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AQUIFER DEMARCATION AND GROUNDWATER RESOURCES ASSESSMENT IN LOHAGARA MUNICIPALITY, NARAIL, BANGLADESH

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ABSTRACT

This study presents the state-of-the-art methodology for investigating existing hydrogeological framework for delineating underlying aquifer system and existing groundwater (GW) resource assessment in Lohagara Municipality of Narail district in Bangladesh. Numerous hydrogeological, lithological, hydrological, meteorological and other relevant data and information in the study area have been collected. A number of hydrostratigraphic columnar sections representing the extent of aquifer system have been produced and yield properties of sediment formations are determined. The striplog distributions reveal that a productive aquifer exits beneath the study area with the alteration of fine sand aquifer, aquitard and aquiclude layers. The analysis also demonstrates that two major (upper and lower) aquifers are present within the depth from 61 m to 95 m and from 198 m to 216 m or beneath the study area. It is found that a prominent aquifer exists at 200 m to 235 m throughout the study area containing varying thickness of more or less 36 m below the aquiclude. However, estimated specific yield of aquifer materials varies from 0.07 to 0.20 indicating that the aquifer consists of fine to medium sand. The analysis of storage coefficient and hydrostratigraphic sections shows that the upper aquifer is semi-confined and lower aquifer is confined in nature. Based on the GW modelling results by an integrated MIKE-11 and MIKE-SHE platform, the study estimates that GW resources for shallow aquifer on May 01, 2003 for 6 m and 7 m depths are 7.48 million cubic meters (MCM) and 10.00 MCM, respectively, whereas on November 01, 2003, the resource is estimated as 11.29 MCM and 13.81 MCM for 6 m and 7 m depths, respectively. According to water balance studies, the GW recharge is found as 390 mm for the deeper aquifer in 2003 and the corresponding annual aquifer storage volume is estimated as 7.25 MCM, which mostly comes from the horizontal flow. Based on long-term simulation of GW model using potential water withdrawal options in future, the study concludes that the aquifer is sustainable for GW use in Lohagara Municipality of Narail district in Bangladesh.

Keywords: *Aquifer, Groundwater modelling, Hydrogeological framework, MIKE-11, MIKE-SHE, Recharge, Specific Yield.*

1. INTRODUCTION

Groundwater (GW) is usually considered as a source of potable water supply in the developing world because it is readily available in nature and naturally protected from the contamination. It is commonly used for irrigation and supplying water for meeting industrial and domestic requirements all over the world (Hoque et al., 2007). Like many other natural resources, GW resource is being abstracted at an increasing rate all over the world and thus, exploitation of this useful resource is an important issue in the field of modern hydrogeology (Balek, 1989; Butler, 2000; Elango and Sivakumar, 2005; Hoque et al., 2007). It is now widely recognized that sustainability of existing GW supply structure and supplementary use of surface water depends on the reliable assessment of available GW resources for the area under consideration. For this purpose, an integrated distributed hydrogeological model is often required. The model serves as a tool to simulate the recharge, flow and potential head of GW within the defined hydrogeological boundary (Anderson and Woessner, 1992; Sinha, 2005; Kumar, 2011). The numerical model helps in estimating the present available resources and subsequently helps in predicting the potential effect on GW changes under different options of water allocation scenarios (Anderson and Woessner, 1992; Sinha, 2005; El Yaouti et al., 2008). Therefore, numerous studies have been carried out in Bangladesh (MPO, 1987; SWMC, 1996; Nobi and Das Gupta, 1997; SWMC, 2000; Rahman and Roehrig, 2006; Hoque et al., 2007; Wahid et al., 2007; Yasmin, 2008; Adhikary et al., 2011) as well as in other countries of the Asia and other continents (Ala Eldin et al., 2000; Naik and Awasthi, 2003; Kazama et al., 2007; El Yaouti et al., 2008; Igboekwe et al., 2008; Chatterjee et al., 2009; Kushwaha et al., 2009; Praveena and Aris, 2010; Parveena et al., 2010; Rani and Chen, 2010; Raj, 2011; Singh et al., 2011) for the assessment of GW resources as well as

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hydrogeological investigations of the aquifers for appropriate utilization and management of this valuable resources. Underground aquifers are usually very convenient sources of water because they are naturally occurring underground reservoirs, which usually have an enormous storage capacity. However, it is often essential to understand the system dynamics within this aquifer system, when it is subjected to natural and artificial stresses prior to introducing appropriate water resources management practices (El Yaouti et al., 2008). Since many aquifers contain high quality waters, their application as suitable production source of drinking water and human consumption is obvious and they are used as a source of potable water source all over the world. As their storage capacity is quite large, they can provide a continuous supply of water, even in dry seasonal periods when rainfall is very less and/or nearly absent and surface water is rapidly depleted.

GW is the principal source of drinking and irrigation water supplies in Bangladesh. About 97% of the population in Bangladesh used to rely on GW for drinking purposes while more than 70% of the total irrigated area is served with GW sources (Hasan et al., 2007; BGS and DPHE, 2001). In Bangladesh, GW occurs in the extensive alluvial aquifers at shallow depth (<10 mbgl) within widespread alluvial deposits (Shamsudduha et al., 2011; Michael and Voss, 2009; MPO, 1987) and meets most of the water demands for domestic, industrial supply and irrigation uses (Hasan et al., 2007; Hoque et al., 2007; Shamsudduha et al., 2008). More than 10 million shallow hand pumped wells, locally known as hand tube wells (HTWs), are used to provide drinking water to the almost entire rural areas and in urban areas of the country, where there is no piped water supply (Hasan et al., 2007). Development of the GW resource for irrigation and other uses is a vital component of the government's agricultural strategy to achieve food self-sufficiency in Bangladesh (Wahid et al., 2007), which is also highlighted in the national water management plan of the country (WARPO, 2001). A lack of proper understanding of the GW system, in terms of resource utilization, is one of the major limitations to the effective management of GW resources in Bangladesh (Hoque et al., 2007). Thus, there is an urgent need to formulate a strategic plan for appropriate assessment and development of its GW resources for an aquifer system under consideration. Balek (1989) and Karanth (1987) reported that the component of GW study generally contains two major sub-components such as hydrogeological studies and GW modelling and assessment. Hydrogeological study has been carried out to understand the regional and local hydrogeological setting, hydrostratigraphical framework, delineation of the underlying aquifer system, status of groundwater level (GWL) fluctuations and groundwater quality (GWQ). The GW model is developed for understanding GW flow dynamics and assessment of existing GW resource at the present as well as future development scenarios. In the present study, the hydrogeological setting and available GWR in Lohagara Municipality under Narail district of Bangladesh have been studied. Although Lohagara Municipality is largely dependent on GW resources for domestic and irrigation purposes, currently there is no management plan in place and large scale uncontrolled GW exploitation is taking place.. Lack of appropriate understanding of the GW system in terms of resource utilization, is one of the major limitations to the effective management of this resource especially in the urban and peri-urban areas of Bangladesh (Hoque et al., 2007). Therefore, the major objectives of this present study are to investigate the existing hydrogeological framework and underlying aquifer characteristics as well as to quantify the available GW resources in relation to natural recharge and extraction options in Lohagara Municipality under Narail district of Bangladesh.

2. DESCRIPTION OF THE STUDY AREA

2.1 Location

The study area, Lohagara Municipality, is located in Lohagara upazilla (sub-district) under Narail district of Bangladesh (Figure 1). The area is about 16.16 sq. km for the present case study. It is bounded by the Ganges River on the North, the River Padma on the East and the Western border upazillas on the west. The southern boundary of the study area is defined as the boundaries of the upazillas of Sharsha, Jhikargacha, Jessore Sadar, Narail Sadar, Lohagara, Kashiani and Muksudpur.

2.2 Climate

The study area experiences a typical tropical monsoon climate, with hot wet summers from May to September and cool dry winters. The rainy season occurs approximately from May to October and almost 90% of the total annual rainfall occurs during this period. Both temperature and relative humidity remain high in this season. Mean daily temperature is fairly constant between months of April and September and show little variation across the region, being of the order of 28^0 C. From October, temperature begins to decline, and mean daily temperature reaches to a minimum of about 19 to 19.5^0 C in January. In April, maximum daily temperature in the region can often exceed 35^0 C, while in January minimum daily values can be below 10^0 C. The rainfall

distribution in the study area is not uniform. The lowest mean annual rainfall is about 1800 mm, which is observed in northwest stretched strip and increases towards eastward and reaches about 2100 mm and 2400 mm in Narail and Bhanga, respectively.

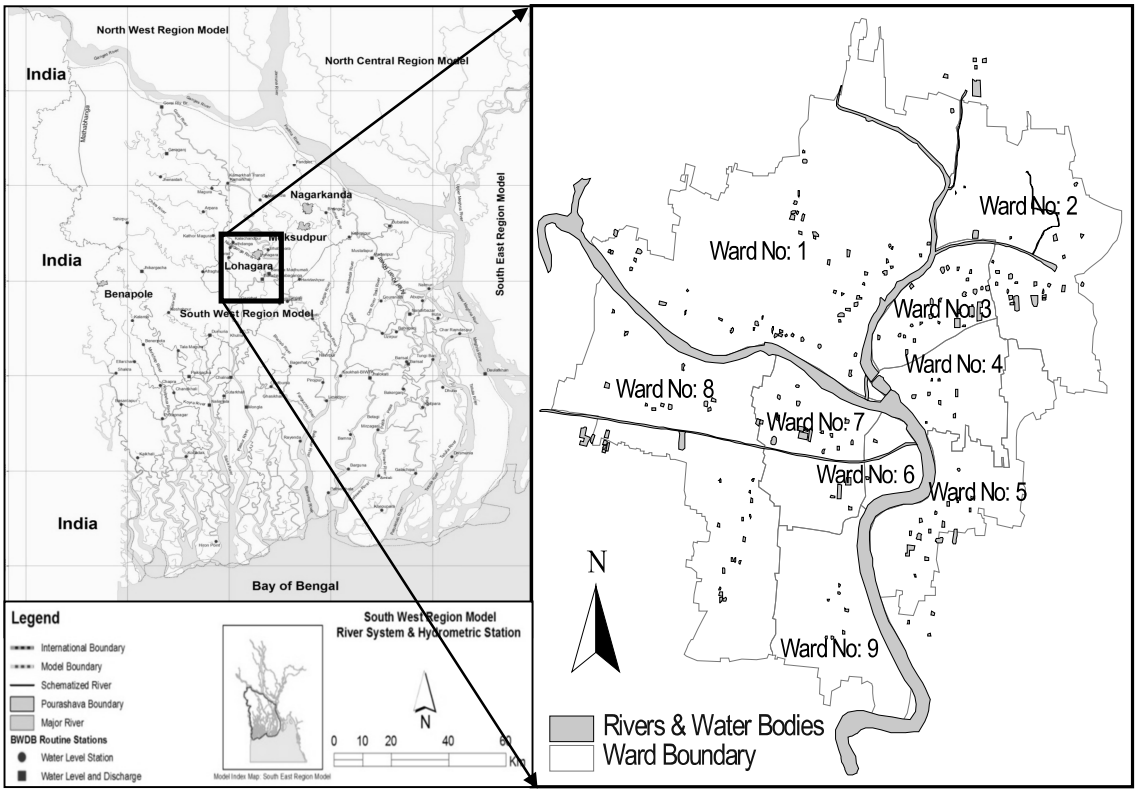

Figure 1 The study area (Lohagara Municipality) in Lohagara Upazilla under Narail district of Bangladesh.

2.3 Topography and Soil Characteristics

The study area has an almost flat topography and characterised by a fairly plane land except the water bodies such as rivers, ponds, depressions and beels etc. Peat occurs extensively in the Gopalganj-Khulna Beels and locally in some Haors of the Sylhet basin. The soils contain organic matter at the surface or buried under a mineral soil layer below at a depth of up to 40 cm. The organic material that forms the Histic horizon varies from dark brown, fibrous peat to semi-liquid black muck. They have been included as Histosols. Soils of this area are result of deposition of Ganges alluvium. Ganges alluvium is calcareous when deposited, but most basin clays and some older ridge soils have been decalcified and acidified in their upper layers; lime is found only in the subsoil or substratum of such soils. Clay soils predominate in basins and on the middle parts of most ridges, with loamy soils (and occasionally sands) occurring mainly on ridge crests. The cut-off parts of the Meghna floodplain have a smooth relief and predominantly silty soils, which are deeply flooded by rainwater in the monsoon season. The unit covers most of the districts of Rajshahi, Natore, Pabna, all districts of Khulna division, and parts of Manikganj, Narayanganj, Munshiganj, Shariatpur, Madaripur, Barisal, Gopalganj. This physiographic unit is almost triangular in shape and bounded by the Ganges tidal floodplain on the south. On its southern end it traps the Gopalganj-Khulna Beels. Values of pH in soil ranges from 7.0 to 8.5.

2.4 Geomorphological and Hydrogeological Setting

Geomorphologically, Lohagara upazilla belongs to Ganges River floodplain which comprises the active floodplain of the Ganges and the adjoining meander floodplain. The latter mainly comprises a smooth landscape of ridges, basins and old channels. The relief is locally irregular alongside the present and former river courses, especially in the west, comprising a rapidly alternating series of linear low ridges and depressions. The Ganges channel is constantly shifting within its active floodplain, eroding and depositing large areas of new char land each flood season, but it is less braided than that of the Brahmaputra-Jamuna. Seasonal flooding is mainly

shallow in the west and north, with the highest ridge crests remaining above normal flood levels, but flood depths increase towards the east and the south. Flooding is mainly by accumulated rainwater and the rising GW table except on the active Ganges floodplain and close to distributary channels which cross the meander floodplain. Hydrogeological investigations had been undertaken to assess aquifer information of sedimentary formation. Past studies (BWDB, 1993) give an idea about the depth and thickness of the aquifer layers in the study area. Hydrogeological parameters of this area are governed by the litho-stratigraphic and prevailing tectonic activities, which is part of the regional hydrogeological setting and tectonic features. The Quaternary sequence provides good aquifers, which have been extensively exploited in Bangladesh. The aquifers are generally thick multilayered with high transmissivity and storage coefficient. In addition, the aquifer systems can broadly be distinguished in the study area is recent sand forming both confined and semi-confined aquifers.

2.5 Existing Landuse and Agricultural Practices

The major part of the study area is agricultural land. It has homestead, pond and depressions (locally named as beels) also. The crop calendar reveals that T. Aman, HYV-Aman, HYV-Boro, and Potato are the main crops in the study area. Land use and vegetation are used in the model to calculate actual evapo-transpiration depending on the actual crops grown in the project area. Under the present study, spatial distribution of crops has been determined from a comprehensive field campaign. However, for the model input, these cropping types and cropping pattern have further been simplified considering the major crops that require irrigation water. A crop database for each crop, which defines leaf area index, root depth and other properties of each crop are developed based on Food and Agricultural Organization (FAO) of United Nations (UN) publications (FAO, 1979) and used in the model. Paddy is grown almost everywhere through the year in each of the Karif-I (March-June), Karif-II (July-October) and Rabi (November-February). Pulse, oilseeds, vegetables, jute, wheat, sugar cane, potato, Mango, etc, are major non-paddy crops. With all availability of irrigation water, growers of the study area shifted towards growing more productive Boro-Fallow-HYV T. Aman. Spatial distribution of landuse and cropping patterns is presented in Figure 2.

Figure 2 Spatial land use map for a larger area including the study area (Lohagara Municipality).

3. RESULTS AND DISCUSSIONS

3.1 Establishment of Hydrogeological Setting

Assessment of GW resources largely depends on hydrogeological investigation and GW modeling. The data regarding the hydrogeological setting helps to describe the physical system such as topography, lithological characteristics, aquifer geometry, its different hydraulic properties, and hydrology (Wahid et al., 2007). However, it includes mostly the parameters that do not change with time.

3.1.1 Topography

A well-prepared Digital Elevation Model (DEM) is essential for visualizing the floodplain topography and for accurate modelling. A DEM of 300m resolution has been developed to define the topography of the study area and used in the model development (Figure 3). A larger area has been considered, which covers the actual study area. Topographic data for the study area has been extracted from the topographic database developed by FAP-19 based on irrigation planning maps available at IWM and also from the topographic survey conducted for Lohagara Municipality by IWM in 2011. Roads alignment and homestead coverage also have been collected from Roads and Highway Department (RHD) and Local Government Engineering Department (LGED). Utilizing these data, a DEM of 300m resolution has been developed to define the topography of the study area. DEM shows that elevation of the area varies from 0.60 to 9.00 mPWD (meters above Public Works Datum in Bangladesh).

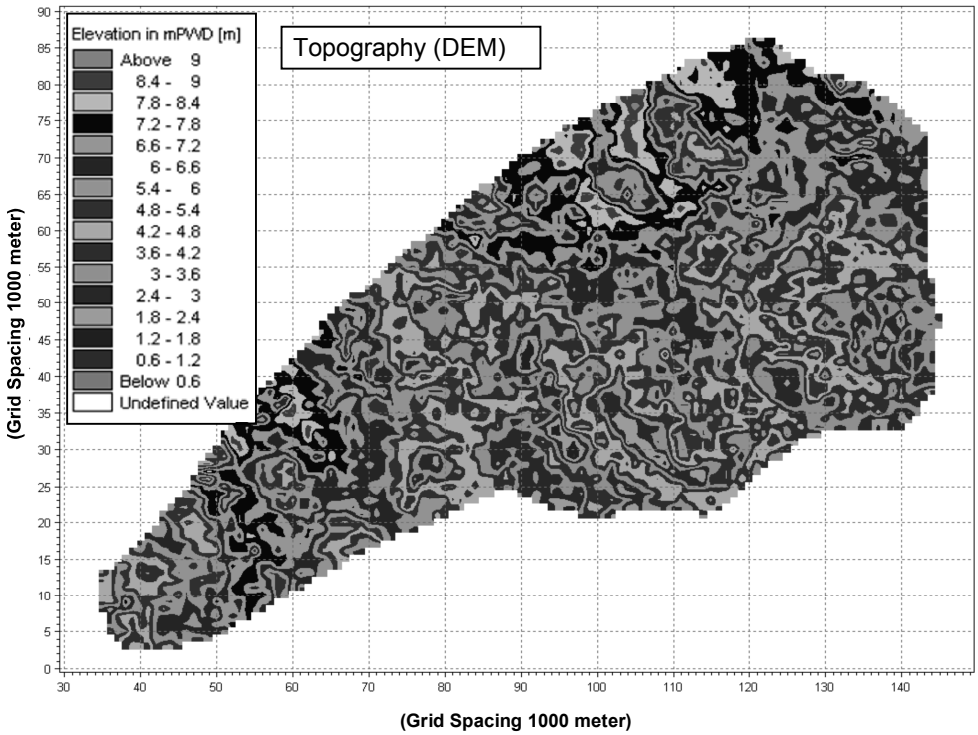

Figure 3 Digital Elevation Model (DEM) for a larger area including the study area (Lohagara Municipality).

3.1.2 Stratigraphic Analysis and Aquifer Demarcation

Hydrogeological investigation for the Lohagara Municipality has been carried out to define the hydrostratigraphic layers. Eight lithological borelogs were collected from DPHE and BWDB for lithological characterization of the sub-surface sedimentary formation, producing hydrostratigraphic cross-sections and for preparing input data of GW model. Among the borelogs of the area, maximum depth of the available borelog is 305m. Sub-surface lithological characterization of the study area and configuration of the hydrostratigraphic units has been prepared by analyzing the individual lithological units and depth of different aquifers. IWM customized software "depth-storage" model has been used for producing the columnar sections and determining the specific yield of sediment formations. Spatial distributions of eight striplogs and their locations are projected all over the study area (Figure 4 and Figure 5). Hydrostratigraphic columnar sections represent the nature and extent of aquifer in and around the municipality area. From striplogs distribution (Figure 5), it reveals that a productive aquifer exits below the alteration of fine sand aquifer, aquitard and aquiclude layers.

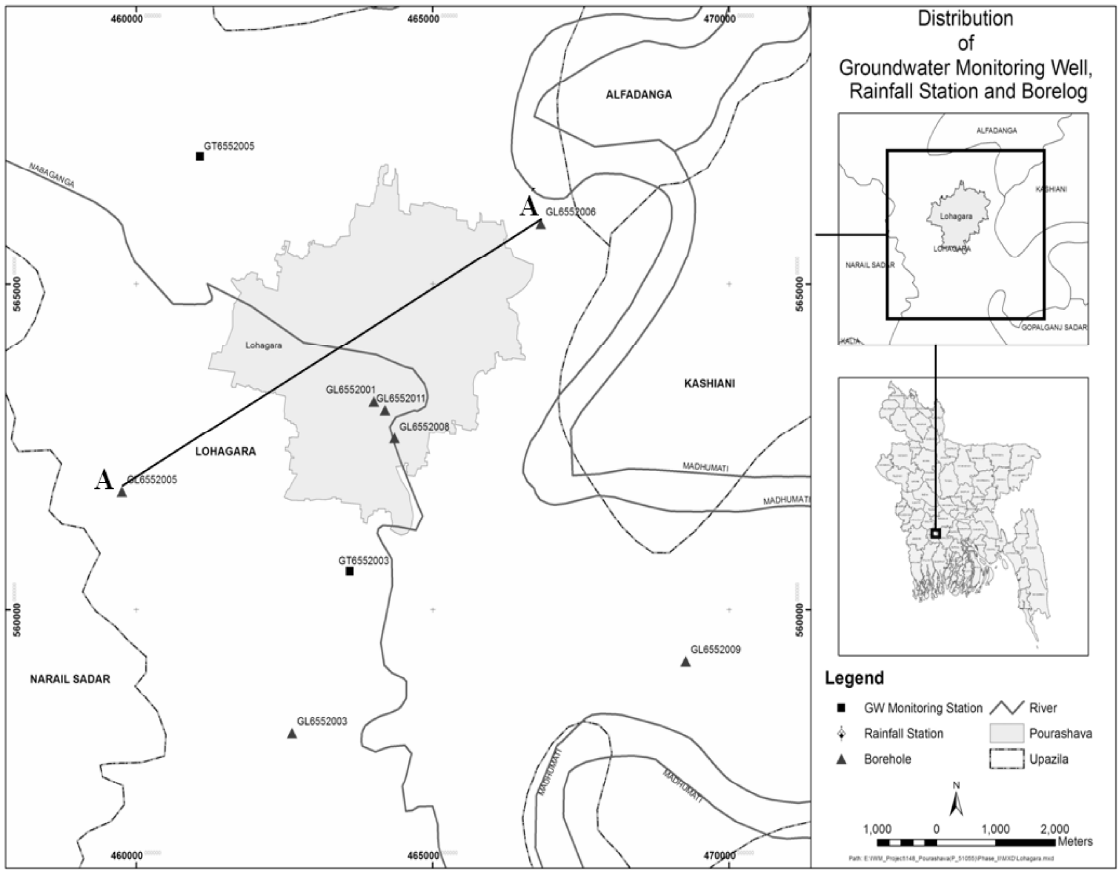

Figure 4 Borelog location and hydrostratigraphic section alignment in and around Lohagara Municipality

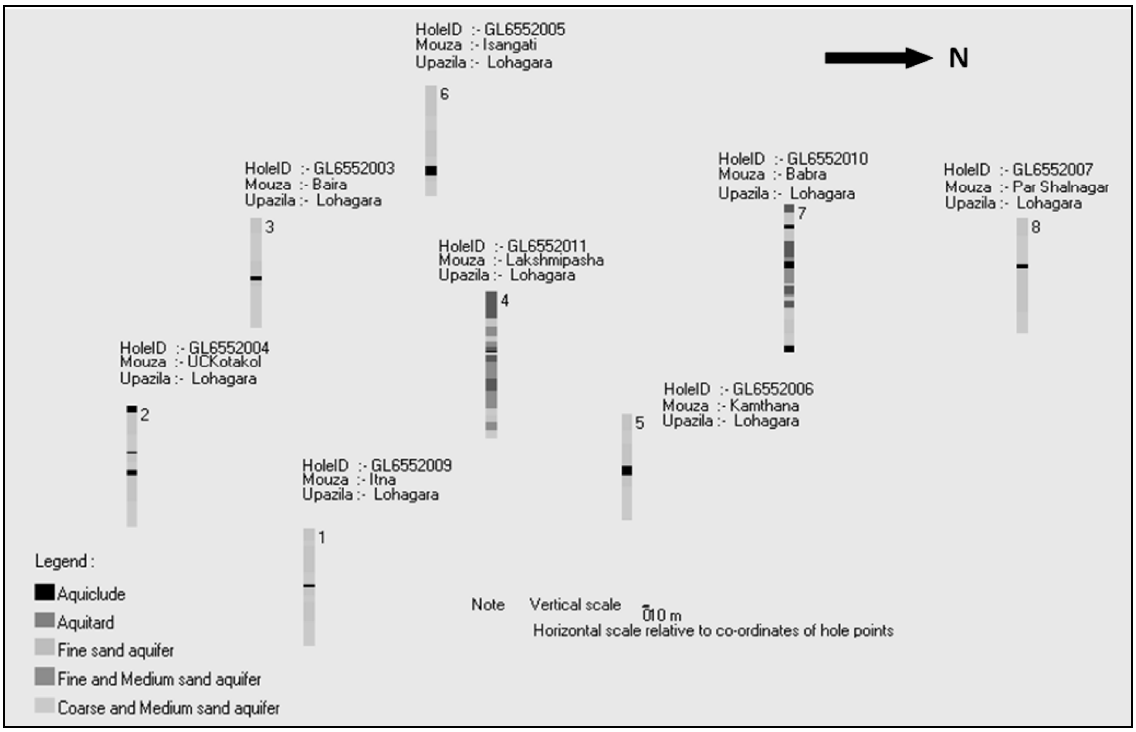

Figure 5 Striplogs and distribution of borelog location in and around Lohagara Municipality

3.1.3 Groundwater Table Fluctuations

GWL variation over the period is the primary indicator, which reveals the aquifer response on recharge, abstraction, and aquifer discharge as gravity release. GW hydrograph has been developed from the analysis of the collected data for assessing annual GWL fluctuation. GWL data were collected from the Bangladesh Water Development Board (BWDB) and long-term GWL hydrograph (Figure 6) is constructed. It reveals that GWL fluctuates between 1.5 m and 5 m with annual recharge–discharge conditions. From the hydrograph, it is also observed that there are fluctuations in the water level of the study area but having no declining trend.

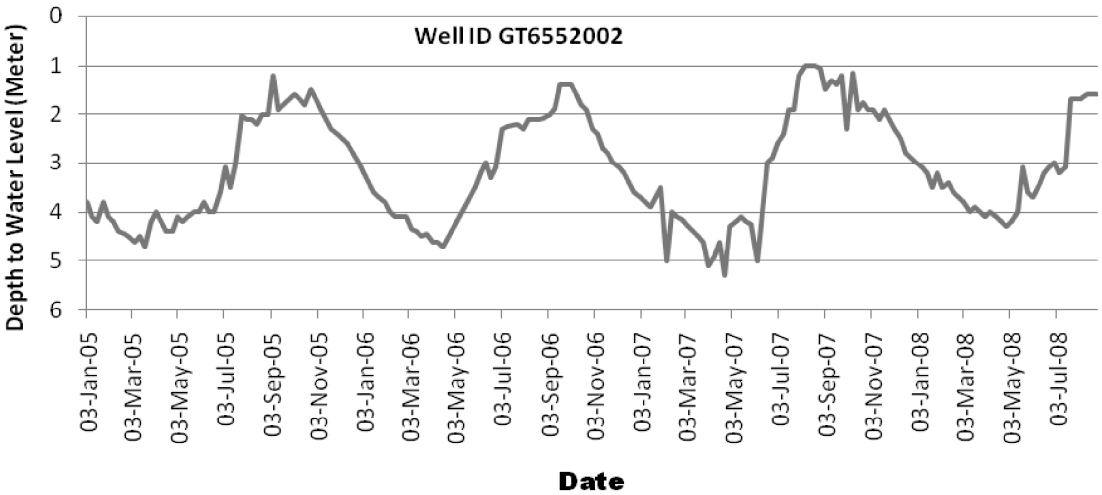

Figure 6 Hydrograph of GW fluctuations in Lohagara Municipality and its surrounding area

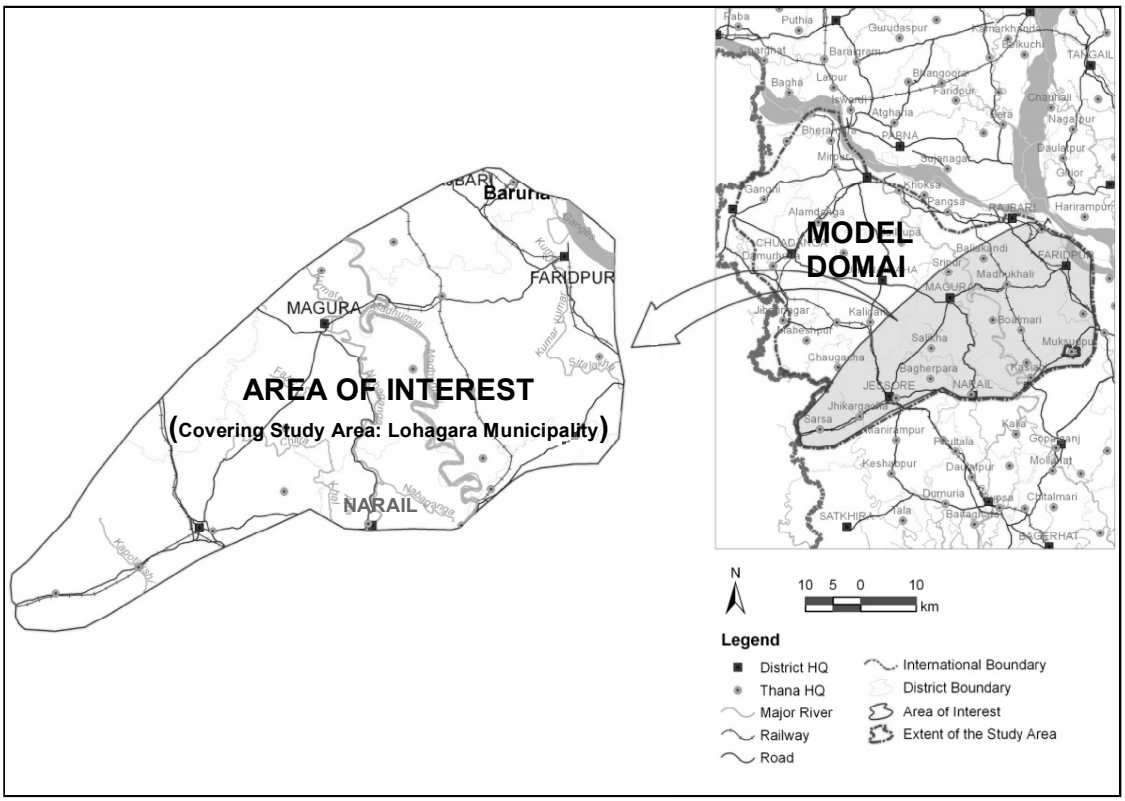

Figure 7 Model domain for GW simulation in a larger area including the study area (Lohagara Municipality).

3.2 Groundwater Modelling and Resources Assessment

For hydrogeological study and GW resources assessment, specific emphasis has been given for the municipality area and its vicinity at least the area of Lohagara upazilla. For the GW modelling, a larger study area is generally considered to avoid the boundary influences in model computations (Anderson and Woessner, 1992; Kumar, 2011). Based on these criteria, the developed GW model domain (Figure 7) covers an area of about 9,582 sq. km. in this study, which includes Meherpur, Kushtia, Chuadanaga, Jhenaidah, Magura, Rajbari, Faridpur and Part of Gopalganj, Narail and Jessore districts of Bangladesh.

3.2.1 Data Acquisition and Analysis

For the purpose of GW source identification and resource assessment, large numbers of hydrogeological and meteorological data have been collected from BWDB, DPHE, BMD. From these secondary data and also from own data-bank of IWM, relevant data to the study area have been used in hydrogeological and GW modelling studies. For hydrogeological study of the Lohagara Municipality and its surrounding area, secondary data has been collected for analysis. Collected secondary data first assessed through necessary quality control procedure and subsequently used for further analysis. There is no aquifer test data is available from secondary source (BWDB, 1997) for the target location of the study area. As such, aquifer properties could not be determined for the Lohagara Municipality and its surrounding area. The model has been developed based on the secondary data collected from the field and also with the data available in IWM. To quantify the resources precisely, the primary data such as geophysical investigation to identify the geological formation and also pump test data to determine the aquifer properties is needed. The model has been calibrated based on secondary data which needs to be validated with the primary data collected in the field.

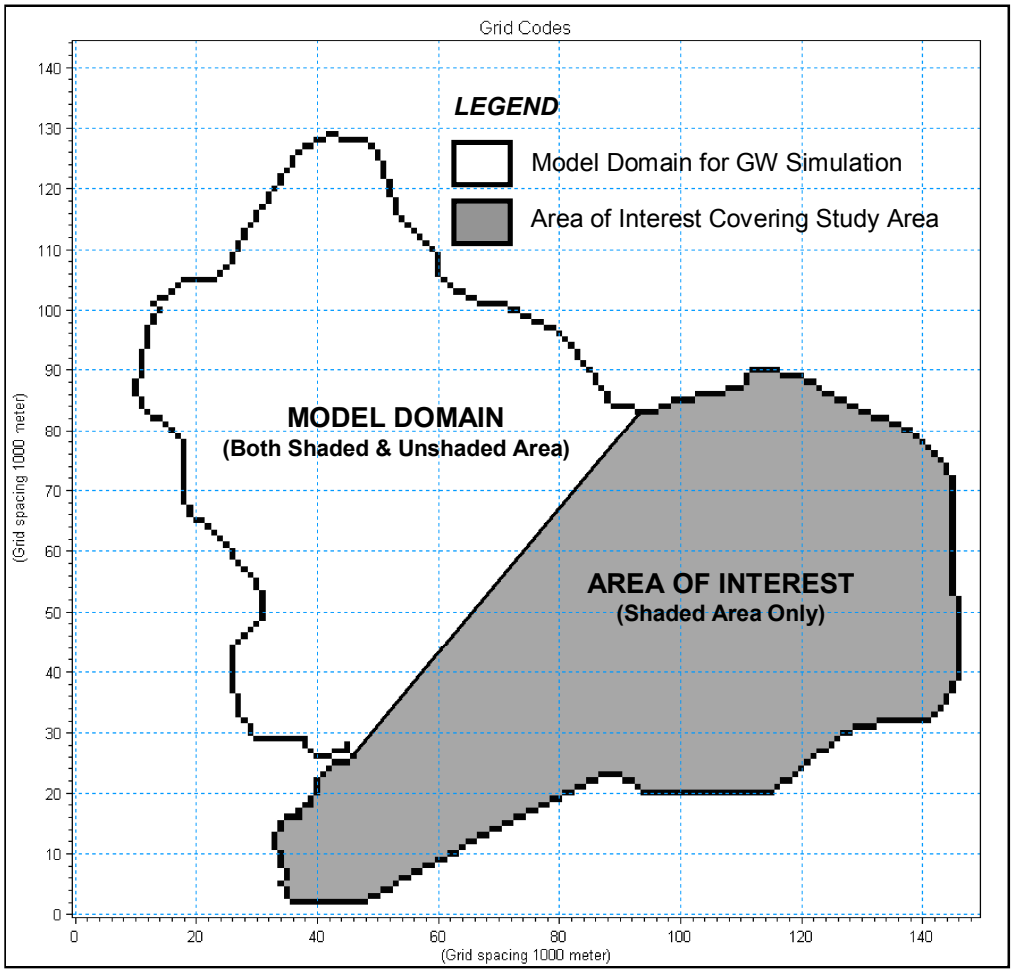

Figure 8 Model domain of a larger area including the study area (Lohagara Municipality) for GW simulation.

3.2.2 Model Setup and Simulation Specifications

GW model setup involves a geometrical description and specification of physical characteristics of the hydrological system of the study area. In this study, the model has been developed using MIKE-SHE mathematical modelling software tool, developed by DHI Water and Environment Pty Ltd. (DHI, 1999). MIKE-SHE is a comprehensive mathematical modelling system that covers the entire land-based hydrological cycle, simulating surface flow, infiltration, flow through the unsaturated zone (UZ), evapotranspiration and GW flow; it is designed to address dynamic exchange of the water between these components. Major components of the model setup include evapotranspiration, unsaturated zone, saturated zone, overland flow and river systems. The default time step control and computational control parameters for overland flow (OL), UZ and saturated zone (SZ) have been used for entire simulation period of 10 years from 1997 to 2007. The spatial and temporal variations of the potential head is described mathematically by the non-linear Boussinesq equation and solved numerically by an iterative implicit finite difference technique. Setting up the SZ component includes defining the geological layers, hydrogeological characteristics, initial and boundary conditions and finally the degree of drainage. However, simulation periods of the calibration, validation and prediction models were different and user specified. The study area has been discretized into 1 km. square grids in the horizontal plan (Figure 8). The model consists of 9,998 grid cells, where 420 grids are the boundary cells and the rest are computational cells. The grid cells are the basic units to provide all the spatial and temporal data as input and to obtain corresponding data as output. The coupling of surface water (SW) and GW model involves a number of specifications. The river reaches where the coupling will take place have been defined in the river model. In the present study, all the major rivers and small channels (locally named as khals) within the study area have been coupled with GW system. Type of river-aquifer exchanges and the flooding conditions have also been defined. The flow exchange between the SZ component and the river component is mainly dependent on head difference between river and aquifer and properties of riverbed material such as leakage coefficient (Nobi and Das Gupta, 1997; El Yaouti et al., 2008). For river-aquifer exchange, leakage coefficients along with the hydraulic conductivity of SZ are taken into account for most of the river reaches. The hydrogeological input parameters used in the SZ setup include several parameters such as transmissivity, hydraulic conductivity and specific yield or storage coefficients.

3.2.3 Calibration and Validation

The purpose of model calibration is to achieve a satisfactory agreement with the measured data by adjusting the input parameters within acceptable range. As a coupled SW-GW model contains huge numbers of input data, the parameters to adjust during the calibration could be numerous. During the calibration, it is therefore important to adjust the parameters within the acceptable range determined from field measurements, and also to minimize the number of adjusted parameters. In this study, the initial input parameters have been obtained from field measurements and other secondary sources. The model has been calibrated for the period of 1997 to 2003. During calibration overland leakage coefficient, vertical hydraulic conductivity, storage coefficient and river leakage coefficient have been adjusted. In the present model, calibration was done against observed GWL and a total of 62 observation wells were used for the calibration and validation purposes. It is customary that the calibrated model should be verified outside the calibration period (Anderson and Woessner, 1992). In order to increase the reliability of the model, it should be validated using another set of data. The period of validation was taken as 2004 to 2007.

3.2.4 Selection of Design Year for Technical Evaluation

For GW resources assessment, rainfall data are analyzed to estimate the rainfall events for different return periods. In selecting design event, most weight has been given to 80% dependable of annual rainfall, because this is considered usually most significant for domestic requirement considerations. In view of that, analysis is concentrated on rainfall event for 5–years return period and the corresponding design year is determined. Observed annual rainfall from all 21 monitoring stations located in and around the study municipality has been considered for the statistical analysis for a period of 30 years from 1980 to 2009. According to the recommendation of FAP25 study in Bangladesh, data has been fitted to three-parameter Log Normal distribution to find out the average and extreme dry year. The statistical software HYMOSv4.0 has been used for this purpose and the obtained results for all 21 stations are presented in Table 1. It is quite obvious from the obtained results that all rainfall events for each station will not represent a unique design year due to the randomness of rainfall events. For this reason, it is necessary to select a design year on the basis of rainfall stations representing a unique design year. Table 1 demonstrates that 5 rainfall stations namely Bhanga, Chaugacha, Hogalbaria, Jhenaidah and Salikha represent the year 2003 as 5-years return-period event. Therefore, the year 2003 has been selected as the design year for technical evaluation and assessment purpose in the present study.

Table 1 Annual average rainfall (mm) for different return periods

Station	2 yrs Return Period	Year of Matching	5 yrs Return Period	Year of Matching	10 yrs Return Period	Year of Matching	25 yrs Return Period	Year of Matching
Alamdanga	1729.2	2001	1453.3	1996	1301.5	2003	1133.8	1994
Amla	1661.7	1995	1407.4	1996	1270.7	2003	1121.9	1994
Benapole	1804.1	2004	1463.1	2005	1281.5	2002	1085.6	1989
Bhanga	1866.1	2000	1585.5	**2003**	1435.2	1994	1272.1	2008
Bheramara	1635.1	1991	1417.6	1996	1300.3	2003	1172.5	2003
Boalmari	1841.1	2006	1597.1	2008	1468.5	2005	1330.7	1992
Chaugacha	1827.9	2004	1554.8	**2003**	1411.2	2005	1257.5	2009
Chuadanga	1608.8	2004	1407.2	2002	1291.3	2003	1159.3	2003
Faridpur	1894.4	2007	1583.1	2005	1415.0	1994	1231.6	2003
Hogalbaria	1567.5	2002	1390.5	**2003**	1296.3	2009	1194.7	2009
Jessore	1783.4	2006	1550.4	2001	1427.5	2003	1295.7	1994
Jhenaidah	1682.7	2000	1368.3	**2003**	1199.1	2008	1015.2	2008
Kaliganj	1816.6	2000	1505.8	2001	1339.8	1995	1160.3	2009
Kushtia	1649.6	2006	1370.1	1998	1221.3	2008	1060.9	1996
Magura	1715.4	2007	1424.5	2006	1266.8	2003	1094.5	2003
Meherpur	1616.1	2004	1353.9	1997	1214.3	2003	1063.5	1991
Modhukhali	1794.8	2001	1499.1	2006	1333.6	2005	1148.6	1992
Narail	1773.3	1996	1533.0	2004	1405.1	2001	1267.1	2003
Rajbari	1811.8	2005	1536.3	1989	1387.1	2003	1224.3	2009
Sailkupa	1698.7	2006	1301.5	2008	1069.7	1996	802.3	1995
Salikha	1635.4	2007	1345.1	**2003**	1188.6	1992	1018.3	1992

3.2.5 Options for Technical Evaluation

In this study, two different options have been considered and model simulations are performed accordingly. Results of the option simulations are analyzed, presented and compared with the base condition (existing situation) in the two distinctive manners such as analysis of (i) GWL hydrographs and (ii) spatial distribution map of depth to GW table.

Option I: Base Condition (Existing Situation): The base condition includes hydrological situation and other existing situations that prevail in the field in the design year (2003). The main purpose of the base option is to understand the present status of the study municipality under design year in terms of volume of water presently being used, whether it crosses the potential recharge of the aquifer, present state of GW table, crop coverage and scope for further irrigation expansions considering the water availability. Crop coverage under different crops in existing condition has been considered in base option. Total amount of water required for irrigation activities is abstracted from the aquifer.

Option II: Long-term Simulation: Option II is the future development option, which mainly includes the future potential abstraction of water from underlying aquifer to meet the domestic and industrial demand for Lohagara Municipality. The purpose of this option is to assess the potential impact of future development activities on the present state of water and environment with respect to the GW tables whether it exceeds the safe and/or sustainable yield of the aquifer.

3.2.6 Groundwater Resources Assessment

The data analysis suggests that only two aquifer layers exist within 7 m depth. Saturated thicknesses of these two layers have been calculated based on the three different considerations, which are explained below.

- Case (a): if thickness of first layer exceeds 6 m or 7 m depth, entire saturated thickness lies only in first layer.
- Case (b): if thickness of first layer remains above GWL, entire saturated thickness lies only in second layer.
- Case (c): if case (a) & case (b) do not occur, then saturated thickness lies in both first and second layers. To find out the thickness of first layer within the saturated thickness, simply depth of water table is subtracted from the thickness of first layer. Then, part of first layer within the saturated thickness is subtracted from the entire saturated thickness to find out the thickness of second layer within the saturated thickness.

The availability of GW resources within the 6 m and 7 m depths are estimated based on the available saturated thickness up to 6 m and 7 m depths multiplied by the specific yield (S_Y) of the area under consideration. The volume of the available GW resources is calculated using the equation as = area x Δh x S_Y, where Δh is the saturated thickness within 6 m and 7 m depths. By using this procedure, model grid wise GW resources availability on 2003 (design year) has been estimated. Saturated thickness of first and second layers are multiplied by the corresponding specific yield (S_Y) values and summed up to get the depth of water availability of a grid. Availability in volumes is calculated by multiplying the depth of water availability by the area of the grid. Finally, the available GW resource is estimated based on the number of grids that lie within the study area.

4. RESULTS AND DISCUSSIONS

4.1 Aquifer System in Lohagara Municipality

The developed columnar section and estimated specific yield of three borelogs are presented in Figure 9, which indicates that fine sand dominated all over the study area from the top most layers varying in depth from place to place. Two prominent aquifers (e.g. upper and lower) are present within the depth from 63 m to 90 m and from 198 m to 216 m or more beneath the study area. Specific yield of the aquifers varies from 0.07 to 0.20, which describes that the aquifer consists of fine to medium sand. Hydrostratigraphic section along A-A′ (Figure 4) represents the hydrostratigraphic layers distribution of the Lohagara Municipality and its surrounding area, which is presented in Figure 10. It reveals that top most layer is aquitard. Below the aquitard layer, alteration of fine sand dominated and medium sand dominated aquifer is evidenced within different depths and separated from the lower productive aquifer by the clay layer. A thick aquifer having thickness approximately 30 m exists at Isangati and Kamthana Lohagara. However, a prominent aquifer is evidenced at 200 m to 235 m throughout the study area at varying thickness having thickness more or less 36 m below the aquiclude. From the analysis of storage coefficient and hydrostratigraphic section, it appears that the upper aquifer is semi-confined and lower aquifer is confined in nature. By analyzing the stratigraphy of the study area, major hydrostratigraphic units are delineated and average thickness of hydrostratigraphic unit are summarized in the Table 2.

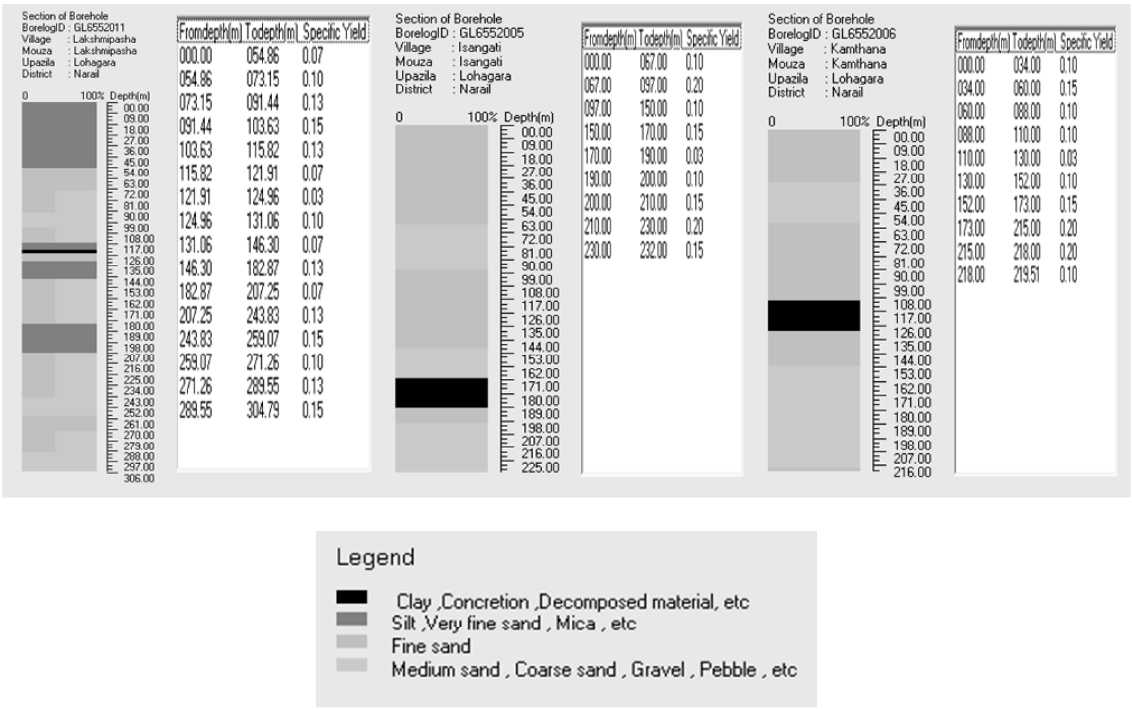

Figure 9 Three columnar sections and specific yield of borelog in and around the Lohagara Municipality

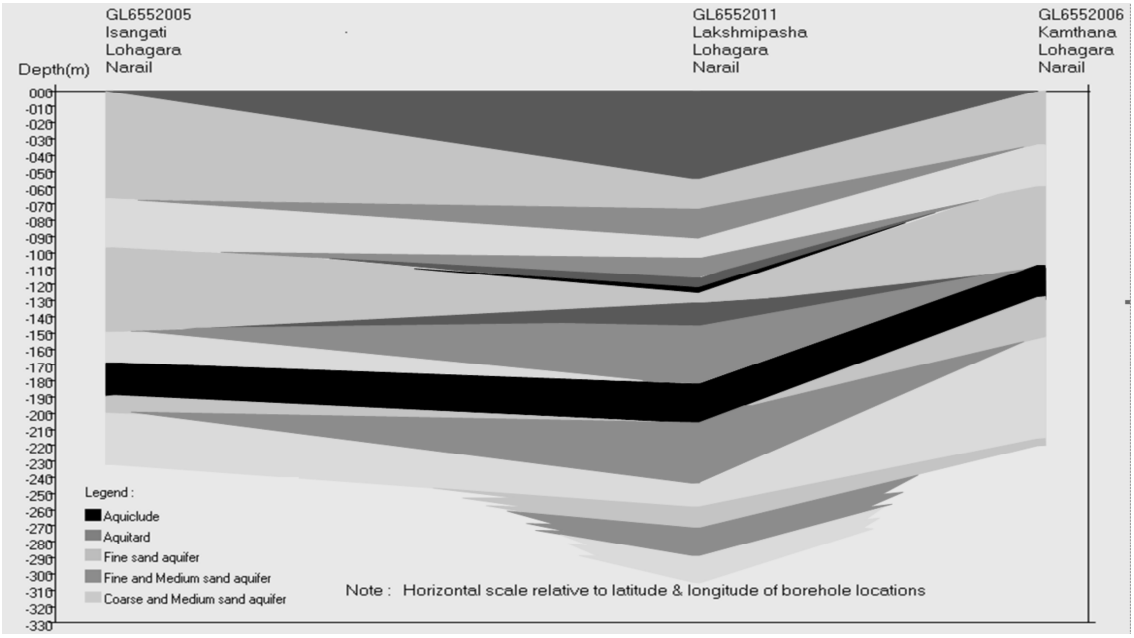

Figure 10 Hydrostratigraphic section along A-A´ in Lohagara Municipality of Narail district.

Table 2 Summary of hydrostratigraphic units and their extents

Hydrostratigraphic Unit	Depth (m)	Average Thickness (m)
1st Aquitard	0 to 30	30
1st Fine Sand Aquifer	31 to 60	30
1st Aquifer	61 to 95	36
2nd Fine Sand Aquifer	96 to 150	55
1st Aquiclude	170 to 190	21
2nd Aquifer	200 to 235	36

4.2 Calibration and Validation of GW Model

In this study, initial condition of GWL, in terms of potential head of GW, is based on recordings in observation wells at the start of the simulation. A contour map of potential head is used as input in the model development phase. Boundary condition is based on data from GW observation wells located along the boundary of the study area. A boundary GWL time-series data file is generated from observed GWL data, which has been used as input to the GW model. Drainage flow includes all major regional rivers and is simulated by linear routing process to the respective rivers. Finally, the developed GW model is calibrated and validated against the observed GWL from a total of 62 monitoring wells in and around the study area. The model has been calibrated to achieve an acceptable agreement between measured and simulated GWL, by adjusting the model parameters within the acceptable range, defined by field data or published reports (MPO 1987). The main parameter used for calibration is the vertical conductivity of the upper layer, although horizontal conductivity, specific yield and Manning's roughness coefficient is also varied to a lesser extent during the calibration process. Also, since the model consists of two geological layers, different values of horizontal conductivity have been estimated in these layers. The sample calibration and validation plots of GWL in the representative monitoring wells are presented in Figure 11 and Figure 12, respectively. In general, a good agreement between simulated and observed GWL is achieved. The average calibrated values are given in Table 3. From the results of the model validation, it could be concluded that the parameters used in the calibrated model are acceptable. Thus, the model can be used for prediction purpose. Hydrographs of simulated groundwater tables (GWT) were obtained at some pre-selected locations, which show that the maximum and minimum depth to GWT occurs at the end of April and end of October respectively. Hydrographs of observed GWT also supports the above findings. Based on these findings, spatial distribution maps of depth to phreatic surface on May 01, 2003 and November 01, 2003 within Lohagara Municipality area (Figure 13 and Figure 14).

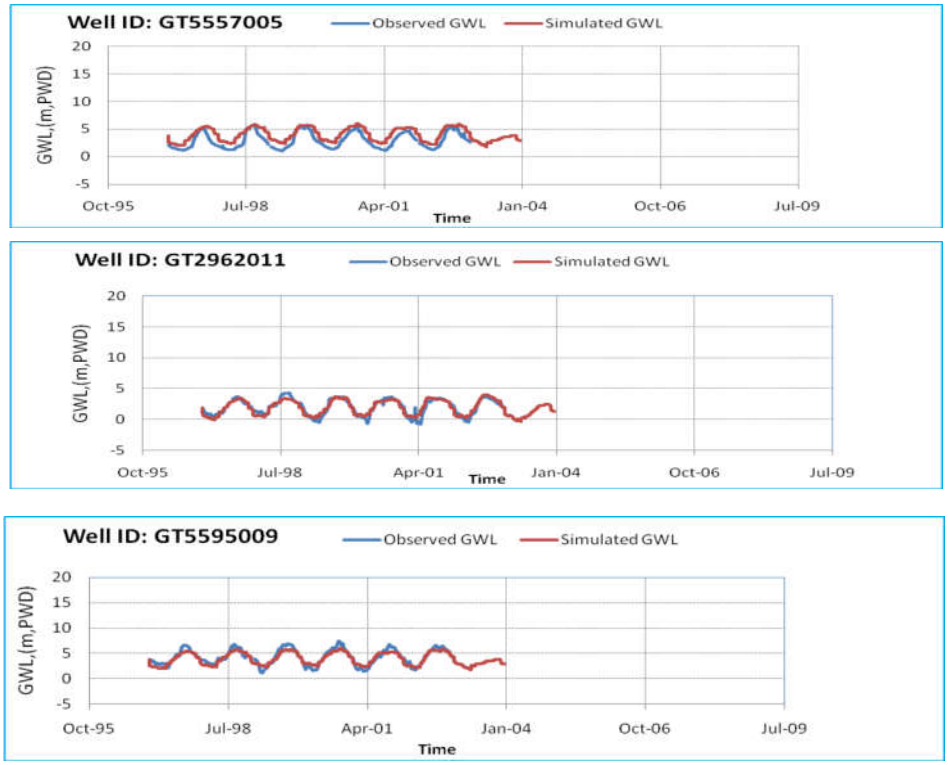

Figure 11 Observed and simulated plots of GWL showing calibration of GW model

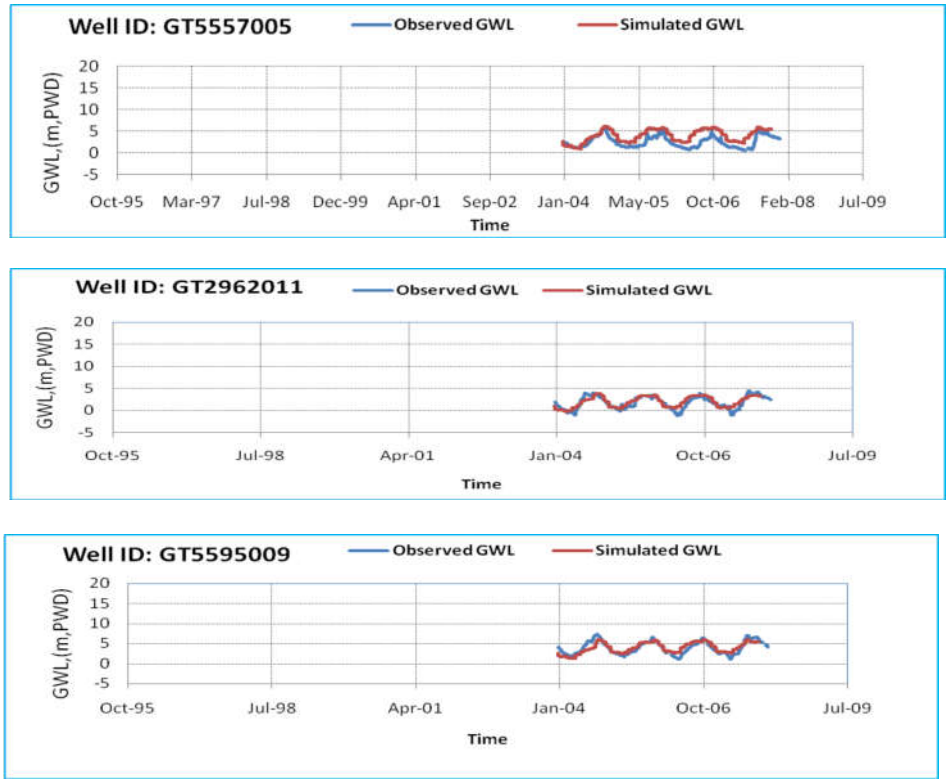

Figure 12 Observed and simulated plots of GWL showing validation of GW model

Table 3 Summary of average calibrated parameters in GW model

Aquifer layer	Horizontal hydraulic conductivity (m/s) x 10^{-3}		Vertical hydraulic conductivity (m/s) x 10^{-3}		Specific yield		Storage cefficient (m^{-1})
	Range	Average	Range	Average	Range	Average	
Upper (1- 6 m)	0.12 – 5.9	1.3	0.009 – 0.021	0.015	0.06 – 0.22	0.13	$1e^{-5}$
Lower (6 m+)	0.19 – 10.1	2.8	0.025 – 0.083	0.056	0.09 – 0.27	0.18	$2e^{-5}$

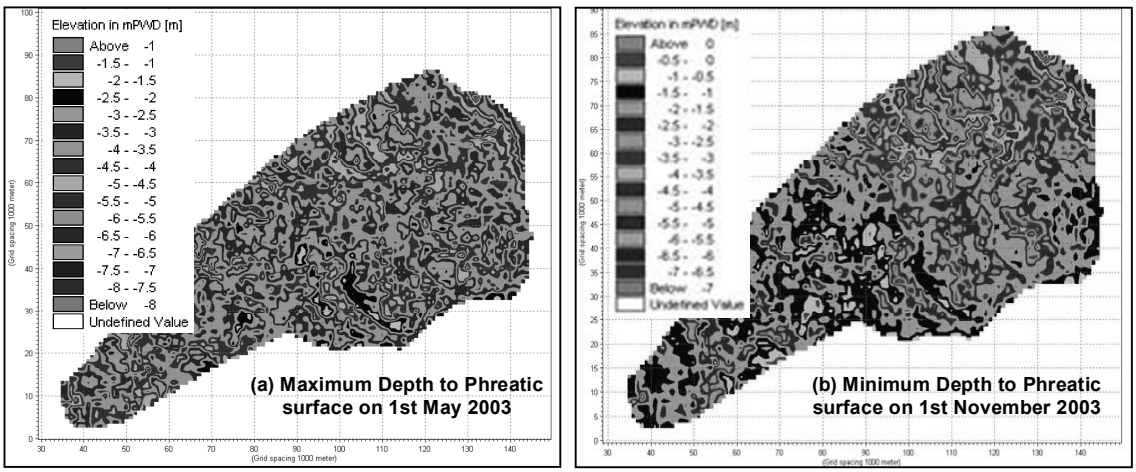

Figure 13 Map of Depth to phreatic surface under option I for a larger area including Lohagara Municipality.

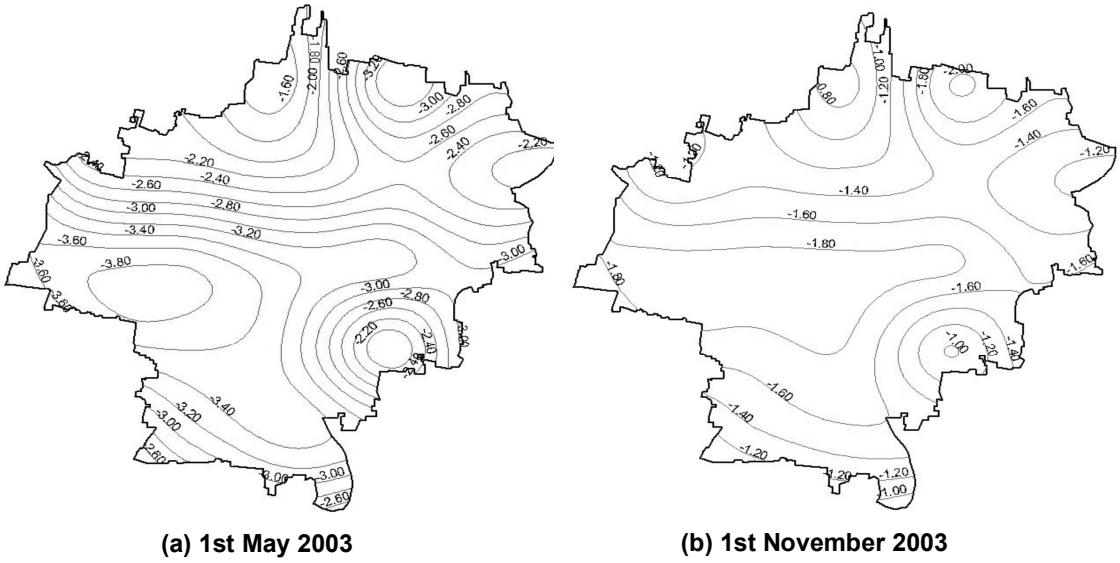

Figure 14 Contour map of depth to phreatic surface under option I for Lohagara Municipality.

4.3 Assessment of Groundwater Resources

4.3.1 Groundwater Resources in Shallow Aquifer

The base condition in this study refers to hydrological situations and other existing conditions that prevail in the practical field in the design year (2003), which has been estimated based on return period analysis of observed rainfall records (Table 1). The main purpose of simulating the base option is to understand the present state of

the project under design year in terms of volume of water presently being used, whether it crosses the potential recharge of the aquifer, present state of GWT, crop coverage and scope for further irrigation expansions considering the water availability. Crop coverage under different crops at existing conditions has been considered in base option. Total amount of water required for irrigation is abstracted from the underlying aquifer of the study area. In the study area, GW is being used to meet the irrigation as well as domestic demands. Thus, reliable assessment of GW resources is essential for effective water resources management and preservation of environment. Accordingly, GW resources of the study area has been estimated based on the available resources before irrigation period. The availability of GW in Lohagara Municipality of Narail district has been estimated on May 01, 2003 and November 01, 2003 for two different depths of 6 m and 7 m. It has been estimated that GW resources in the shallow depth for Lohagara Municipality at the date of May 01, 2003 for 6 m and 7 m depths are 7.48 MCM and 10.00 MCM, respectively. In addition, the GW resources in the shallow aquifer at the date of November 01, 2003 are found as 11.29 MCM for 6m depths and 13.81 MCM for 7m depths.

4.3.2 Groundwater Resources in Deep Aquifer

The GW resource in the deeper aquifer is calculated based on the water balance study for the individual layers, since most of the water supply for domestic uses mainly depends on the availability of water resources at the deeper aquifer, A trial and error method is applied to find out the maximum abstraction without any negative changes of storage for the deeper aquifer. The net recharge for the deeper aquifer is estimated based on the final water balance study and presented in Figure 15.

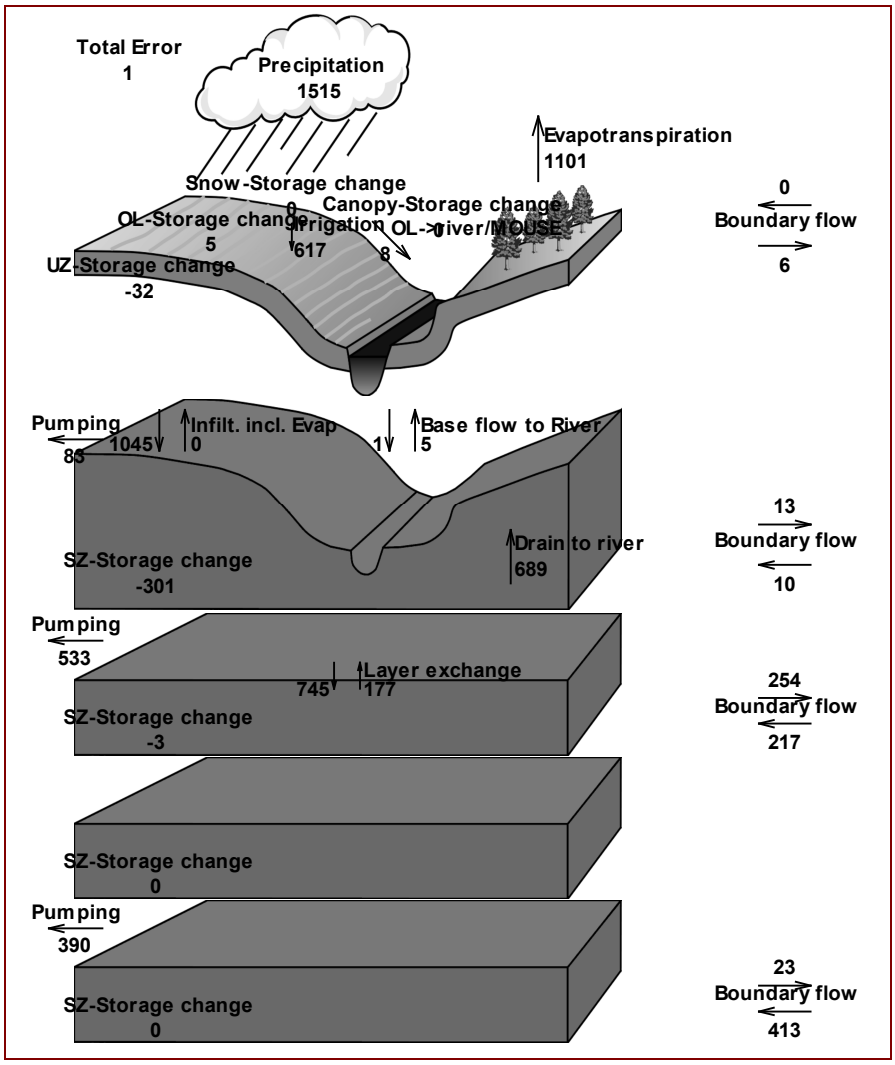

Figure 15 Water balance (in mm) for base condition on 2003 in Lohagara Municipality.

However, this assessment is based on the secondary data by assuming that the aquifer properties and boundary data for the deeper aquifer is similar to the upper aquifer. The main limitation of this assessment is that this obtained result need to be verified further with the availability of field pump test data. The net recharge for the deeper aquifer is calculated as net recharge = 0 mm (from upper layer) – 23 mm (for outflow) + 413 mm (for inflow) = 390 mm. This amount of recharge mostly comes from the horizontal flow as presented in Figure 15. For this amount of GW recharge, the corresponding annual aquifer storage volume is estimated as 7.25 MCM.

4.3.3 Evaluation of Aquifer Sustainability

The developed GW model is simulated under option II for identifying the potential impacts due to the water withdrawal activities in future. Sample plot of GWL hydrograph is presented in Figure 16. The sample plot of GW head reveals that the declining of GWL is reasonably insignificant compared to the GWL of option I (base condition in 2003). The main reason is that the GWL becomes steady state within 6 months due to recharging of the aquifer. This implies that GW can be withdrawn from the underlying aquifer, which is being recharged seasonally by the sources of precipitations and boundary flows. It represents that GW withdrawal rate from the underlying aquifer remains within the safe limit (safe yield) of the aquifer, which makes it sustainable for further GW utilization in the study area. However, it should be emphasized that the assumed conditions must prevail in future without any change. Thefore, it is noteworthy that conjunctive utilization of SW and GW will be a good option to utilize the aquifer effectively for sustainable water supply of the Lohagara Municipality in Bangladesh.

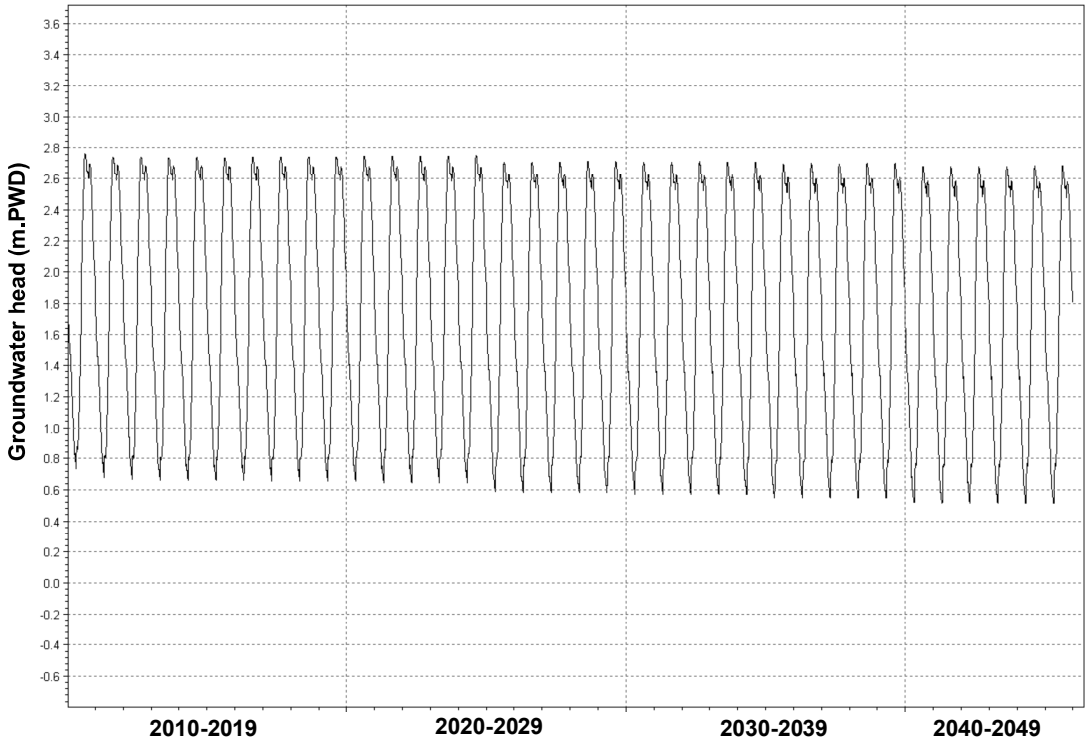

Figure 16 GWL hydrograph under option II during long-term GW simulation for aquifer sustainability.

5. CONCLUSIONS

From the developed hydrographs and water balance studies for different periods in the present study, the following conclusions can be drawn for the Lohagara Municipality of Narail district of Bangladesh:

- It can be concluded from the stratigraphic analysis that two major (upper and lower) aquifers are evidenced within the depth from 61m to 95m and from 198m to 216m beneath the ground surface throughout the study area. In addition, a thick aquifer having thickness approximately 30m exists at Isangati and Kamthana Lohagara. However, there exists a prominent aquifer at 200m to 235m throughout the study area containing varying thickness of more or less 36m below the aquiclude.

- The analysis of storage coefficient and hydrostratigraphic sections shows that the upper aquifer is semi-confined and lower aquifer is confined in nature. In addition, estimated specific yield of the aquifers indicates that the aquifer mainly consists of fine to medium sand.
- Maximum depth to GWT occurs at the end of April mainly due to irrigation abstraction and natural drainage which, however, recovers almost to its original position due to natural recharge at the end of September.
- The present study also estimates that GWR in the shallow aquifer for Lohagara Municipality at the date of May 01, 2003 for 6m and 7m depths are 7.48 MCM and 10.00 MCM, respectively whereas the GWR at the date of November 01, 2003 found as 11.29 MCM for 6m depths and 13.81 MCM for 7m depths.
- From the water balance studies, the present study concludes that the GW recharge is about 390mm for the year 2003 for the deep aquifer, which comes mostly from the horizontal flow. For this amount of GW recharge, the corresponding aquifer storage volume is found to be 7.25 MCM annually.

For the purpose of aquifer sustainability, following recommendations are suggested:

- Conjunctive use of SW and GW to meet the domestic, irrigation and industrial demand should be promoted and a conjunctive water allocation plan should be established.
- GWT and quality monitoring should be conducted regularly. The production well monitoring should also be done periodically to minimize the operation and maintenance cost of the project as well as to optimize the resource utilization.

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