODFLOW</td>
</tr>
<tr>
<td>--------------------------</td>
<td>----------------------------------------------</td>
</tr>
<tr>
<td>Snow Melt</td>
<td>Not included</td>
</tr>
<tr>
<td>Finer Model Grid</td>
<td>Finer model grid can be used for detailed study at specific area of interest</td>
</tr>
<tr>
<td>Calibration</td>
<td>Calibrates against observed hydraulic heads</td>
</tr>
<tr>
<td>Auto Calibration</td>
<td>The following model parameters can be automatically calibrated: 1) Horizontal hydraulic conductivity or transmissivity; 2) Vertical leakance; 3) Specific yield or confined storage coefficient; 4) Pumping rate of wells; 5) Conductance of drain, river, stream or head-dependent cells; 6) Recharge flux; 7) Maximum evapotranspiration rate; and 8) Inelastic storage factor</td>
</tr>
<tr>
<td>Water Quality</td>
<td>MODFLOW simulate changes in concentration of up to 30 different species miscible contaminants in groundwater considering advection, dispersion and simple chemical reaction</td>
</tr>
<tr>
<td>User Interface &amp; Operation Speed</td>
<td>MODFLOW produces 3-D water quality model</td>
</tr>
<tr>
<td>Presentation</td>
<td>User Interface is much easier (like MS Word/Excel) and can be learned quickly from the users’ manual. Operation speed and compilation time are much faster</td>
</tr>
<tr>
<td></td>
<td>Using the Presentation tool, you can create labeled and color filled contour maps of any kind of data, including input data and simulation results. Report-quality graphics maybe printed (with preview) or saved to several file formats, including SURFER, DXF, HPGL and BMP (Windows Bitmap). The Presentation tool can even create and display 2D animation sequences using the simulation results</td>
</tr>
</tbody>
</table>

Result Extractor allows extracting...
Simulation results from any period to a spreadsheet. Field Interpolator takes point-wise measurement data and interpolates the data to model grid. The model grid can be irregularly spaced. Field Generator generates fields with heterogeneously distributed transmissivity or hydraulic conductivity values. It allows the user to statistically simulate effects and influences of unknown small-scale heterogeneities. Water Budget Calculator not only calculates the budget of user-specified zones but also the exchange of flows between such zones. This facility is very useful in many practical cases. It allows the user to determine the flow through a particular boundary. Graph Viewer displays scatter diagrams to aid in model calibration and temporal development curves of simulation results including hydraulic head, drawdown, subsidence, compaction and concentration.

| Model Description | Modular 3D finite-difference groundwater model of the US Geological Survey, to the description and prediction of the behavior of groundwater systems | 3-D finite difference model. |

2.4 Basic Equations of MIKE SHE and MODFLOW

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

Saturated Flow

The governing equation for three-dimensional flow in saturated porous media which is used both in MIKE SHE and MODFLOW is
\[
\frac{\partial}{\partial x} \left( K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_{zz} \frac{\partial h}{\partial z} \right) + W = S_s \frac{\partial h}{\partial t} \] \tag{2.1}
\]

where, \(K_{xx}, K_{yy}, \) and \(K_{zz}\) = values of saturated hydraulic conductivity along the x, y, and z coordinate axes (L/T), which are assumed to be parallel to the principle axes of hydraulic conductivity tensor; \(h\) = potentiometric/hydraulic head (L); \(W\) = volumetric flux per unit volume representing sources and/or sinks of water, with \(W<0.0\) for flow out of the groundwater system, and \(W>0.0\) for flow into the groundwater system (T^-1); \(S_s\) = specific storage coefficient of the porous material (L^-1).

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

Besides the above equation, MIKESHE uses the following equations for Overland Flow, Evapotranspiration and Unsaturated Flow modules.

**Overland Flow**

When the net rainfall rate exceeds the infiltration capacity of the soil, water gets ponded on the ground surface. This water is available as surface runoff, to be routed downhill towards the river system. The exact route and quantity is determined by the topography and flow resistance, as well as the losses due to evaporation and infiltration along the flow path.

The water flow on the ground surface is calculated by MIKE SHE’s Overland Flow Module, using the diffusive wave approximation of the Saint Venant equations, or using a semi-distributed approach based on the Mannings equation.
**Diffusive wave approximation:** Using Cartesian coordinates in the horizontal plane \((x, y)\), let the ground surface level be \(z_g(x, y)\), the flow depth above the ground surface be \(h(x, y)\), and the flow velocities in the \(x\)- and \(y\)-directions be \(u(x, y)\) and \(v(x, y)\), respectively. Let \(i(x, y)\) be the net input into overland flow (net rainfall less infiltration). Then the conservation of mass gives
\[
\frac{\partial h}{\partial t} + \frac{\partial}{\partial x} (uh) + \frac{\partial}{\partial y} (vh) = i \quad \text{.......................... (2.2)}
\]
and the momentum equation gives
\[
S_{fx} = S_{ax} - \frac{\partial h}{\partial x} - \frac{u}{g} \frac{\partial u}{\partial x} - \frac{1}{g} \frac{\partial u}{\partial t} - \frac{qu}{gh} \quad \text{.......................... (2.3a)}
\]
\[
S_{fy} = S_{ay} - \frac{\partial h}{\partial y} - \frac{v}{g} \frac{\partial v}{\partial y} - \frac{1}{g} \frac{\partial v}{\partial t} - \frac{qv}{gh} \quad \text{.......................... (2.3b)}
\]
where \(S_f\) is the friction slopes in the \(x\)- and \(y\)-directions; \(S_o\) is the slope of the ground surface and \(q\) is the specific discharge in \(m^2/s\). Equations (2.2), (2.3a) and (2.3b) are known as the St. Venant equations and when solved yield a fully dynamic description of shallow, (two-dimensional) free surface flow.

The dynamic solution of the two-dimensional St. Venant equations is numerically challenging. Therefore, it is common to reduce the complexity of the problem by dropping the last three terms of the momentum equations. Thereby, we are ignoring momentum losses due to local and convective accelerations and lateral inflows perpendicular to the flow direction. This is known as diffusive wave approximation, which is being implemented in MIKE SHE.

Considering only flow in the \(x\)-direction the diffusive wave approximation is
\[
S_{fx} = S_{ax} - \frac{\partial h}{\partial x} - \frac{\partial z_g}{\partial x} - \frac{\partial h}{\partial x} \quad \text{.......................... (2.4)}
\]
If we further simplify Eq (2.4) using the relationship \(z = z_g + h\) it reduces to
\[
S_{fx} = -\frac{\partial}{\partial x} (z_g + h) = -\frac{\partial z}{\partial x} \quad \text{.......................... (2.5)}
\]
in the \(x\)-direction. In the \(y\)-direction Eq (2.5) becomes
\[
S_{fy} = -\frac{\partial}{\partial y} (z_g + h) = -\frac{\partial z}{\partial y} \quad \text{.......................... (2.6)}
\]
Use of the diffusive wave approximation allows the depth of flow to vary significantly between neighboring cells and backwater conditions to be simulated. However, as with any numerical solution of non-linear differential equations numerical problems can occur when the slope of the water surface profile is very shallow and the velocities are very low.

Now, a Strickler/Manning-type law for each friction slope can be used; with Strickler coefficients $K_x$ and $K_y$ in the two directions, the equations can be written as

$$S_{f_x} = \frac{u^2}{K_x^2 h^{4/3}}$$

$$S_{f_y} = \frac{u^2}{K_y^2 h^{4/3}}$$

Substituting Eqs (2.5) and (2.6) into Eqs (2.7a) and (2.7b) result in

$$\frac{u^2}{K_x^2 h^{4/3}} = -\frac{\partial \xi}{\partial x}$$

$$\frac{u^2}{K_y^2 h^{4/3}} = -\frac{\partial \xi}{\partial y}$$

After simplifying Eqs (2.8a) and (2.8b) and multiply both sides of the equations by $h$, the relationship between the velocities and the depths may be written as

$$uh = K_x \left(-\frac{\partial \xi}{\partial x}\right)^{1/2} h^{5/3}$$

$$vh = K_y \left(-\frac{\partial \xi}{\partial y}\right)^{1/2} h^{5/3}$$

Note that the quantities $uh$ and $vh$ represent discharge per unit length along the cell boundary, in the x- and y-directions, respectively.

Also note that the Stickler roughness coefficient is equivalent to the Manning $M$. The Manning $M$ is the inverse of the commonly used Mannings $n$. The value of $n$ is typically in the range of 0.01 (smooth channels) to 0.10 (thickly vegetated channels), which correspond to values of $M$ between 100 and 10, respectively.
Simplified overland flow routing: Figure 2.1 represents a schematic of overland flow on a planar surface of infinite width with uniform rainfall. Precipitation falls on the plane, builds on the surface in response to the surface roughness, and flows down the slope in the positive x-direction. In the figure, $L$ is the length of the slope, $y$ is the local depth of water on the surface at any point along the surface and $\alpha$ is the slope. Then, from the continuity equation

$$\frac{\partial q}{\partial x} = R - \frac{\partial y}{\partial t} \quad \text{.........................................................(2.10)}$$

where $q$ is the specific discharge and $R$ is the rainfall. For turbulent flow on a plane of infinite width, the Manning equation for specific discharge is

$$q = M y^{5/3} \sqrt{\alpha} \quad \text{[m}^2/\text{s]} \quad \text{.........................................................(2.11)}$$

Now, at equilibrium, the depth no longer changes and the specific discharge approaches the rainfall rate.

$$\frac{\partial y}{\partial t} = 0 \Rightarrow \frac{\partial q}{\partial x} = R \Rightarrow q_e = R_x \quad \text{.........................................................(2.12)}$$

where $q_e$ is the equilibrium specific discharge. Then, at equilibrium, the volume of water detained on the surface, $D_e$, can be calculated by

Figure 2.1: Schematic Diagram of overland flow on a plane
\[ D_e = \int y \, dx = \int \left( \frac{q_s}{M\sqrt{\alpha}} \right)^{\frac{3}{5}} \, dx = \int \left( \frac{Rx}{M\sqrt{\alpha}} \right)^{\frac{3}{5}} \, dx \]

\[ D_e = \frac{5}{8} \frac{R^{\frac{3}{5}} L^{\frac{8}{5}}}{M^{\frac{3}{5}} \alpha^{\frac{3}{10}}} \quad [m^3/m] \quad \text{(2.13)} \]

The depth, \( y_e \), near the leading edge of the flow plane can be related to the depth at equilibrium by

\[ y = \left( \frac{t}{t_e} \right) y_e \quad \text{................................................(2.14)} \]

where \( t \) is the time and \( t_e \) is the time until the equilibrium is reached. Then from Eq (2.11) we can write

\[ q = M \left( \frac{\frac{t}{t_e}}{M\sqrt{\alpha}} \right)^{\frac{3}{5}} y_e^{\frac{2}{5}} \sqrt{\alpha} \quad [m^3/s] \quad \text{................................................(2.15)} \]

Now if we integrated the specific discharge from time \( t_e \) to when the equilibrium is reached, we can calculate the total volume discharged, \( Q \), (per unit width of the plane) by

\[ Q = \int_0^{t_e} q \, dt = \left[ M \left( \frac{\frac{t}{t_e}}{M\sqrt{\alpha}} \right)^{\frac{3}{5}} y_e^{\frac{2}{5}} \sqrt{\alpha} \right] dt \]

\[ Q = \frac{3}{8} M y_e^{\frac{5}{3}} \sqrt{\alpha} t_e \quad [m^3] \quad \text{................................................(2.16)} \]

From Eq (2.15), at equilibrium, \( (t = t_e) \), the depth of water at the leading edge of the plane \((x = L)\) is

\[ q = M y_e^{\frac{5}{3}} \sqrt{\alpha} = R.L \quad \text{................................................(2.17)} \]

which yields

\[ y_e^{\frac{5}{3}} = \frac{R.L}{M \sqrt{\alpha}} \quad [m^{5/3}] \quad \text{................................................(2.18)} \]

From continuity, the total volume of inflow up until equilibrium must equal the total outflow minus the amount retained on the surface. Thus,

\[ \text{Inflow - Outflow} = \text{Surface storage} \]

which from Eqs (2.16) and (2.13) yield

\[ R.L t_e - \frac{3}{8} M y_e^{\frac{5}{3}} \sqrt{\alpha} t_e = \frac{5}{8} R^{\frac{3}{5}} L^{\frac{1}{5}} \quad \text{................................................(2.19)} \]
which when simplified yields the time to reach equilibrium

\[
L^{3/5} = \frac{8 D_e}{5 R L} \quad t_e = \frac{L^{3/5}}{R^{2/5} M^{3/5} \alpha^{3/10}}
\]

If we now assume that the flow on the sloping plane is uniform, that is the change in discharge as a function of \( x \) is zero, then the depth prior to equilibrium is simply

\[
y = R t
\]

and the relationship between depth, \( y \), and the surface storage at equilibrium, \( D_e \), is given by

\[
y = \frac{8 D_e}{5 L} \quad \text{[m]} \quad \text{(2.22)}
\]

The relationship between the depth, \( y \), and the detained surface storage prior to equilibrium, \( D \), is given by an empirical model (Fleming, 1975; Crawford and Linsley, 1966) as

\[
y = \frac{D}{L} \left[ 1 + \frac{3}{5} \left( \frac{D}{D_e} \right)^3 \right] \quad \text{[m]} \quad \text{(2.23)}
\]

where during the recession part of the hydrograph, when \( D/D_e \) is greater than 1, \( D/D_e \) is assumed to be equal to 1.

Substituting Eq (2.23) into the Manning Eq (2.11) yields

\[
q = M \sqrt{\alpha} \left[ \frac{D}{L} \left[ 1 + \frac{3}{5} \left( \frac{D}{D_e} \right)^3 \right] \right]^{5/3} \quad \text{[m}^2/\text{s]} \quad \text{(2.24)}
\]

**Evapotranspiration**

Evapotranspiration (ET) is one of the components of MIKE SHE model. This model uses a modification of the Kristensen-Jensen (1975) method which was developed at the Royal Veterinary and Agricultural University (KVL) in Denmark to calculate actual ET. This method is based on addition of the three evapotranspiration components – interception storage, transpiration by the plant and evaporation from the soil surface, to compute total actual evapotranspiration.

\[
\text{ET actual} = \text{ET canopy} + \text{ET transpiration} + \text{ET pond} + \text{ET soil}
\]
In this model, the actual evapotranspiration and the actual soil moisture status in the root zone is calculated from the potential evaporation rate, along with maximum root depth and leaf area index for the plants. The empirical equations in the model are based on actual measurements. The model generally assumes the temperature to be above 0°C and hence, that precipitation does not occur as snow.

**Unsaturated Flow**

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

1. the full Richards equation, which requires a tabular or functional relationship for both the moisture-retention curve and the effective conductivity,
2. a simplified gravity flow procedure, which assumes a uniform vertical gradient and ignores capillary forces, and
3. a simple two-layer water balance method for shallow water tables.
Richards equation in vertical direction: The driving force for transport of water in the unsaturated zone is the gradient of the hydraulic head, \( h \), which includes a gravitational component, \( z \), and a pressure component, \( \Psi \). Thus

\[
h = z + \Psi
\]

(2.25)

The gravitational head at a point is the elevation of the point above the datum (\( z \) is positive upward). The reference level for the pressure head component is the atmospheric pressure. Under unsaturated conditions the pressure head, \( \Psi \), is negative due to capillary forces and short range adsorptive forces between the water molecules and the soil matrix. These forces are responsible for the retention of water in the soil. As these two forces are difficult to separate, they are incorporated into the same term. Although the physical phenomena creating the pressure head under unsaturated and saturated conditions are very different, the pressure head is considered to be a continuous function across the water table, with the pressure being negative above and positive below the water table.

For vertical flow, the driving force for the transport of water is the vertical gradient of the hydraulic head. Thus,

\[
\Delta h = \frac{\partial h}{\partial z}
\]

(2.26)

The volumetric flux is then obtained from Darcy's law:

\[
q = -K(\theta) \frac{\partial h}{\partial z}
\]

(2.27)

where \( K(\theta) \) is the unsaturated hydraulic conductivity. Assuming that the soil matrix is incompressible and the soil water has a constant density, the continuity equation will be:

\[
\frac{\partial \theta}{\partial t} = -\frac{\partial q}{\partial z} - S(z)
\]

(2.28)

where \( \theta \) is the volumetric soil moisture and \( S \) is the root extraction sink term. Combining Eqs (2.25), (2.27) and (2.28) yield

\[
\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left( K(\theta) \frac{\partial \Psi}{\partial z} \right) + \frac{\partial K(\theta)}{\partial z} - S(z)
\]

(2.29)
The dependent variables, $\theta$ and $\psi$, in Eq. (2.29) are related through the hydraulic conductivity function, $K(\theta)$, and the soil moisture retention curve, $\psi(\theta)$. Eq. (2.29) is general, in the sense that it is equally valid in both homogeneous and heterogeneous soil profiles, and there are no constraints on the hydraulic functions.

Introducing the concept of soil water capacity

$$C = \frac{\partial \theta}{\partial \psi} \tag{2.30}$$

which is the slope on the soil moisture retention curve, then the tension-based version of Eq (2.29) is

$$\frac{\psi}{h} = \frac{\partial}{\partial z} \left( K(\theta) \frac{\partial \psi}{\partial z} \right) + \frac{\partial K(\theta)}{\partial z} \tag{2.31}$$

This equation is usually referred to as Richards equation, which is named after L.A. Richards who first used it in 1931. It still applies when $\psi$ becomes positive, in which case the equation degenerates to the Laplace equation.

The sink term in Eq (2.31) is calculated from the root extraction for the transpiration in the upper part of the unsaturated zone. The integral of the root extraction over the entire root zone depth equals the total actual evapotranspiration. Direct evaporation from the soil is calculated only for the first node below the ground surface.

**Gravity flow**: The driving force for transport of water in the unsaturated zone is the gradient of the hydraulic head, $h$, which includes a gravitational component, $z$, and a pressure component, $\Psi$. Thus

$$h = z + \psi \tag{2.32}$$

The gravitational head at a point is the elevation of the point above the datum ($z$ is positive upward). The reference level for the pressure head component is the atmospheric pressure. Under unsaturated conditions the pressure head, $\Psi$ is negative due to capillary forces and short range adsorptive forces between the water molecules and the soil matrix. However, in the gravity flow module, the pressure head term is ignored and the driving force is entirely due to gravity.
Thus for vertical flow, the vertical gradient of the hydraulic head becomes,

\[ \Delta h = -\frac{\partial z}{\partial z} = 1 \]

(2.33)

The volumetric flux is obtained from Darcy's law:

\[ q = -K(\theta) \frac{\partial h}{\partial z} = -K(\theta) \]

(2.34)

where \( K(\theta) \) is the unsaturated hydraulic conductivity. Assuming that the soil matrix is incompressible and the soil water has a constant density, the continuity equation will be:

\[ \frac{\partial \theta}{\partial t} = -\frac{\partial q}{\partial z} - S(z) \]

(2.35)

where, \( S \) is the root extraction sink term. In the present modeling study a simplified gravity flow procedure is used for computing the flow in unsaturated zone.

### 2.6 Previous Studies and Researches

During the study period different study reports, project documents and previous investigations, particularly for groundwater resource assessment related to the study area are reviewed. The most relevant studies are summarized below:

**UNDP-BWDB (1982):** During this study countrywide groundwater survey was carried-out. Observation wells were set up. Test borings (shallow and deep) were drilled and aquifer tests were conducted. Specific study areas were selected to collect more representative hydrogeological data. Based on these data along with previous data of geology and climate, hydrogeological conditions of Bangladesh were described broadly. Geological cross-sections were drawn, hydraulic properties were estimated, and water quality (except arsenic) was studied. Minimum and maximum groundwater recharges were estimated based on climatic data and assumed values of runoff and field capacity of soil profiles. Contour maps of transmissivity of main aquifers were prepared. The identification of potential groundwater development areas were based on i) annual volume of recharge, ii)
capacity of the system to act as a long term storage reservoir, iii) energy source for the pumping lift and iv) water quality. According to this report the current study area has limited thick sandy aquifer especially in the high Barind area and transmissivity-value ranging from 500 to 1500 m²/day. Annual recharge varied from a minimum of 80 to a maximum of 190 mm. This study was based on limited data for generalized appraisal of hydrogeological condition of the country and therefore, was in need of a detailed study of available groundwater resources for formulation of the project.

**MacDonald (1983):** This study reports briefly the geology, infiltration rate, permeability range, storage range, water level fluctuations and finally development potential of the study area. It was based on existing data analysis and a water balance study. The study area consists mainly of three aquifers namely Sibganj (1200 km²), High Barind Area (3634 km²) and Little Jamuna (980 km²). Sibganj aquifer has been classified as semi-confined. The infiltration rate is 1.7 mm/day in wetland and 12 mm/day in dry land. Permeability ranges from 30 to 60 m/day with an average of 40 m/day. The specific yield of upper layer is 6%. Drilling of DTW is not constrained except in deeply flooded areas. The high Barind aquifer has been classified as semi confined and multi-layered. The infiltration rate is 1.5 mm/day in wetland and 7.5 mm/day in dry land. Permeability ranges from 25 to 40 m/day with an average of 30 m/day. Specific yield of the upper layer is approximately 4%. Drilling of DTW is not promising because of the large depth to poor aquifer and fine materials, which require special design. Recharge could also be a limiting factor and trial borings were recommended. The Little Jamuna aquifer has been classified as unconfined to semi-confined. Infiltration rate is 1.5 mm/day in wetland and 5 mm/day in dry land. Permeability ranges from 50 to 80 m/day with an average of 65 m/day. Specific yield averages 5%. There is a good potential for drilling of DTW in this area and the recharge is unlikely to hinder development.

**Asaduzzaman (1983)** in the report on Barind Tract, Rajshahi-Groundwater Exploration Follow-up highlighted successes and problems of drilling deep tubewells (DTW) and recommended actions to facilitate drilling of DTW. The report contains thanawise recommended number of DTW for 45% development level (as
per Northwest Bangladesh Groundwater Modelling Report), well fixtures, discharge and thanawise fluctuation of groundwater level (average), and rainfall, bore log as well as construction procedure of DTW. In another report Asaduzzaman (1985) highlighted the achievements and bottlenecks of drilling DTW and proposed measures to expedite the drilling of DTW.

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

Master Plan Organization (MPO, 1986) Technical Report No-5 on Groundwater Resources was part of a planning for development of water resources in Bangladesh. Groundwater resources of the country were assessed based on existing hydrogeological data and information. The report also uses the results based on detailed primary data collected from 8 representative areas spreading all over Bangladesh. A country-wide contour map of transmissivity was prepared using data based on aquifer tests and development tests of tubewells. In the current study-area the transmissivity values have been estimated in the range of 1000 to 2000 m²/day; for thin aquifers it may vary from 200-700 m²/day. A contour map of specific yield was also prepared using bore logs and aquifer test data assuming that the specific yield increases linearly with the increase of depth from ground surface for increase of sand in the aquifers. Specific yield values have been assigned for each layer occurring within 25 m depth from ground surface and later to estimate its average value. The average value of specific yield for the study area is in the range of 2% to 5%. This value depends on the accuracy of identification of aquifer materials in the bore-log. The groundwater recharge model was developed from the study of catchment recharge in the eight representative areas. The catchments were taken as multi-layer single cell models in which only the vertical components of flow were considered. Outputs were the annual rates of potential recharge for each catchment area summarized from simulated ten-day rainfall and soil infiltration using 25 years of climatic data. A relation between rainfall and annual potential recharge was
developed, indicating that the higher the rainfall, the higher the annual potential recharge for an area. Potential and available recharge for the study area was estimated to be in the range of respectively 200 to 500 mm, and 100 to 400 mm.

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

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

WARPO (2000) contains database for upazila-wise water resources. Groundwater resource assessment was done on the basis of hydrograph analysis of groundwater levels measured by BWDB. Deep percolation rate and specific yield ($S_y$) of water table fluctuation zones were estimated using those data. The MPO recharge model was also used to check the results. Potential recharge was estimated from the values of deep percolation and $S_y$. The estimated potential recharge values of the current
study area were in the range of 304 to 700 mm against the net requirement of 430 mm for full development by irrigation. Available recharge is in the range of 228 to 504 mm. The study has limitation on consideration that very few hydrographs might not be representative for the entire upazila area and the estimation of irrigation coverage was not based on field survey.

**Barind Multi-Purpose Development Authority (BMDA)-IWM Study (2006):**

IWM has carried out a model study (integrated both surface water and groundwater) in the Barind area, which covers 25 upazilas of Rajshahi, Nawabganj and Noagaon districts with an area of 7500 km². Integrated MIKE11-MIKE SHE modeling system with grids size of 1000m×1000m squares has been applied in the study. Based on the data available up to 2005 the study confirms that groundwater resources are inadequate in 11 upazilas to meet the present water demand for Boro crops while in 5 upazilas the present withdrawals of groundwater are more compare to potential recharges and available groundwater resources.
CHAPTER 3

STUDY AREA

3.1 Geographical Location

The study area is situated in the North western part of Bangladesh. The area is bounded by Indian Territory on the North and part of West, Ganges River on the South, Mohananda river in the west. The study area is located in Tanore and Godagari Upazilas of Rajshahi district, Patnitala, Niamatpur, Porsha, and Sapahar Upazilas of Naogaon district and Nachole, Nawabganj Sadar and Gomastapur Upzilas of Nawabganj District (Figure 3.1).
The geographic boundary of the study area is 326500E, 696000N for the South Western corner and 369000E, 789000N for the North Western corner and covers approximately 2,23,625 ha where the cultivated area is about 2,22,350 ha.

3.2 Climate
The study area experiences a tropical humid monsoon climate. In summer the mean maximum temperature is well above 35°C whereas in winter the mean minimum temperature is below 10°C. The cool weather begins in October and continues up to the end of March. The early summer is dry, with scorching winds and the rainy season is not so wet with average annual rainfall of 1600mm. Almost 80% of the rainfall occurs during June to October. The dry season (November to May) net evapotranspiration of that area is from 500mm to 600mm. The relative humidity in the study area varies from 46% to 83%.

3.3 Topography of the Study Area
The study area is relatively high and uneven. Topography of the area varies from 13.3m PWD in Tanore to 47.0m PWD in Nachol-Niamatpur area. The area is almost flood free making it suitable for round the year cultivation. The DEM is shown in Figure 3.2. The relation between area and elevation of the study area from this DEM is also shown in Figure 3.3.
Figure 3.2 Topography

Figure 3.3: Area Elevation Curve – High Barind Area
3.4 Geomorphology and Hydrogeological Setting

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

Study Area and Regional Geological Setting

The present geomorphologic setting of the study area is the result of tectonic adjustment within the Bengal Basin. Tectonically Bangladesh is lying on the Indian Plate and occupies the major part of the Bengal Basin. Geological data indicates that the area is traversed by a basement-controlled faults named Tanor fault (Khan, 1991).

Figure 3.4: Generalized Tectonic Map of Bangladesh and Adjacent Area (Source GSB, 1990)
The study area experienced lateral discontinuities of terrace materials indicate that the Barind Terrace is large elevated block. The blocks are bordered by raised shelf type terrain due to step faulting along eastern and western margins. The Barind Terrace has significant effect on both the terrestrial and subsurface geological environment that ultimately influences the ground water regimes of the area.

**Geomorphology**

The landforms of the study area are mostly undulating. Moreover the terrace area land mass is slightly tilted to the southeast direction.

**Hydrogeological Setting**

Based on so far available hydro-stratigraphic data and reports it appears that within the exploited depth one-aquifer unit exists in the study area. However, there is a clay layer but not continuous within this aquifer. The upper part of this aquifer is composed of grey and light brown coloured very fine-to-fine sand with lenses of fine to medium grained sand and occasionally with clay, silt and trace mica lenses. The lower part of this aquifer is considered as principal source of groundwater production in the study area. The lower part of this aquifer has composed of medium to coarse-grained sand with occasional fine sediment lenses. The geometry and confining properties of both of this aquifer are variable with its location in the study area and controlled by local subsurface geology. According to UNDP-BWDB (1982) report the study area aquifer systems has the transmissivity value ranges from 500 m²/day to 1500 m²/day.

Steep gradient of groundwater elevation exists in the study area which may have maximum outflow situation and direction is towards the Padma River.

### 3.5 Drainage and River System

The study area appears to be well drained because of some channels, which criss-cross the study area and most of the drainage water flows through the river Ganges and Mohananda. Due to higher topography, the study area is rarely subjected to flooding. There occur some very shallow flashy floods in river valleys.
3.6 Soil Condition

The Soil Resources Development Institute (SRDI) prepared soil association maps of the country including the study area. Terrace soils are Modhupur clay. It is reddish to brown sticky clay and it contains 13% silt and 87% clay.

3.7 Agricultural Practice

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

1. HYV Aman followed by potato followed by Maize
2. HYV Aman followed by potato followed by HYV Boro
3. HYV Aman followed by mustard followed by HYV Aus
4. HYV Aus / Jute followed by HYV Aman followed by wheat
5. HYV Aman followed by HYV Boro
6. HYV Aman followed by wheat
7. HYV Aman followed by potato
8. HYV Aman followed by rabi vegetables
9. HYV Aman followed by Maize
10. HYV Aman followed by pulses
11. Local variety Aman followed by wheat/potato/maize
12. Fruit trees

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

3.8 Irrigation System and Coverage

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

Table 3.1: Irrigation Equipment & Irrigated Area during 2005

<table>
<thead>
<tr>
<th>Upazilla Name</th>
<th>District name</th>
<th>Total Thana Area (km²)</th>
<th>Model Area (km²)</th>
<th>% of Model Area</th>
<th>Cultivable Area</th>
<th>No of DTW</th>
<th>Area of DTW</th>
<th>No of STW</th>
<th>Area of STW</th>
<th>Total Area of Irrigation</th>
<th>% of Irrigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patnitala</td>
<td>Naogaon</td>
<td>382</td>
<td>102.3</td>
<td>26.8</td>
<td>7291</td>
<td>124</td>
<td>2728</td>
<td>1987</td>
<td>3113</td>
<td>5841</td>
<td>73</td>
</tr>
<tr>
<td>Sapkhar</td>
<td>Naogaon</td>
<td>245</td>
<td>231</td>
<td>94.3</td>
<td>16058</td>
<td>162</td>
<td>3565</td>
<td>989</td>
<td>3644</td>
<td>7209</td>
<td>44</td>
</tr>
<tr>
<td>Porsha</td>
<td>Naogaon</td>
<td>253</td>
<td>227.9</td>
<td>90.1</td>
<td>14702</td>
<td>174</td>
<td>3828</td>
<td>1363</td>
<td>3832</td>
<td>7660</td>
<td>52</td>
</tr>
<tr>
<td>Gomostapur</td>
<td>Nawabganj</td>
<td>318</td>
<td>220.5</td>
<td>69.3</td>
<td>17961</td>
<td>200</td>
<td>4400</td>
<td>578</td>
<td>2126</td>
<td>6526</td>
<td>39</td>
</tr>
<tr>
<td>Niamatpur</td>
<td>Naogaon</td>
<td>449</td>
<td>368.4</td>
<td>82</td>
<td>25683</td>
<td>450</td>
<td>9900</td>
<td>3038</td>
<td>8514</td>
<td>18414</td>
<td>70</td>
</tr>
<tr>
<td>Nachole</td>
<td>Nawabganj</td>
<td>284</td>
<td>276.4</td>
<td>97.3</td>
<td>13557</td>
<td>350</td>
<td>8895</td>
<td>104</td>
<td>380</td>
<td>9275</td>
<td>68</td>
</tr>
<tr>
<td>Nawabganj</td>
<td>Nawabganj</td>
<td>452</td>
<td>81.6</td>
<td>18</td>
<td>5201</td>
<td>32</td>
<td>760</td>
<td>536</td>
<td>1886</td>
<td>2646</td>
<td>52</td>
</tr>
<tr>
<td>Tanore</td>
<td>Rajshahi</td>
<td>295</td>
<td>208.8</td>
<td>70.8</td>
<td>13758</td>
<td>365</td>
<td>8030</td>
<td>219</td>
<td>1031</td>
<td>9081</td>
<td>63</td>
</tr>
<tr>
<td>Godagari</td>
<td>Rajshahi</td>
<td>472</td>
<td>404.3</td>
<td>85.6</td>
<td>23807</td>
<td>550</td>
<td>11670</td>
<td>1758</td>
<td>5678</td>
<td>17349</td>
<td>66</td>
</tr>
</tbody>
</table>

The percentage of irrigation coverage was in the range of 39% to 73% of the net cultivated area. Total irrigated area was 83,980 ha out of net cultivated 138,018 ha the percentage of irrigation was 60.8.
CHAPTER 4
METHODOLOGY

4.1 General Approach

Modeling of any physical phenomenon is an iterative development of a process. Model refinements are based on the availability and quality of data, hydrological understanding and scopes of the project. The general approach that has been followed in the current study can be summarized in the flowchart given in Figure 4.1.

Figure 4.1: Flowchart of the General Methodology Applied in the Study
The study involves the development of two groundwater models using MIKE SHE and MODFLOW. At first MIKE SHE model is calibrated by adjusting parameters and finally validated for a certain data series. Recharge is estimated in the calibrated MIKE SHE model, and that recharge is used in MODFLOW model as input. In the present modeling study river flow is not included as there is no river in the study area. With the results of MIKE SHE model, assessment of groundwater resource and recharge potential has been made. Analysis has also been done to get simple relation between recharge and other time-variant parameters like rainfall, irrigation, etc.

4.2 Data Collection and Processing

According to the modeling requirements, a significant amount of data has been collected from the Institute of Water Modelling (IWM). The data used in this study was checked for quality and consistency and then processed in the required format of the model. In addition to the data quality checking, data analysis has also been carried out for estimation of different model parameters. For the model development using MIKE SHE and Visual MODFLOW, the following data were required:

- Rainfall and evaporation data for the entire study area
- Piezometer reading for groundwater level – to define the initial and boundary conditions and to compare model results with observations from each formation
- Lithological data along with top and bottom elevations of different formations
- Aquifer properties for horizontal and vertical hydraulic conductivities, specific yield and specific storage distributions for different formations
- Land use, soil type, and topographic data for the entire study area
- Groundwater abstraction data

4.2.1 Rainfall and Evaporation

There are eight BWDB rainfall stations (Table 4.1) that have influence in the study area. Data is collected on daily basis for 1997 to 2005. The annual rainfall of eight stations for the period is plotted in Figure 4.2 as a bar chart for comparison purpose.
The mean annual rainfall in the study area has come out around 1600 mm during the period 1997-2005. Missing data are filled up by taking average of the data of stations surrounding the station in question. It is assumed that the normal rainfalls of surrounding stations are within 10 to 12% of that concerned station (Subramanya, 1984). Quality checking of rainfall data includes visual inspection of plots, preparation of double mass curves, estimation of yearly mean values, and comparison of monthly values. An example plot of a double mass curve is given in Figure 4.3. More plots on rainfall data consistency checking are presented in Appendix-A. The analysis reveals that rainfall data are consistent for all the stations.

### Table 4.1: BWDB rainfall stations in the study area

<table>
<thead>
<tr>
<th>SL</th>
<th>Station ID</th>
<th>Station Name</th>
<th>Data Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>R 211</td>
<td>Shapahar</td>
<td>1997-2005</td>
</tr>
<tr>
<td>2</td>
<td>R 194</td>
<td>Nithpur</td>
<td>1997-2005</td>
</tr>
<tr>
<td>3</td>
<td>R 208</td>
<td>Rohanpur</td>
<td>1997-2005</td>
</tr>
<tr>
<td>4</td>
<td>R 190</td>
<td>Nachole</td>
<td>1997-2005</td>
</tr>
<tr>
<td>5</td>
<td>R 219</td>
<td>Tanore</td>
<td>1997-2005</td>
</tr>
<tr>
<td>6</td>
<td>R 195</td>
<td>Chapai Nawabganj</td>
<td>1997-2005</td>
</tr>
<tr>
<td>7</td>
<td>R 172</td>
<td>Godagari</td>
<td>1997-2005</td>
</tr>
<tr>
<td>8</td>
<td>R 205</td>
<td>Rajshahi</td>
<td>1997-2005</td>
</tr>
</tbody>
</table>
BWDB maintains only one evaporation station in the study area (Table 4.2). It has been seen that there is relatively little variation of evapotranspiration between the study area and outside the study area. It is due to the fact that important parameters such as temperature and sunshine hours are largely similar across the area. As such, data from this one station has been used for the whole study area. Pan coefficient of 0.7 has been used to calculate open water evaporation from pan evaporation data of the station. Evaporation values outside the range of 2.0-7.0 mm have been rejected. The mean annual evaporation in the study area is around 1059 mm for the period of 1997-2005.

### Table 4.2: Evaporation station in the study area

<table>
<thead>
<tr>
<th>SI</th>
<th>Station ID</th>
<th>Station name</th>
<th>Data availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>E44</td>
<td>Rajshahi</td>
<td>1997-2005</td>
</tr>
</tbody>
</table>

### 4.2.2 Groundwater Level

Groundwater observation level data is an important parameter to the groundwater model as it is used for calibration, boundary condition and initial condition of the model. There are 30 groundwater observation wells of BWDB and BMDA selected in the study area. Among them 19 observation wells are on the boundary (Figure 4.13) which have been used as boundary condition and 11 observation wells are inside the study area which have been used for calibration purpose (Figure 4.14). The frequency of measurement in the observation wells is generally once in a week. The measured groundwater levels are expressed in terms of a national datum,
mPWD. Data has been checked by visual inspection of those time series plots of groundwater levels as shown in Figure 4.4. Missing data is filled up by interpolation of nearby stations. However, topography, groundwater level fluctuation and rainfall pattern of those nearby stations are taken into consideration during filling the missing data.

Figure 4.4: Groundwater level plot from a piezometer at Rasulpur, Sapahar

4.2.3 Lithology

A general purpose subsurface lithology of the Barind area was prepared by IWM through analyzing sedimentary structure, its thickness and depth. A sub-set of this lithology has been taken for this model study. The depth of the lithology studied is around 80m. Considering lithological variation and groundwater flow capacity, 5 hydro-stratigraphic units of the study area have been defined as Clay Top, Upper Aquifer, Clay Middle, Lower Aquifer and Clay Bottom. It reveals from the analysis that within the study area Upper Aquifer and Lower Aquifer is interconnected. Clay Middle is not a continuous layer. As a result both the aquifers act as a composite aquifer in the study area. One geological cross-section of the formations at Northing 756,000 is shown in Figure 4.5. Other geological cross sections are shown in Appendix B.
4.2.4 Aquifer Properties

There are 9 sets of aquifer test data available from IWM in connection to Barind Integrated Development Project. IWM has applied different methods based on aquifer condition to their field data to estimate the values of hydraulic conductivity (K) and specific yield (Sₚ). It has been found that in High Barind area the specific yield mostly varies between 0.01 and 0.1. Hydraulic conductivity in most of the High Barind area is below 10 m/day although in some parts it varies between 10 m/day and 13 m/day. Low specific yield may cause excessive draw-down in tube wells. Spatial distribution map of specific yield and hydraulic conductivity based on those values are shown in Figures 4.6 and 4.7 respectively.
Figure 4.6: Distribution of specific yield data in the study area

Figure 4.7: Distribution of hydraulic conductivity data in the study area
4.2.5 Soil Properties

The physical properties of the soil including texture, permeability, and capillary pressure with water content relationships are required to calculate the vertical flow through unsaturated zone. Thana Land and Soil Resource User Manuals for all the upazilas of study area have been collected from the Soil Resource Development Institute (SRDI). Eight soil series have been identified to represent the study area. IWM and the Department of Geology and Mining of Rajshahi University carried out soil sample testing and analysis in 15 specified locations in the study area. In each location, both undisturbed and disturbed samples were collected at depths of 15, 50, 100 and 150/200 cm intervals. Most commonly occurring textures have been found as clay, silty clay, silty clay loam, silty loam and fine sand. The vertical distribution of soil in the study area is highly heterogeneous. Soil moisture retention curve and hydraulic conductivity curve for clayey soil is shown in Figures 4.10 and 4.11.

4.3 Model Setup

Model setup involves a geometrical description and specification of the hydrological system of the study area. The major components of MIKE SHE setup include evapotranspiration (ET), unsaturated zone (UZ), saturated zone (SZ), overland flow (OL) and river systems. MODFLOW does not cover ET, UZ and OL. In that case MODFLOW was simulated with the recharge data taken from calibrated MIKE SHE model. In the present study river system has not included as there is no river in study area.

Brief descriptions of the groundwater model setup are given below:

Model Domain and Grid Size

The study area has been discretized into grids of 500 by 500 m square cells as shown in Figure 4.8. The model has 186 rows and 85 columns and total of 8945 active cells in each layer. The grid cells are the basic units to provide all the spatial and temporal data as input and to obtain corresponding data as output. The geographic boundaries of the model domain are given in Bangladesh Transverse Mercator (BTM) coordinates as shown in Table 4.3.
The five geological layers define 5 computational layers as vertical discretization of the groundwater model. Special consideration is given to the unsaturated zone, where the vertical resolution can be as fine as 0.05m, 0.1m and 0.5m towards the increasing depths.

Table 4.3: Geographic limits of the study area

| Easting minimum | 326500 | Easting maximum | 369000 |
| Northing minimum | 696000 | Northing maximum | 789000 |

Figure 4.8: Discretization of the model domain

Topography
A well-prepared DEM is essential for visualizing the topography and for accurate modeling. A DEM of 300 m resolution developed by IWM has been used in the model as shown in Figure 3.2.
Precipitation
Rainfall data is needed as input to the MIKE SHE model. It is mentioned earlier that 8 rainfall stations are available in and around the study areas. To account for the spatial variation in rainfall, the time series data for each station has been assigned to Thiessen Polygon as shown in Figure 4.9.

![Figure 4.9: Thiessen polygons of rainfall stations in the study area](image-url)

Evapotranspiration
Time series of the potential evapotranspiration are given as input to the model. Evaporation data for only Rajshahi station (Station ID E44) has been used in the model for the period of 1997 to 2005.

Land Use
Land use and vegetation information are used in the MIKE SHE model to calculate actual evapotranspiration depending on the actual crops grown in the study area. The
actual evapotranspirations are estimated by MIKE SHE on the basis of potential evapotranspiration rates, the root depths and leaf area indices of different crops over the seasons. The major part of the study area is agricultural land. It has homestead, pond and forest also. Under the present study, spatial distribution of crops has been collected from IWM. A crop database which defines leaf area index, root depth and other properties of each crop developed by IWM is used in this model.

**Overland Flow**

It is applicable only for MIKE SHE model. When the net rainfall rate exceeds the infiltration capacity of the soil, water gets ponded over the ground surface. This water is then routed down-gradient towards the river system, called as surface runoff. The study area is dominated by agricultural land and the main crops are different varieties of paddy. In the study area, there are some small channels exist. Considering the fact, detention storage is taken 0.05 m for the initiation of the runoff flows. Since the area is dominantly agricultural land, a constant value can be considered for the entire area. However, it can be changed through the process of calibration of the model. The value of Manning number (M) that has been considered in the present study is 10.

**Unsaturated Zone**

It is also only applicable for MIKE SHE model. The unsaturated zone (UZ) extends from the ground surface to the groundwater table. The Governing Equation (Richards equation) for the unsaturated flow requires information about two hydraulic functions: The soil moisture retention curve $\psi(\theta)$ (Figure 4.10) and the hydraulic conductivity function, $K(\theta)$ (Figure 4.11) are important for characterizing the individual soil profiles of the study area.

This information, along with the following parameters, is stored in the soil property database:

- soil moisture at saturation ($\theta_s$) [-]
- soil moisture at effective saturation ($\theta_{eff}$) [-]
- capillary pressure at field capacity ($p^F_{fc}$)
- capillary pressure at wilting point ($p^F_w$)
- residual soil moisture content ($\theta_r$) [-]
- saturated hydraulic conductivity ($K_s$)

pF is defined as $\log_{10}(-100\psi)$ where $\psi$ is the matric potential. Notice that $\psi$ is always negative under unsaturated conditions.

The soil moisture at effective saturation $\theta_{eff}$ is the maximum achievable soil moisture content.

The relationship between the water content, $\theta$ and the matric potential, $\psi$ is known as the soil moisture retention curve, which is basically defined by the texture and structure of the soil. The amount and type of organic material may also have an influence on the relationship. Characteristically, the pressure head decreases rapidly as the moisture content decreases. Hysteresis is also common. Typically, the soil moisture curve is measured in a laboratory or assumed based on typical values for similar soils. If laboratory data is available, the measured $\theta$-$\psi$ values can be input directly into MIKE SHE as tabular data. Intermediate values are then calculated by MIKE SHE, using a cubic spline method, and stored internally in the code. Alternatively, the measured values can be fitted to commonly used functional relationships. The appropriate function parameters can be input directly or more refined tabular data may be generated externally to MIKE SHE (e.g. in MS Excel) and input as tabular data.

<table>
<thead>
<tr>
<th>Pf</th>
<th>0.00</th>
<th>0.50</th>
<th>1.00</th>
<th>1.50</th>
<th>2.00</th>
<th>2.50</th>
<th>3.00</th>
<th>3.50</th>
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<td>0.53</td>
<td>0.52</td>
<td>0.51</td>
<td>0.50</td>
<td>0.45</td>
<td>0.40</td>
<td>0.36</td>
<td>0.34</td>
<td>0.32</td>
</tr>
</tbody>
</table>

Figure 4.10: Soil suction vs moisture content relationship of clayey soil in the study area
The hydraulic conductivity decreases strongly as the moisture content $\theta$ decreases from saturation. This is not surprising since the total cross-sectional area for the flow decreases as the pores are getting filled with air. The experimental procedure for measuring the $K(\theta)$ function is rather difficult and not very reliable. Alternatively procedures have been suggested to derive the function from more easily measurable characterizing properties of the soil or simply to rely on empirical relationships.

![Image of hydraulic conductivity vs moisture content relationship of clayey soil in the study area](image)

**Figure 4.11: Hydraulic conductivity vs moisture content relationship of clayey soil in the study area**

**Saturated Zone**

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

**Geology and Hydrogeology:** In the present study, sub-surface geology of the study area has been defined by five hydro-stratigraphic layers as: Clay Top, Upper Aquifer, Clay Middle, Lower Aquifer and Clay Bottom. Base elevations of these layers are used in the model to define the computational formations. Lower aquifer is the main aquifer. The hydraulic properties obtained from aquifer tests, carried out by IWM and BWDB, are used in the model study. Initially to start the model the
vertical hydraulic conductivity was considered as half of horizontal hydraulic conductivity. During calibration it has been changed accordingly.

**Initial Condition:** Potential head of groundwater has been specified as initial condition in the model. Potential heads of the monitoring wells are used to generate initial condition contour map (Figure 4.12) and is taken applicable for all the computational layers alike.

**Boundary Condition:** Every model requires an appropriate set of boundary conditions to represent the system's relationship with the surrounding environment. In the case of a groundwater flow model, boundary conditions will describe the exchange of flow between the model and the external system. A total of 19 monitoring wells of BWDB and BMDA are available along the boundary line (Figure 4.13). Using the observed groundwater a time series head boundary file has been prepared along the boundary. All the layers are assumed leaky in nature and thus interconnected. Therefore the same boundary condition is applicable for all the computational layers.

![Figure 4.12: Initial potential heads of the model](image)
Abstraction Data: Information on cropping pattern and crop coverage is needed to estimate water requirement and thus abstraction obtained. Abstraction data was not available for the study area. To overcome this limitation, water abstractions for 1997 to 2005 have been estimated. The main assumption behind this estimation was that the irrigation coverage and water requirement is directly proportional to the rate of irrigation abstraction. The total abstractions by the DTWs and STWs for different cropping seasons (Rabi, Kharif-I and Kharif-II) have been estimated based on the seasonal irrigation water requirement. Number of DTWs & STWs, their area coverage, their running hour and total water requirement were required to calculate abstraction. Yearly number of DTWs & STWs and their area coverage was collected from Minor Irrigation Survey Report. Running hours of tubewells were assumed taking some consideration. Crop water requirement was calculated by CROPWAT.
4.4 MIKE SHE Model Calibration

Model calibration is an iterative process through which simulated results (e.g., heads) are matched with the measured head values by adjusting aquifer parameters, boundary conditions, and stresses within plausible ranges. This process is complicated by the number of input parameters need to be adjusted, the number of variables available for calibration targets, and the possibility of achieving non-unique model solutions. The goal of this calibration procedure is to minimize differences between the observed data and simulated values. Usually, the model is considered calibrated when it reproduces historical data within some acceptable level of accuracy (Delleur, 1999).

The first step in model calibration is the identification of the calibration targets. The second step consists of determining the acceptable range of errors between simulated and measured calibration targets. At the third step, trial and error and inverse simulations are performed until simulated parameters are within the acceptable range of errors.

The model consists of five layers, each one represented by 8495 active cells. This equates to a possible 5×8495 input variables that can be altered to achieve the calibration target. The calibration was based on the comparison between the calculated and observed head on original observation well data rather than interpolated values because of the uncertainty involved in the interpolation process. A set of 11 observation wells was selected for calibration matching.

As mentioned above, the purpose of the model calibration is to achieve an acceptable agreement with measured data by adjusting the input parameters within acceptable ranges. Due to the huge number of input data, the parameters are also numerous. During the calibration it is therefore important to adjust the parameters within acceptable ranges determined from field measurements, and also to minimize the number of adjustment parameters. In this study, the initial input parameters have been obtained from secondary sources. The calibration has been done against groundwater levels for 1997 to 2003.
The High Barind area is very different from other areas of Bangladesh as the groundwater flow and available water resources to a large extent are controlled by the ridge and deep incised channels at the periphery. It also contains relatively thick impermeable clay layer and limited aquifer extent in the area. Hence, the geological delineation is one of the major components in the setting of the model. During calibration overland leakage co-efficient, soil properties, vertical hydraulic conductivity and storage coefficient have been adjusted. The distribution of calibration and validation points in the model area is shown in Figure 4.14. A list of those 15 observation wells of BWDB and BMDA inside the study area which have been used for the calibration purpose is given in Table 4.4.

Table 4.4: List of calibration piezometers in the study area

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Old ID</th>
<th>New ID</th>
<th>X</th>
<th>Y</th>
<th>Thana</th>
<th>District</th>
</tr>
</thead>
<tbody>
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<td>1</td>
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<td>Nia_BW32</td>
<td>354824</td>
<td>752133.5</td>
<td>Niamatpur</td>
<td>Naogaon</td>
</tr>
<tr>
<td>2</td>
<td>GT6486051</td>
<td>Sap_BW51</td>
<td>356091.2</td>
<td>776487.8</td>
<td>Sapahar</td>
<td>Naogaon</td>
</tr>
<tr>
<td>3</td>
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<td>Por_BW46</td>
<td>352958</td>
<td>766552</td>
<td>Porsha</td>
<td>Naogaon</td>
</tr>
<tr>
<td>4</td>
<td>GT7056007</td>
<td>Nac_BW07</td>
<td>336415.3</td>
<td>733509.7</td>
<td>Nachole</td>
<td>Nawabganj</td>
</tr>
<tr>
<td>5</td>
<td>GT7056009</td>
<td>Nac_BW09</td>
<td>337544.3</td>
<td>743465.5</td>
<td>Nachole</td>
<td>Nawabganj</td>
</tr>
<tr>
<td>6</td>
<td>GT7066012</td>
<td>Naw_BW12</td>
<td>338322.5</td>
<td>723518.4</td>
<td>Nawabganj</td>
<td>Nawabganj</td>
</tr>
<tr>
<td>7</td>
<td>GT8134016</td>
<td>God_BW16</td>
<td>339283.7</td>
<td>719076.6</td>
<td>Godagari</td>
<td>Rajshahi</td>
</tr>
<tr>
<td>8</td>
<td>GT8194047</td>
<td>Tan_BW47</td>
<td>352496.2</td>
<td>723360.6</td>
<td>Tanore</td>
<td>Rajshahi</td>
</tr>
<tr>
<td>9</td>
<td>BM09</td>
<td>Nac_BM09</td>
<td>342963.9</td>
<td>739034.9</td>
<td>Nachole</td>
<td>Nawabganj</td>
</tr>
<tr>
<td>10</td>
<td>BM10</td>
<td>Nac_BM10</td>
<td>343624.2</td>
<td>729475.9</td>
<td>Nachole</td>
<td>Nawabganj</td>
</tr>
<tr>
<td>11</td>
<td>BM12</td>
<td>God_BM12</td>
<td>333734.1</td>
<td>705052.7</td>
<td>Godagari</td>
<td>Rajshahi</td>
</tr>
<tr>
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<td>God_BM11</td>
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</tr>
<tr>
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<td>Nia_BM32</td>
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<td>Niamatpur</td>
<td>Naogaon</td>
</tr>
<tr>
<td>14</td>
<td>BM33</td>
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<td>764231</td>
<td>Porsha</td>
<td>Naogaon</td>
</tr>
<tr>
<td>15</td>
<td>BM34</td>
<td>Por_BM34</td>
<td>345572.3</td>
<td>768066.9</td>
<td>Porsha</td>
<td>Naogaon</td>
</tr>
</tbody>
</table>

Some representative calibration plots of the model are shown in Figures 4.15 to 4.17. All the calibration and validation plots by MIKE SHE are given in Appendix-C.
Figure 4.14: Distribution of calibration points in the study area

Figure 4.15: Calibration plot of groundwater level of Nia_BM32 at Niamatpur
In general, the overall calibration of the model is acceptable, but there is scope for further improvement. Some of the reasons of deviation between observed and simulated groundwater levels have been identified as:

i) as the exact field abstraction data were not available, there were uncertainty in calculating crop water requirement and irrigation demand, as such, the estimation for irrigation water abstraction might not be accurate enough;

ii) even distribution of irrigation water extraction has given overestimation of drawdown in areas with low density of irrigation tube well, and underestimation of drawdown in areas with high density of irrigation tube well;

iii) the geological structure of the High Barind area is more complex than assumed and it is challenging to obtain a good match between observed and
simulated values with large grid size, as many local features may be missed on the structure.

4.5 MIKE SHE Model Validation

To check whether the calibrated model is an adequate representation of the physical system or not, validation is carried out on the calibrated model. The common test for validation was to run the calibrated model in predictive mode to check whether the prediction reasonably matches the observation of a reserved data set, deliberately excluded from calibration data set. In the present study the MIKE SHE model has been validated against groundwater level by two ways. The GWL of above 13 wells of BWDB and BMDA have been validated for the period 2004-2005. Again the model is validated against GWL by new installed observation wells of IWM. The location of IWM’s observation wells is given in Figure 4.18. Two representative plots of validation have been shown in Figures 4.19 and 4.20. The rest of the plots are given in Appendix-C.

Table 4.5: List of IWM Wells Used in the Validation Purpose

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Well ID</th>
<th>New ID</th>
<th>X</th>
<th>Y</th>
<th>Thana</th>
<th>District</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>GD-02</td>
<td>God_IW02</td>
<td>334750.8</td>
<td>713600.6</td>
<td>Godagari</td>
<td>Rajshahi</td>
</tr>
<tr>
<td>2</td>
<td>TN-01</td>
<td>Tan_IW01</td>
<td>346543.3</td>
<td>721686.8</td>
<td>Tanore</td>
<td>Rajshahi</td>
</tr>
<tr>
<td>3</td>
<td>PR-01</td>
<td>Por_IW01</td>
<td>348218.1</td>
<td>759324.6</td>
<td>Porsha</td>
<td>Naogaon</td>
</tr>
<tr>
<td>4</td>
<td>NM-01</td>
<td>Nia_IW01</td>
<td>346738.9</td>
<td>744667.8</td>
<td>Niamatpur</td>
<td>Naogaon</td>
</tr>
<tr>
<td>5</td>
<td>SP-01</td>
<td>Sap_IW01</td>
<td>347272.8</td>
<td>775454.2</td>
<td>Sapahar</td>
<td>Naogaon</td>
</tr>
<tr>
<td>6</td>
<td>GM-02</td>
<td>Gom_IW02</td>
<td>337212.9</td>
<td>757688</td>
<td>Gomastapur</td>
<td>Nawabganj</td>
</tr>
</tbody>
</table>
Figure 4.18: Location of IWM Wells used for Validation Purpose

Figure 4.19: Validation Plot of GWL for the Piezometer at Por_BM33 at Porsha

Figure 4.20: Validation Plot of GWL for the Piezometer of IWM at Sapahar-49
Overall, validation results show similar trend of groundwater fluctuation and quite good matching of groundwater levels between observed and simulated values. From the results of the model validation, it could be concluded that the parameters used in the calibrated model are acceptable. Hence, the model can be used for prediction purposes.

4.6 MODFLOW Model Simulation

In this study the groundwater model using MIKE SHE has been calibrated and validated against groundwater level of 1997-2003 and 2004-2005 respectively. During development of model using MODFLOW, recharge data which is the main calibration parameter of MODFLOW, is directly taken from calibrated MIKE SHE model to use as model input. All the other common parameters have remained unchanged. The model was run for the period 1997-2003. As the parameters are once calibrated during development of MIKE SHE, and those calibrated parameters are used in MODFLOW, no calibration is done on MODFLOW model. Simulated groundwater levels by MODFLOW are plotted and compared with observed data. Some representative plots are shown in Figures 4.20 and 4.21. All the plots of simulation by MODFLOW are given in Appendix-D. From the groundwater level hydrograph simulated by MODFLOW it is worth to mention that the results of two models have good match though there is also some variation which is quite normal and it is in acceptable range.

Figure 4.21: Comparison plot of groundwater level hydrograph of Nac_BM10 at Nachole
4.7 Assessment of Groundwater Resources

Groundwater resource of the study area has been assessed based on recharge characteristics, potential recharge and safe yield criteria.

4.7.1 Recharge Characteristics

Recharge means the replenishment of groundwater storage that is depleted by withdrawal through artificial and natural processes. The sources of groundwater replenishment of the study area are deep percolation of rainwater and irrigated water from crop fields, seepage from the channels, khals, ponds and other water bodies. Recharge to groundwater depends on different physical and climatic conditions as well as hydraulic properties related to soil, and aquifer. 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 end of March.

The aquifers become full in the months of August/September but excess rainfalls 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 stored within the bund that surrounds the paddy field. This water is available for recharging the groundwater after meeting the demand of evapotranspiration. The long-term average annual replenishment of groundwater may be considered as safe yield. Groundwater storage reduces due to withdrawal for irrigation, domestic and industrial 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 also attributes to depletion of groundwater storage.

4.7.2 Potential Recharge

Potential recharge is the actual recharge plus rejected recharge. The main source of groundwater is rainfall in the study-area. In the study area, generally recharge to groundwater starts from the 3rd decade of April and continues till the end of October when aquifer becomes full in average hydrologic condition. During October there is still some rainfall, which goes 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. This water is termed as rejected recharge. This rejected recharge can be included to the actual recharge to estimate the potential recharge. The potential recharge can be estimated as: \[ V_p = K_v \times t, \] where \( V_p \) is the potential recharge volume (mm), \( K_v \) is the deep percolation rate (mm/day) and \( t \) is the time of recharge in days. The time \( t \) is considered from the start date of recharge (May) till the end of October when rainfall virtually ceases.

To evaluate the potential recharge, MIKE SHE was applied for the hydrological situation of monsoon 2001. It has been considered that 2001 is an average year. The intention was to simulate a situation with a storage that maintains a representative situation for estimation of potential recharge. This has been done by starting the simulation with an artificially low groundwater level to ascertain that all the available recharge from rainfall will enter the saturated zone where soil properties are the only controlling factor against recharge. This low groundwater table has been determined from long-term groundwater level hydrographs in such a way so that groundwater returns to its original position at the end of the monsoon.
Upazila-wise potential recharge has been estimated from the model results for monsoon 2001. The 30th April is the end of irrigation period when the lowest water table generally occurs, after that water table starts rising due to recharge to groundwater from rainfall. The components that influence the groundwater storage after 30th April are mainly rainfall, overland flow, overland storage, drain to river, evapotranspiration, boundary inflow and outflow. Potential recharge has been estimated by subtracting the components of evapotranspiration, overland flow, overland storage, drain to river and net outflow (inflow ~ outflow) from the net rainfall.

4.7.3 Safe Yield Criteria
Upazila-wise groundwater resources have been assessed based on safe yield criteria so that the aquifers would be replenished periodically. Safe yield is defined as the amount of water extracted from the aquifer without producing any undesirable results. Because of the limited scope of surface water development, groundwater is being used for abstracting irrigation water by DTWs and STWs. HTWs are being used for drinking water supply. As HTWs and STWs operate under suction-mode, these become inoperable when depth to groundwater table goes below suction limit, i.e., 7m from ground surface. However, from the existing observed groundwater level hydrographs and the model results, it is found that in most of the areas groundwater level has declined more than 7m during irrigation period. In that case, HTW needs to be replaced by Tara pump or any suitable technology to ensure drinking water supply in the places where groundwater level goes beyond 7m. Considering the fact, 7m depth to groundwater table has been considered as safe yield limit to ensure drinking and irrigation water through HTW and STW with full operational efficiency.

4.7.4 Groundwater Resource Assessment
In general, dry period crops, HYV Boro in particular requires maximum amount of irrigation from groundwater source because during this period practically there is almost no rainfall. Dry season irrigation starts in the 1st decade of January. As such available groundwater resources in the 1st decade of January would determine areas
that can be brought under irrigation. Considering this, 1st January has been chosen for the assessment of groundwater resources. The values of specific yield of the saturated thickness of the corresponding layers have been taken from the calibrated model. Considering these facts, maximum depths of groundwater level have been determined from long-term groundwater level hydrographs in such a way so that it returns to its original position at the end of monsoon.

To estimate groundwater resource, the availability of groundwater within the allowable depths are estimated based on available saturated thickness up to these depths multiplied by specific yield of the area

\[ V_w = A \times \Delta h \times S_y \]

Where \( V_w \) is the volume of water, \( \Delta h \) is the saturated thickness within allowable depths and \( S_y \) is the specific yield of the aquifer. The saturated thickness as used in the groundwater resources assessment is defined as the depth from the groundwater table on 1st January to the allowable maximum depth from the ground surface. The values of specific yield of the saturated thickness of the corresponding layers have been taken from the calibrated model.

In order to estimate model grid wise ground water availability, saturated thickness within allowable maximum depths are determined simply by subtracting depth to groundwater table on 1st January from corresponding allowable maximum depth. 90% of available resources have been taken as usable resources as there are some natural losses during irrigation period.
CHAPTER 5
RESULTS AND DISCUSSIONS

Ground-water models attempt to simulate the behavior of a ground-water system using a mathematical counterpart. Models typically are used to evaluate changes to the water budget of an aquifer caused by pumping, land-use changes, and climate, and how these changes affect ground-water storage, streamflow, lake levels, and other environmental variables.

Reliable assessment of groundwater resource is essential for effective irrigation management and protection of environment. Accordingly, groundwater resource of the study area has been assessed based on recharge and water budget simulation for the period 1997-2003 using two mathematical model: MIKE SHE and MODFLOW. Results of those two simulations are analyzed, presented and compared in the following sections.

5.1 Comparison of Simulated Hydrographs using MIKE SHE and MODFLOW

The main difference between two models is; MIKE SHE includes the unsaturated zone, so it calculates infiltration, actual evapotranspiration and recharge from physical laws; on the other hand MODFLOW deals with saturated zone only. The calculation of unsaturated zone has to do separately. In this study recharge data taken from MIKE SHE has been used for MODFLOW.

In this study, GWL is simulated using MIKE SHE first, then taking the recharge from calibrated MIKE SHE model, MODFLOW model is developed and simulated GWL from MODFLOW is found. However some comparison plots of simulated hydrographs using MIKE SHE and MODFLOW are given in the figures below (Figure 5.1 to Figure 5.5).
Figure 5.1: Comparison of two model results at Nia_BW32 at Niamatpur

Figure 5.2: Comparison of two model results at Nac_BM10 at Nachole
Figure 5.3: Comparison of two model results at Por_BM34 at Porsha

Figure 5.4: Comparison of two model results at Nia_BM32 at Niamatpur
Figure 5.5: Comparison of two model results at Nac_BW07 at Nachole

From the above figures the following finding have arisen

- Simulated GWL from two models have quite a good match with observed data and each other also

- In some cases MIKE SHE model has initialization problem (Figure 5.3, 5.5), but MODFLOW did not face that problem as MODFLOW has already been started with calibrated parameters

- Hydrographs of groundwater tables show that the maximum and minimum depth to groundwater table occurs at the end of April and at the end of September respectively

- Some of the wells show variation at peaks of two simulated GWL hydrographs. For example in Figure 5.5 overestimated of peak in MODFLOW represents MIKE SHE provides higher recharge in that place. On the other hand in figure 5.4 underestimated of peak represents MIKE SHE provides lower recharge in that place.

- Over estimation of drawdown during the dry period is also present in groundwater level hydrograph (Figure 5.5)
5.2 Outputs from MIKE SHE Model Simulation

5.2.1 Water Balance Components

Water balance includes the hydrological components come as inflow to or outflow from the system. The difference between inflow and outflow is the net storage change within the system. Recharge to groundwater depends on different physical, climatic and hydraulic properties related to soil and aquifers. Water balance components of Nawabganj Upazila for the period of January 7, 1997 to January 2, 1998 are graphically shown in Figure 5.6 while the same data in tabular form are given in Table 5.1.

Figure 5.6: Water Balance Components of Nawabganj Upazila: January 7, 1997 to January 2, 1998
### Table 5.1: Water Balance Components for Nawabganj Upazila for January 7, 1997 to January 2, 1998

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Components</th>
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<th>Saturated Zone (SZ)</th>
<th>GW Recharge/Discharge</th>
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</thead>
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<td>Outflow (mm)</td>
<td>Inflow (mm)</td>
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<td>Irrigation</td>
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<td>5</td>
<td>Capillary rise &amp; ET from SZ to UZ</td>
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<tr>
<td>6</td>
<td>Deep percolation to SZ</td>
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<td>Boundary Flow</td>
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<td>11</td>
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<tr>
<td></td>
<td><strong>Total</strong></td>
<td><strong>2352</strong></td>
<td><strong>1835</strong></td>
<td><strong>704</strong></td>
</tr>
</tbody>
</table>

#### Net Balance = Inflow-outflow

<table>
<thead>
<tr>
<th>Explanation:</th>
<th>Inflow/Outflow of SZ</th>
<th>Change in storage</th>
<th>Net recharge/discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>517</td>
<td>-8</td>
<td>553</td>
</tr>
</tbody>
</table>

**Percentage of ET to applied water (rainfall+irrigation) = 53%**

**Percentage of net recharge to applied water = 30%**

**Percentage of other components to applied water = 70%**

It appears from the Table 5.1 that in unsaturated zone (UZ) 2352mm water enters into the system mainly from rainfall and irrigation while 1835mm water goes out from UZ mainly as evapotranspiration (ET) and outflow through boundary. The amount of ET is 53% of rainfall and irrigation application. The net flow, 509mm from the UZ enters into the SZ. In addition, another 195mm enters into SZ making total inflow 704mm while 712mm goes out from SZ resulting in a negative change of storage of 8mm.

### 5.2.2 Actual Recharge

Recharge means the replenishment of groundwater storage that is depleted by withdrawal of groundwater with the 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 and seepage from the channels. Under this study upazila-wise actual recharge has been estimated from model. Using the values of the components obtained from model run, as shown in Figure 5.6, actual recharge of Nawabganj Upazila for the year 1997 has been estimated above which is 553 mm. For the estimation of actual recharge of all other Upazilas the water balance components for for the period 1997 to 2003 have been extracted from model output. Few of those water balance components are given in Appendix-E. The annual actual recharges of all upazilas for the period 1997 to 2003 are given in Table 5.2.

Table 5.2: Upazila-wise Annual Actual Recharges

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Patnitala</td>
<td>411</td>
<td>480</td>
<td>439</td>
<td>491</td>
<td>495</td>
<td>498</td>
<td>492</td>
</tr>
<tr>
<td>2</td>
<td>Sapahar</td>
<td>300</td>
<td>288</td>
<td>209</td>
<td>284</td>
<td>290</td>
<td>305</td>
<td>298</td>
</tr>
<tr>
<td>3</td>
<td>Porsha</td>
<td>311</td>
<td>365</td>
<td>279</td>
<td>375</td>
<td>392</td>
<td>395</td>
<td>386</td>
</tr>
<tr>
<td>4</td>
<td>Gomastapur</td>
<td>336</td>
<td>408</td>
<td>359</td>
<td>316</td>
<td>324</td>
<td>335</td>
<td>315</td>
</tr>
<tr>
<td>5</td>
<td>Niamatpur</td>
<td>387</td>
<td>445</td>
<td>431</td>
<td>422</td>
<td>447</td>
<td>448</td>
<td>445</td>
</tr>
<tr>
<td>6</td>
<td>Nachole</td>
<td>389</td>
<td>431</td>
<td>432</td>
<td>427</td>
<td>460</td>
<td>490</td>
<td>457</td>
</tr>
<tr>
<td>7</td>
<td>Nawabganj</td>
<td>553</td>
<td>598</td>
<td>619</td>
<td>588</td>
<td>592</td>
<td>601</td>
<td>533</td>
</tr>
<tr>
<td>8</td>
<td>Tanore</td>
<td>437</td>
<td>372</td>
<td>352</td>
<td>382</td>
<td>420</td>
<td>429</td>
<td>383</td>
</tr>
<tr>
<td>9</td>
<td>Godagari</td>
<td>387</td>
<td>469</td>
<td>460</td>
<td>471</td>
<td>520</td>
<td>538</td>
<td>462</td>
</tr>
</tbody>
</table>

5.2.3 Potential Recharge and Usable Recharge

Under the present study, Upazila-wise potential recharge has been estimated from model result simulated for the monsoon period of 2001 which has been considered as an average year rainfall event. For the study area, potential recharge has been estimated considering water balance from May 2001 to October 2001 as water table attains the highest elevation in October. The components that influence the groundwater storage after 30th April are mainly rainfall, runoff, overland flow, overland storage, drain to river, evapotranspiration, boundary inflow and outflow. Potential recharge has been estimated by subtracting the components of evapotranspiration, overland flow, overland storage, drain to river and net outflow.
(inflow ~ outflow) from rainfall. Using the values of the components obtained from model run as shown in Figure 5.7, potential recharge for the Upazila Nawabganj has been estimated as an example:

$$\text{Potential Recharge} = 1268 \text{ mm (for precipitation) } - 8 \text{ mm (for overland flow) } - 334 \text{ mm (evapotranspiration) } - 216 \text{ mm (for outflow) } + 196 \text{ mm (for inflow) } - 118 \text{ mm (for overland storage) } - 167 \text{ mm (for unsaturated storage) } = 621 \text{ mm.}$$

The potential recharge of the study area varies from 395 mm in Porsha Upazila to 621 mm in Nawabganj Upazila.

According to the MPO and NWMP guideline, 75% of potential recharge has been taken as usable recharge for development consideration. It is due to the fact that various uncertainties are inherent in different assumptions for the estimation of potential recharge.
5.3 Available Groundwater Resources before Irrigation Period

Upazila-wise available groundwater resources have been assessed based on safe yield criteria so that groundwater table would replenish the aquifer periodically. In order to estimate model grid-wise groundwater availability, saturated thickness within allowable maximum depths are determined simply by subtracting depth to groundwater table on 1st January from corresponding allowable maximum depth which is 7 m in this study taking some considerations. Ninety percent of available resources have been taken as usable resources as there are some natural losses during irrigation period. Upazila-wise estimation of groundwater availabilities considering allowable maximum depths is given in Table 5.4.

Table 5.4: Upazila Wise Available Groundwater Resources on 1st January

<table>
<thead>
<tr>
<th>Upazila</th>
<th>Model Area (km²)</th>
<th>Available Resource (mm)</th>
<th>Usable Resource (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patnitala</td>
<td>102.3</td>
<td>331</td>
<td>298</td>
</tr>
<tr>
<td>Sapahar</td>
<td>231.0</td>
<td>510</td>
<td>459</td>
</tr>
<tr>
<td>Porsha</td>
<td>227.9</td>
<td>335</td>
<td>302</td>
</tr>
<tr>
<td>Gomastapur</td>
<td>220.5</td>
<td>189</td>
<td>170</td>
</tr>
<tr>
<td>Niamatpur</td>
<td>368.4</td>
<td>236</td>
<td>212</td>
</tr>
<tr>
<td>Nachole</td>
<td>276.4</td>
<td>405</td>
<td>365</td>
</tr>
<tr>
<td>Nawabganj</td>
<td>81.6</td>
<td>913</td>
<td>822</td>
</tr>
<tr>
<td>Tanore</td>
<td>208.8</td>
<td>180</td>
<td>162</td>
</tr>
<tr>
<td>Godagari</td>
<td>404.3</td>
<td>231</td>
<td>208</td>
</tr>
</tbody>
</table>
5.4 Hydrograph Analysis

Hydrographs of simulated groundwater tables at some pre-selected locations, show that the maximum and minimum depths to groundwater tables occur at the end of April and end of September, respectively. Hydrographs of observed groundwater tables also support the above findings. Based on these findings spatial distribution maps of minimum depths to groundwater tables were prepared for 30.09.2001 and 30.09.2002 to see whether groundwater tables of 2002 attain the previous positions occupied in 2001 as a whole fulfilling water requirement of the period elapsed (Figure 5.8 and Figure 5.9).

![Figure 5.8: Depth to Groundwater Table on 30th September 2001](image-url)
It is observed from the Figures 5.8 and 5.9 that at the end of September the GWL remains very near to surface in most of the area. However depth to phreatic surface varies from surface to 18m and in few places it goes upto 29m. The negative sign represents downward direction as the depth to phreatic surface measured from surface to GWL. The mean value of depth to phreatic surface on 2001 is 6.7m and on 2002 this value is 5.6m. So it can conclude that during the time of the monsoon, groundwater table almost recovers to the original positions.

Figure 5.9: Depth to Groundwater Table on 30th September 2002
5.5 Maximum Depth to Phreatic Surface

Figure 5.10: Maximum Depth to Groundwater Table on 1st May 2002

The spatial distribution map of maximum depths to groundwater tables was prepared for 1.05.2002 to see the effect of water abstracted up to 30th April (Figure 5.10). The 30th April is the end of irrigation period when the lowest water table generally occurs, after that water table starts rising due to recharge to groundwater from rainfall. It can be seen from the map that in most of the areas maximum depths to groundwater table remain in the range between 5m to 17m to a maximum depth of 29m. So in most of the areas groundwater table is below suction limit.
To understand the scenario clearly another map is shown in Figure 5.11 on which the red color represents the depth to GWL from ground surface is more than 7m on 30 April 2001 and at blue colored area depth to phreatic surface is less than 7m. So it is apparent from the figure that major part of the study area goes under suction limit on 30th April. In that case STWs will be inoperable in those area and only DTWs will work. At rest of the area both STWs and DTWs will be in operable condition.

Figure 5.11: Depth to Phreatic Surface on 30th April 2001
5.6  Groundwater Velocity

From the MODFLOW model, it is found that in the study area maximum velocity of groundwater flow is 0.017 m/d which occurs on September to October whereas minimum velocity of groundwater flow is 0.0012 m/d which occurs on March to April which is shown in Figure 5.12.

From the following figures it is clear that, the direction of groundwater flow is towards the boundary of the study area. During dry period over drainage of groundwater from the study areas to the surrounding lower area is occurred as groundwater level is substantially higher than the surrounding area. Due to terrain, boundary outflow has occurred in wet period also.

Figure 5.12: Groundwater Flow Velocity Contours, a) Maximum Velocity in October and b) Minimum Velocity in April
5.7 **Relation between Recharge and other Parameters**

From the calibrated model, values of recharge and other components like rainfall, irrigation and evapotranspiration have been extracted and relations have been developed between recharge and those other components.

5.7.1 **Recharge versus Rainfall**

For every Upazila the plot of cumulative recharge versus cumulative rainfall for every year has been drawn. A representative plot of Patnitala for the period January 1998 to December 1998 is shown in Figure 5.13. It shows an exponential relation exists between recharge and rainfall. With the increment of rainfall, recharge is increasing but the rate is slow at initial stage and the rate is comparatively high later.

![Figure 5.13: Cumulative Recharge versus Cumulative Rainfall of Patnitala Upazilla for 1998](image)
5.7.2 Recharge versus Irrigation

Figure 5.14 shows the plot of cumulative recharge versus cumulative irrigation for January 1998 to December 1998 for Patnitala Upazila. The regression type is moving average type. The graph shows that during dry period significant amount of irrigation is present, but the response of recharge is very negligible. But during monsoon recharge is increasing significantly. However, the rates become slower after October. From this analysis, it is worth to be mention that groundwater recharge occurred mostly by rainfall during monsoon. The contribution of irrigation for recharge is very minimum comparative to rainfall.

Figure 5.14: Cumulative Recharge versus Cumulative Irrigation of Patnitala Upazilla for 1998
CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

The main objectives for the present study were to apply MIKE SHE and MODFLOW models for the High Barind area using existing hydro-geological and meteorological data to compare their results, assess groundwater resources and recharge potential from MIKE SHE results and to make relationship between recharge and other time variant meteorological parameters.

6.1 Conclusions

The main conclusions drawn from this study are as follows:

- From model result it is apparent that if recharge is calculated properly from other source, then MODFLOW will give good result. So in the case of groundwater flow study where irrigation is not present, MODFLOW can be used. Otherwise MIKE SHE will be more appropriate.

- The recharge due to rain starts in May and continues up to the end of October. However, recharge characteristics and flow exchange varies from year to year depending on rainfall. The study shows that the average actual recharge of the groundwater is 426mm per year (average of 1997 to 2003) in the study area, varying from 209mm (in Sapahar Upazila) to 619mm (in Nawabganj Sadar Upazila).

- Maximum depth to groundwater table occurs at the end of April mainly due to irrigation extraction and natural drainage. In average year rainfall condition, this maximum depth to groundwater table remains in the range between 2m to 29m. Suction mode tube wells do not operate in most of the areas as groundwater table is normally below 7m from ground surface.

- The groundwater potential in the study area is influenced by rainfall, evapotranspiration, percolation capacity, boundary flow and irrigation abstraction.

- Analysis reveals that the response of recharge for rainfall is more distinct than irrigation water.
• In dry period, major part of the study area goes under suction limit, so STWs will be inoperative in those areas.

• The direction of groundwater flow is towards the boundary of the study area. During dry period over drainage of groundwater from the study areas to the surrounding lower area is occurred as groundwater level is substantially higher than the surrounding area. Due to terrain, boundary outflow has occurred in wet period also.

6.2 Recommendations

The recommendation from the current study can be synthesized as follows:

• In the study area a significant amount of land is cultivable which need irrigation and the geology of the study area is more complex than assumed. As MIKE SHE is a physical based model which can handle the unsaturated zone precisely, for further modeling study in the study area MIKE SHE modeling tool would be more appropriate. If recharge can be calculated exactly from other source, then MODFLOW will provide good result also.

• The geographic location of the deep tube wells (DTW) should be determined. In that case the model could be improved by using the abstraction from DTWs in appropriate location instead of distributing the discharge of the DTWs uniformly over the area.

• Groundwater table and quality monitoring should also be done regularly. As groundwater model is calibrated against groundwater level.

• The groundwater systems of the study area are complex and dynamic and linked with surface water availability in the region. So a groundwater-surface water management plan is required for the study area.

• Investigation of existence of aquifer below 80.0 m, its areal extent and aquifer properties should be carried out for additional sources of irrigation.

• There is a possibility of the existence of fault beside Tanore Upazila; it should be studied in detail.
• For estimation of potential recharge an appropriate methodology could be established.

• Finer resolution model will give better result, as in that case detail features would be incorporated.

• This model can be used for various development options in consultation with local stakeholders.

• In future the relation of recharge with space variant parameters like layer thickness, soil properties etc. can be developed.
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APPENDIX-A

DOUBLE MASS CURVE

Figure A-1: Double Mass curve for Rainfall Station R 194 in Nithpur Upazila

Figure A-2: Double Mass curve for Rainfall Station R208 in Rohanpur Upazila
Figure A-3: Double Mass curve for Rainfall Station R190 in Nachole Upazila

Figure A-4: Double Mass curve for Rainfall Station R172 in Godagari Upazila
Figure B-1: Surface Topography Showing Different Easting and Northing at which Geological Cross Section has been drawn.
Figure B-2: Cross Section A-A’ of Formations at Easting 336000

Figure B-3: Cross Section B-B’ of Formations at Easting 348000
Figure B-4: Cross Section C-C' of Formations at Easting 360000

Figure B-5: Cross Section D-D' of Formations at Northing 708000
Figure B-6: Cross Section E-E' of Formations at Northing 732000

Figure B-7: Cross Section F-F' of Formations at Northing 756000
APPENDIX-C
GWL SIMULATION USING MIKE SHE

Figure C-1: GWL Simulation Using MIKE SHE for the Piezometer Nia_BW32 at Niamatpur

Figure C-2: GWL Simulation Using MIKE SHE for the Piezometer Sap_BW51 at Sapahar

Figure C-3: GWL Simulation Using MIKE SHE for the Piezometer Nac_BW07 at Nachole

Figure C-4: GWL Simulation Using MIKE SHE for the Piezometer Nac_BW09 at Nachole
Figure C-5: GWL Simulation Using MIKE SHE for the Piezometer Nac_BM09 at Nachole

Figure C-6: GWL Simulation Using MIKE SHE for the Piezometer Nac_BM10 at Nachole

Figure C-7: GWL Simulation Using MIKE SHE for the Piezometer God_BM12 at Godagari

Figure C-8: GWL Simulation Using MIKE SHE for the Piezometer at God_BM11 at Godagari

C-2
Figure C-9: GWL Simulation Using MIKE SHE for the Piezometer at Nia_BM32 at Niamatpur

Figure C-10 GWL Simulation Using MIKE SHE for the Piezometer at Por_BM33 at Porsha

Figure C-11: GWL Simulation Using MIKE SHE for the Piezometer at Por_BM34 at Porsha

Figure C-12: GWL Simulation Using MIKE SHE for the Piezometer God_BW16 at Godagari
Figure C-13: GWL Simulation Using MIKE SHE for the Piezometer Por_BW46 at Porsha

Figure C-14: GWL Simulation Using MIKE SHE for the Piezometer Naw_BW12 at Nawabganj

Figure C-15: GWL Simulation Using MIKE SHE for the Piezometer Tan_BW47 at Tanore
Figure C-16: GWL Simulation Using MIKE SHE for the Piezometer of IWM at Godagari-17

Figure C-17: GWL Simulation Using MIKE SHE for the Piezometer of IWM at Gomastapur-24

Figure C-18: GWL Simulation Using MIKE SHE for the Piezometer of IWM at Sapahar-49

Figure C-19: GWL Simulation Using MIKE SHE for the Piezometer of IWM at Porsha-35
Figure C-20: GWL Simulation Using MIKE SHE for the Piezometer of IWM at Niamatpur-47

Figure C-21: GWL Simulation Using MIKE SHE for the Piezometer of IWM at Tanore-18
APPENDIX-D

GWL SIMULATION USING MIKE SHE

Figure D-1: GWL Simulation Using MODFLOW for the Piezometer Nia_BW32 at Niamatpur

Figure D-2: GWL Simulation Using MODFLOW for the Piezometer Nac_BW07 at Nachole
Figure D-3: GWL Simulation Using MODFLOW for the Piezometer Nac_BW09 at Nachole

Figure D-4: GWL Simulation Using MODFLOW for the Piezometer Nac_BM09 at Nachole
Figure D-5: GWL Simulation Using MODFLOW for the Piezometer Nac_BM10 at Nachole

Figure D-6: GWL Simulation Using MODFLOW for the Piezometer Nac_BM12 at Nachole
Figure D-7: GWL Simulation Using MODFLOW for the Piezometer Nae_BM11 at Nachole

Figure D-8: GWL Simulation Using MODFLOW for the Piezometer Nia_BW32 at Niamatpur
Figure D-9: GWL Simulation Using MODFLOW for the Piezometer Por_BM33 at Porsha

Figure D-10: GWL Simulation Using MODFLOW for the Piezometer Por_BM34 at Porsha
APPENDIX-E

WATER BALANCE COMPONENTS

Figure E-1: Water Balance Components of Sapahar Upazila for the year 1997
Figure E-2: Water Balance Components of Gomastapur Upazila for the year 1997

Figure E-3: Water Balance Components of Tanore Upazila for the year 2002