添付資料３　地下水解析報告書

Japan International Cooperation Agency (JICA)

Feasibility Study of Bheramara Combined Cycle Power Plant, Bheramara, Kushtia

Groundwater Modelling of the Proposed Site of Bheramara Power Station and Surrounding Areas

FINAL REPORT

SUBMITTED BY

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ACRONYMS AND ABBREVIATIONS

BADC	Bangladesh Agricultural Development Corporation
BBS	Bangladesh Bureau of Statistics
BM	Bench Mark
BMD	Bangladesh Meteorological Department
BTM	Bangladesh Transverse Mercator
BUET	Bangladesh University of Engineering and Technology
BWDB	Bangladesh Water Development Board
CEGIS	Centre for Geographical Information System
DEM	Digital Elevation Model
DPHE	Department of Public Health Engineering
DOE	Department of Environment
DSHTW	Deep Set Hand Tube Well
DTW	Deep Tube Well
EC	Electrical Conductivity
EIA	Environmental Impact Assessment
GoB	Government of Bangladesh
GPS	Global Positioning System
GSB	Geological Survey Of Bangladesh
GWL	Ground Water Level
GWT	Ground Water Table
HTW	Hand Tube Well
JICA	Japan International Co-operative Agency
JL	Jurisdiction Limit
LGED	Local Government Engineering Department
MPO	Master Plan Organization
NCA	Net Cultivable Area
NWMP	National Water Management Plan
NWP	National Water Plan
PVC	Polyvinyl Chloride
PWD	Public Works Datum
STW	Shallow Tube Well
SW	Surface Water
SoB	Survey of Bangladesh
TOR	Terms of Reference
UNDP	United Nations Development Programme
UNICEF	United Nations Children’s Emergency Fund
WL	Water Level
WQ	Water Quality
WRP	Water Resources Planning

1.0 INTRODUCTION

1.1 Background and Objectives

The site of the proposed Bheramara Combined Cycle Power Station is situated on the right bank of the Padma River, approximately 400m east from the bank, and approximately 600m north from the Pump Station of G.K. (Ganges - Kobadak) Irrigation Project. The site is also situated approximately 1.8 km south from Hardinge Bridge (rail way) / Lalon Shah Bridge (road) and approximately 350m east from the Bheramara Bypass Road toward Kushtia City. The power station will require 1300m^3/hour of water for cooling purposes. Because of the uncertainty in the use of river water it has been decided to evaluate groundwater resources of the project site and surrounding areas.

The prime objective of the study is to design, construct, calibrate and run a digital computer model which would realistically simulate the groundwater system prevailing at the project site and surrounding areas. The purpose of constructing a model is to assess the potentiality of the aquifer system of Bheramara Upazila and surrounding areas to provide a continuous supply of 1300m^3/hour of water for cooling purposes of the power plant.

In accordance with these requirements, using the results of groundwater investigations at the proposed site along with the existing groundwater database and the current understanding of the aquifer system, a model has been constructed to simulate all the principal hydrogeological processes that have been observed in the study area.

Many of these processes are complex and in order to effectively simulate them the model has, of necessity, had to incorporate relatively complex routines. Nevertheless the model has been designed to be easily understood and operated and, if necessary, to facilitate modifications in the future. After calibrating the model and sensitivity analyses, the model was used to predict the condition of groundwater after 20 years of pumping.

This document constitutes the Final Report which described the database and the concept of the model, set out the results of the calibration and testing of the model. This report concentrates upon the results of the model predictive runs and the recommendations.

1.2 Summary of Principal Data Sources

Extensive geological, geomorphological, meteorological and hydrological data are needed for preparing groundwater model. The quality of modelling results depends strongly on the availability and quality of various input data. Geological, meteorological and hydrogeological data of different kinds were collected from Bangladesh Water Development Board (BWDB), Department of Public Health Engineering (DPHE) Bangladesh Agricultural Development Corporation (BADC), Centre for Geographic Information System (CEGIS) and local government offices. Exploratory bore log data of the area were collected from BWDB.

Groundwater investigations in the project site included drilling of 13 boreholes up to a depth of about 100m, investigation of subsurface unconsolidated rock samples using sieve analysis and electrical logging of the boreholes. This provided a clear picture of the hydrostratigraphy at the project site. The delineation of aquifer system at the project site also matched with the pre-existing data of the surrounding area obtained from different sources.

Long term pumping test conducted at the project site provided a unique set of time-drawdown data of 12 observation wells which were analysed using suitable mathematical models to estimate the aquifer property. These data were very important for constructing the model and substantially increased the confidence in generating realistic groundwater model.

2.0 SUMMARY AND RECOMMENDATIONS

This report describes the results obtained from using a mathematical model to evaluate the potential of the groundwater resources to supply 1300m^3/hour of water continuously for the cooling system of proposed power plant. Numerous runs of the model were made to test the sensitivity of the various model parameters. By using the available hydrogeological data it has been possible to simulate historic groundwater fluctuations of the study area for the calibration period of 2005 to 2007 and to predict the future groundwater condition 20 years after the initiation of pumping.

This study concentrated on the overall evaluation of groundwater resources and hydrogeological characteristics of the proposed site and surrounding areas as a prior requirement for developing a realistic groundwater model. Physiographically, the study area falls within Active Ganges River Flood Plain and High Ganges River Flood Plain. The surface geology of the study area comprises unconsolidated alluvial sand, alluvial silt and deltaic silt of Recent to Pleistocene age. The Padma River flows through the study area carrying huge volume of water per year to the Bay of Bengal. The study area enjoys a subtropical monsoonal climate.

Analysis of bore logs of the project site and surrounding areas indicates that the study area is underlain by an extensive aquifer system which in some parts is covered by up to 36m thick clay and silty clay aquitard. The Padma River cuts this layer and this layer is absent at the bottom of the Padma and in some areas adjacent to the river Padma. The thickness of the aquifer is more than 100m throughout the whole area. The bottom of the aquifer has not been encountered in any of the borehole of the study area. In general the entire sequence down to some 120m below ground level becomes coarser with depth. The aquifer is subdivided into the Composite aquifer and the Main aquifer following UNDP (1982) three-layer model. The Composite aquifer is the uppermost aquifer, composed mainly of very fine to fine sand and its thickness in the study area varies from 5 to 51m. The Main aquifer underlies the Composite aquifer. It is composed mainly of medium grained sands with some coarse sands and gravels. The thickness of this layer is more than 75m in most part of the study area. Analysis of pumping test data of the project site provided aquifer transmissivity of 4456 m^2/d, horizontal hydraulic conductivity of 42.5 m/d and storativity of 0.007. These values were used for aquifer characterisation in the model.

The analysis of groundwater level data showed that the minimum elevation of water level in the study area varies from 6 to 8.5 m and the maximum elevation varies from 11 to 14m. In dry season, groundwater moves towards the river. In wet season, surface water moves from the river towards the aquifer. Fluctuation of water table is higher in narrow zone adjacent to the river Padma. The trend of groundwater level in the study area remained regular and steady over the last 10 years. The water chemistry data indicate that the groundwater is suitable for domestic and other uses.

A conceptual model was developed taking into consideration of the hydrostratigraphy of the study area. Model area was chosen carefully so that the stresses to the system provided by the pumping wells at the project site do not reach the boundary. A thee layer transient groundwater flow model was set up with time steps of a month using MODFLOW. Layer 1 comprises low permeability clays and silts. Layer 2 comprises moderately permeable very fine sand to fine sand. Layer 3 comprises medium to coarse sand and gravel. Different hydrogeological parameters were assigned for each of the modelled layer. River, recharge and evapotranspiration boundaries along with municipal and irrigation pumping wells were incorporated to the model. The model was then calibrated by matching the observed head at different parts of the modelled area with the calculated head and the sensitivity analysis was conducted.

After calibration 10 pumping wells with a discharge of 3120 m^3/day were introduced in the model at the project site. Two model scenarios were considered. In the first scenario the pumping wells were arranged in line over a distance of 1 km. In the second scenario the pumping wells were arranged in cluster over a distance of 400m.

For both the scenarios the model was run for twenty years maintaining projected future increase in groundwater abstraction. The modelled minimum elevation of groundwater table occurs in the month of May. The River Padma is effluent in the dry season. However, due to lowering of the head, water from the river bed may pass into the aquifer in areas adjacent to the pumping wells. The modelled maximum elevation of groundwater table occurs in the month of September. It has been found that the Padma River lying in the eastern side of the project site acts as a recharge boundary for the aquifer system in the wet season. The pumping wells in the proposed power plant will get plenty of water supplies from the river and water level in the pumping well will rise substantially. The aquifers system is fully recharged in the wet season.

For the first scenario about 1 km^2 area surrounding the pumping wells of the proposed power plant water level may decline by 1 to 3 m from the existing water level. As the cone of depression is elongated in the direction of the river, the river water from a large area will infiltrate into aquifer due to enhanced vertical head gradient.

For the second scenario about 1 km^2 area surrounding the pumping wells of the proposed power plant water level may decline by 1 to 4 m from the existing water level. The cone of depression is circular and covers a shorter part of the river. The infiltration of river water from a small area will infiltrate into the aquifer.

Taking into consideration of the model predictions it has been recommended from this study that a number of pumping wells of cumulative discharge of 1300 m^3/hr can be set up in a one kilometre or longer line parallel to the river Padma.

Several hundred suction mode tubewells (e.g., HTWs or STWs) inside the cone of depression may fail to draw water from the aquifer in dry season. However, these tubewells can be replaced with force mode hand tubewells (DSHTWs or Tara pumps) which are widely used in different parts of Bangladesh.

It is concluded from this study that the natural aquifer condition in the study area would be suitable for supplying 31200 m^3/day of water continuously without massive lowering of groundwater table and environmental degradations. Padma River contributes significantly in recharging the aquifer in each year.

The MODFLOW results generated through this modeling effort reflect only assumed conditions based on site data, collected data or literature values. It is also assumed that the rainfall, river water level and other climatic factors would not change in the next 20 years.

3.0 THE PHYSICAL BASIS OF THE MODEL

3.1 Introduction

The groundwater model developed during the study was based upon the current level of information and understanding of the hydro-meteorological, hydrological and hydro-geological patterns which prevail in the study area. The model's physical basis has therefore been dictated by the extent of the available database and the major known physical features and processes which control the groundwater response to both seasonal recharge and widespread aquifer withdrawals. Pre-existing data have been supplemented with new data from recent drilling and pumping test in the study area.

3.2 Description of the study area

3.2.1 Location and Extent

The location of the study area is shown in Figure 1. The study area is situated between 23º 56’ and 24º 11’ north latitude and between 88º 54’ and 89º 11’ east longitude. Bheramara Upazila of Kushtia district and Iswardi Upazila of Pabna district constitute the study area. The two Upazilas are separated by the river Padma or Ganges. The two Upazilas were taken into consideration for developing detailed regional model. The catchment of the proposed well field located on the bank of the river Padma is extended to both side of the river Padma. The area is well communicated with the other part of the country by railway, road and river.

3.2.2 Climatic Condition

The study area experiences a tropical monsoon climate with three relatively distinct seasons being recognized:

Monsoon Season: Usually extends from June to October with high humidity, high rainfall and maximum temperatures in excess of 30°C.

Cool Season: Usually extends; from November to February and is characterised by low rainfall and maximum temperatures below 32°C.

Hot season: Usually extends from March to May with temperatures in excess of 30°C and north-westerly cyclonic storms giving intense scattered rainfall.

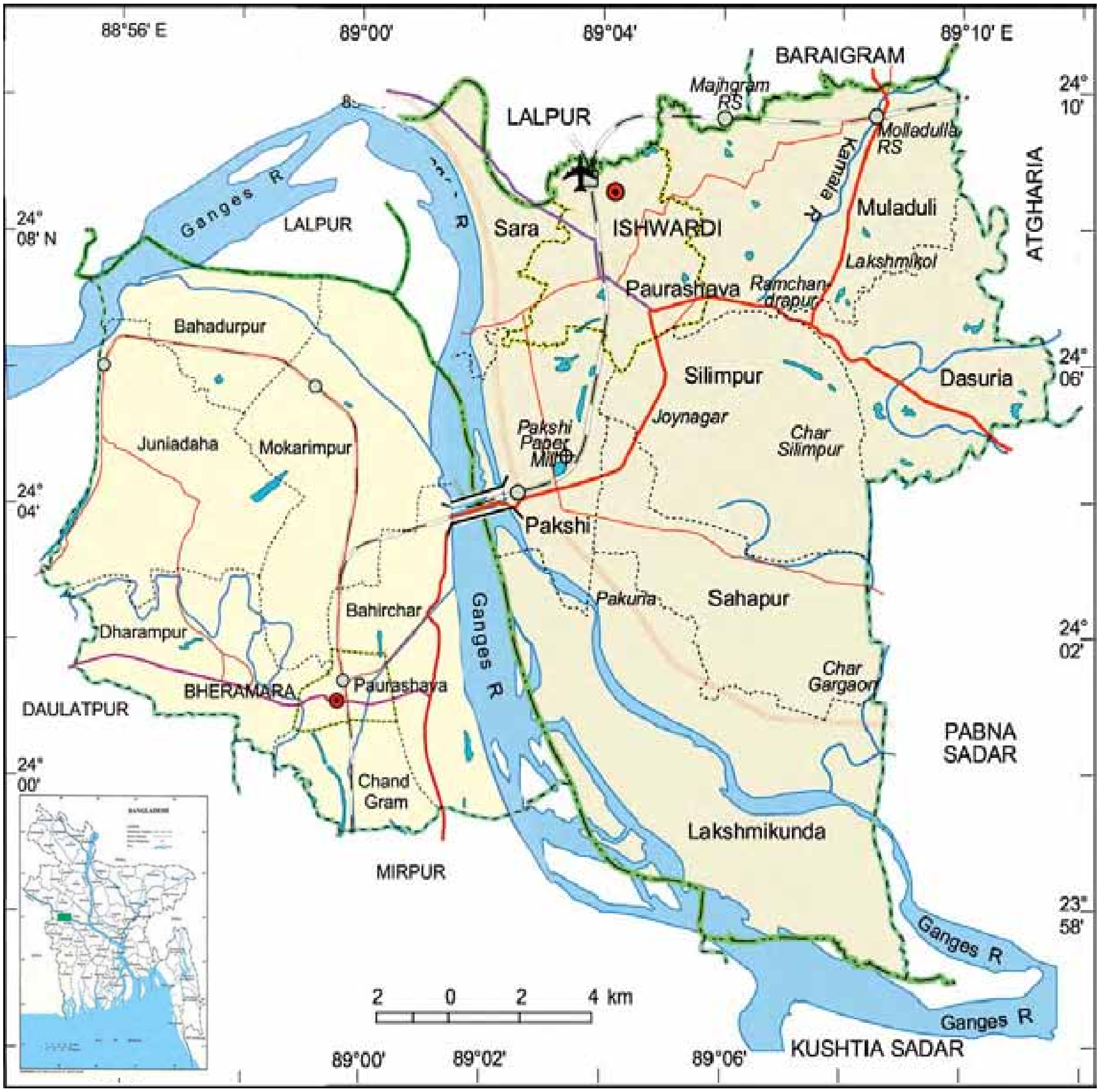


Figure 1. Location map of the study area

The annual distribution pattern emphasises the high summer rainfall when approximately 95% of the total annual rainfall occurs between April and October. Figure 2 and 3 show monthly average rainfall of Bheramara and Iswardi Upazilas, respectively. Annual rainfall averages about 1467 millimetres. The average high temperature is 37.8°C and the average low is 11.2°C. Monthly average humidity of Iswardi Upazila is given in Figure 4. Humidity is low in the month of March and April whereas humidity is high in the month of August and September.

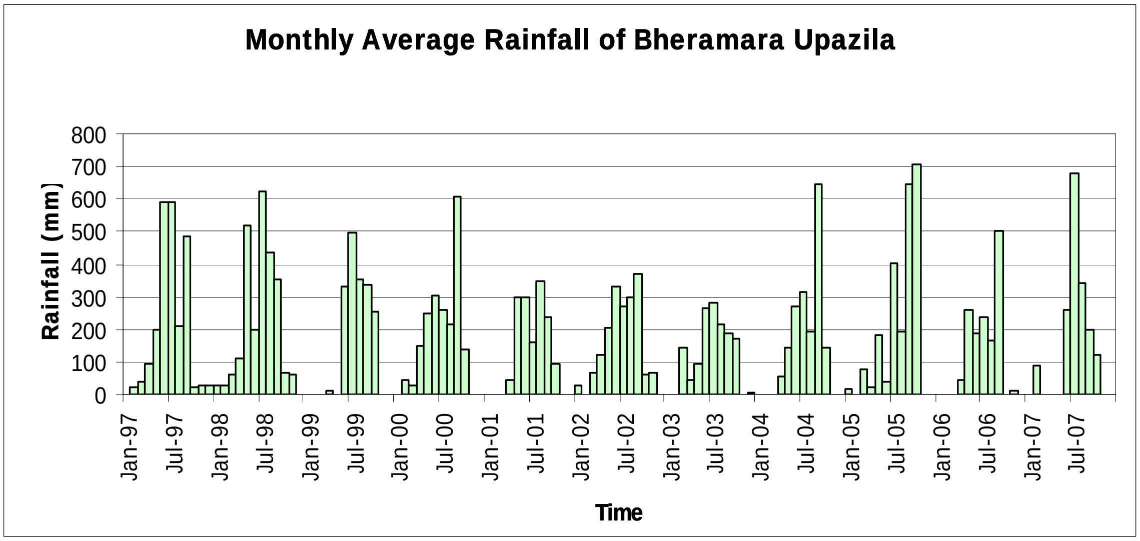


Figure 2. Monthly average rainfall of Bheramara Upazila

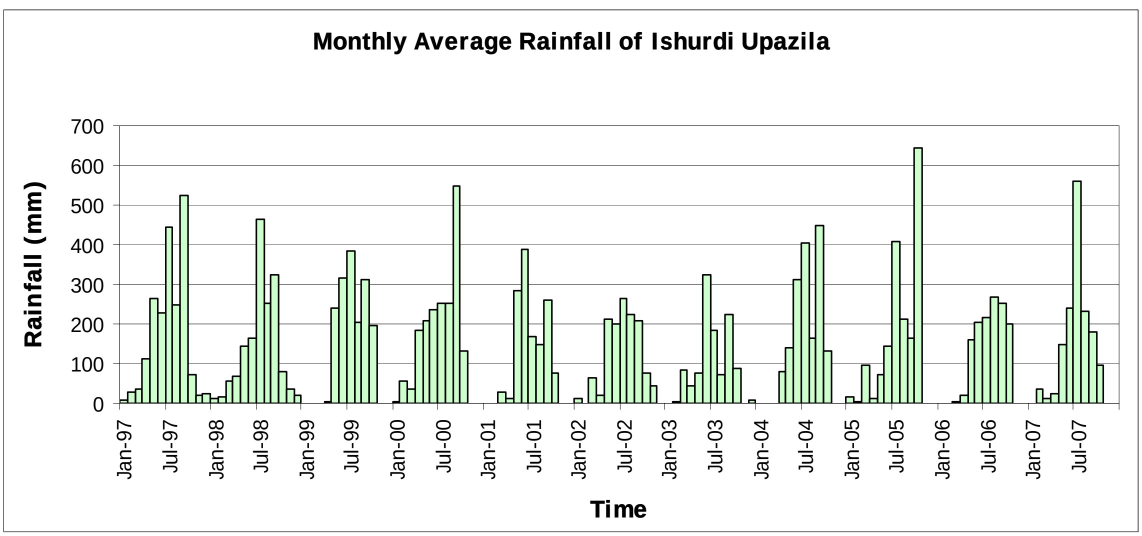


Figure 3. Monthly average rainfall of Iswardi Upazila

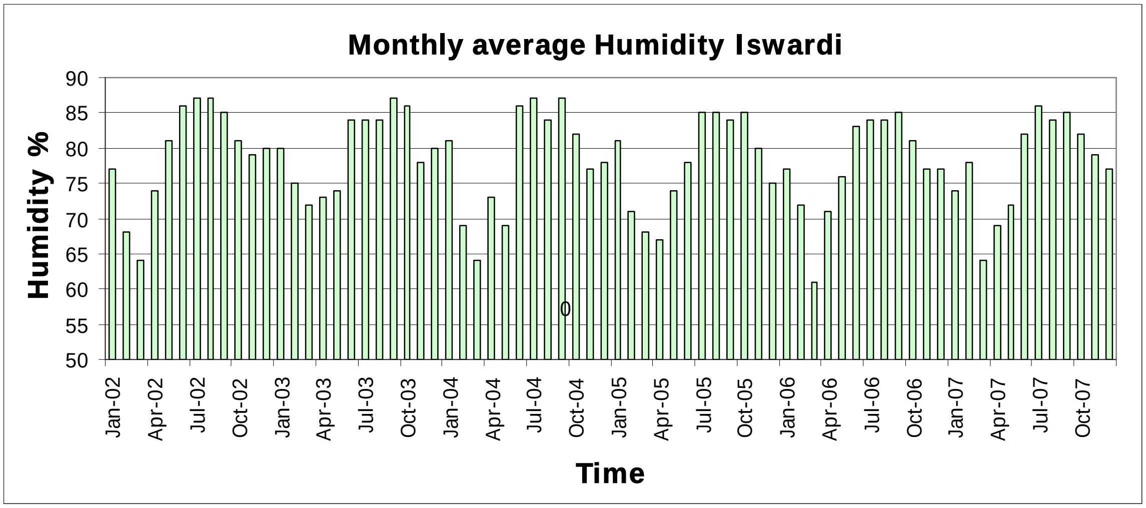


Figure 4. Monthly average humidity of Iswardi Upazila

3.2.3 Topography and Drainage

The study area is a gently undulating deltaic plain generally sloping from northwest to southeast. The area is part of a moribund delta and has as the dominant topographic elements, ridges, inter-ridge depressions and basins, active streambeds and abandoned channels. The ridges are usually linear and comprise level to very gently undulating or sloping young and old levees that form the point bar of meandering rivers.

The average ground surface elevations range from about 16 metres above mean sea level to about 11 metres along the eastern and southern boundary. The elevation between ridges and basins differs by between 2 and 6 metres.

The surface drainage within the study area is provided by many rivers all of which are either major or minor distributaries of the River Ganges. The general drainage direction traverses the study area from north to south. The principal river is the River Ganges.

In each monsoon season surface flooding occurs across some part of the study area, particularly in the area adjacent to the rivers. Figure 5 shows the flood hazard map of the study area.

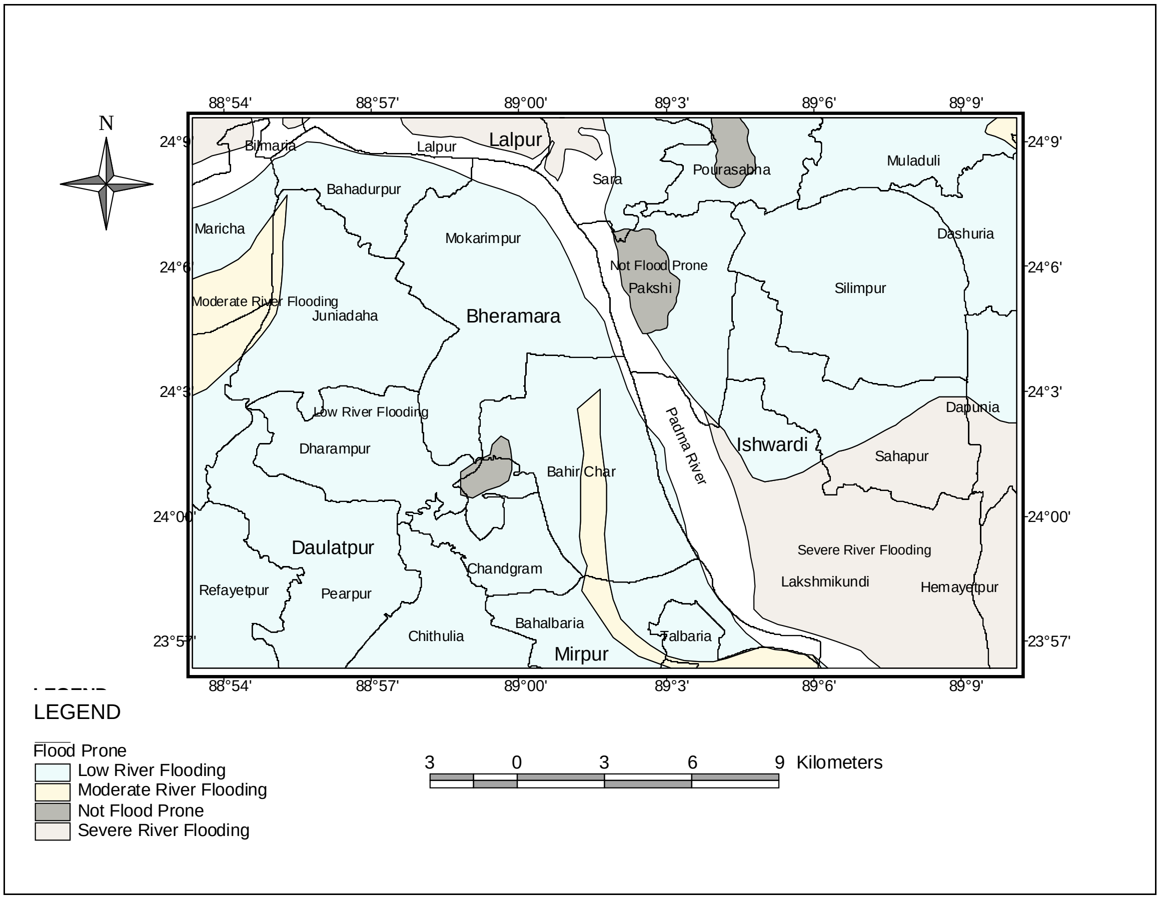


Figure 5. Flood hazard map of the study area

Numerous channels have been excavated in the study area to assist drainage, most of which ultimately connect to the main rivers. As river embankments and drainage systems are improved the extent and depth of flooding will decrease.

Figure 6 shows the physiographic map of the study area. Two major physiographic units are present in the study area. Active Ganges River Flood Plain is relatively younger than the High Ganges River Flood Plain.

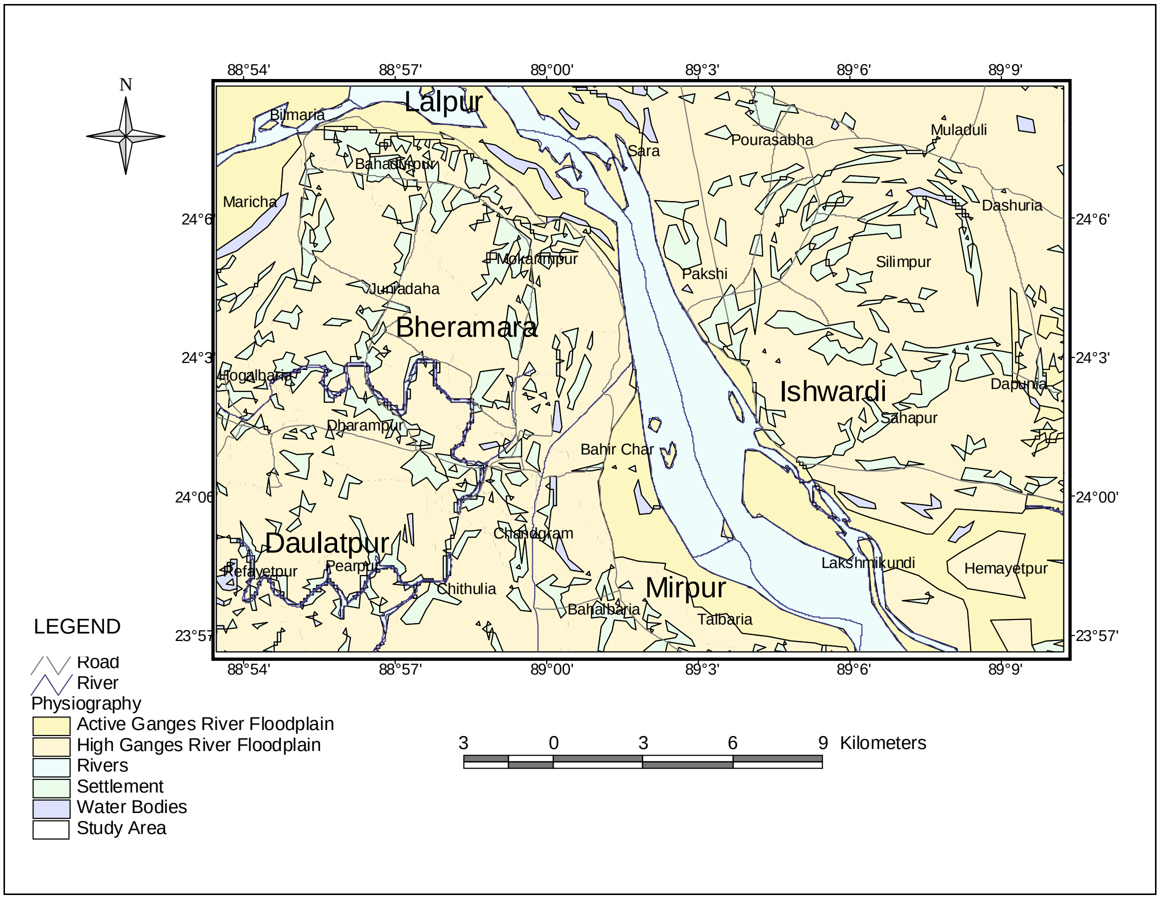


Figure 6. Physiographic map of the study area

3.2.4 Soils and Geology

The soils within the study area constitute calcareous Ganges alluvial sediments of Recent geological age. The fresh alluvium and young soils are usually calcareous throughout the entire profile. The older soils are often decalcified in part of the top and sub-soils, to a maximum depth of 1.2m, with the topsoil becoming medium to strongly acid when dry. Where plough pans are developed the topsoil is often gleyed. The older and better drained soils are usually more oxidised than the younger seasonally flooded soils.

The sediments underlying the study area are derived from the River Padma and thought to be of Pleistocene and Recent age. The surface outcrops of the sediments have been subdivided (Abu Bakr and Jackson, 1964) into the following generic types.

Streambed deposits: Usually consist of fine sands and interbedded silty sands with local occurrence of swamp deposits.

Inter stream deposits: Usually finer than the stream bed deposits with interbedded silts, silty clays, formed from the floods associated with the River Padma and its main distributaries.

Figure 7 shows the surface geological map of the study area. Areas adjacent to the river are covered by alluvial sand. South-western part of the study area is covered by deltaic silt, marshy and peat deposit whereas north-eastern part is covered by alluvial silt.

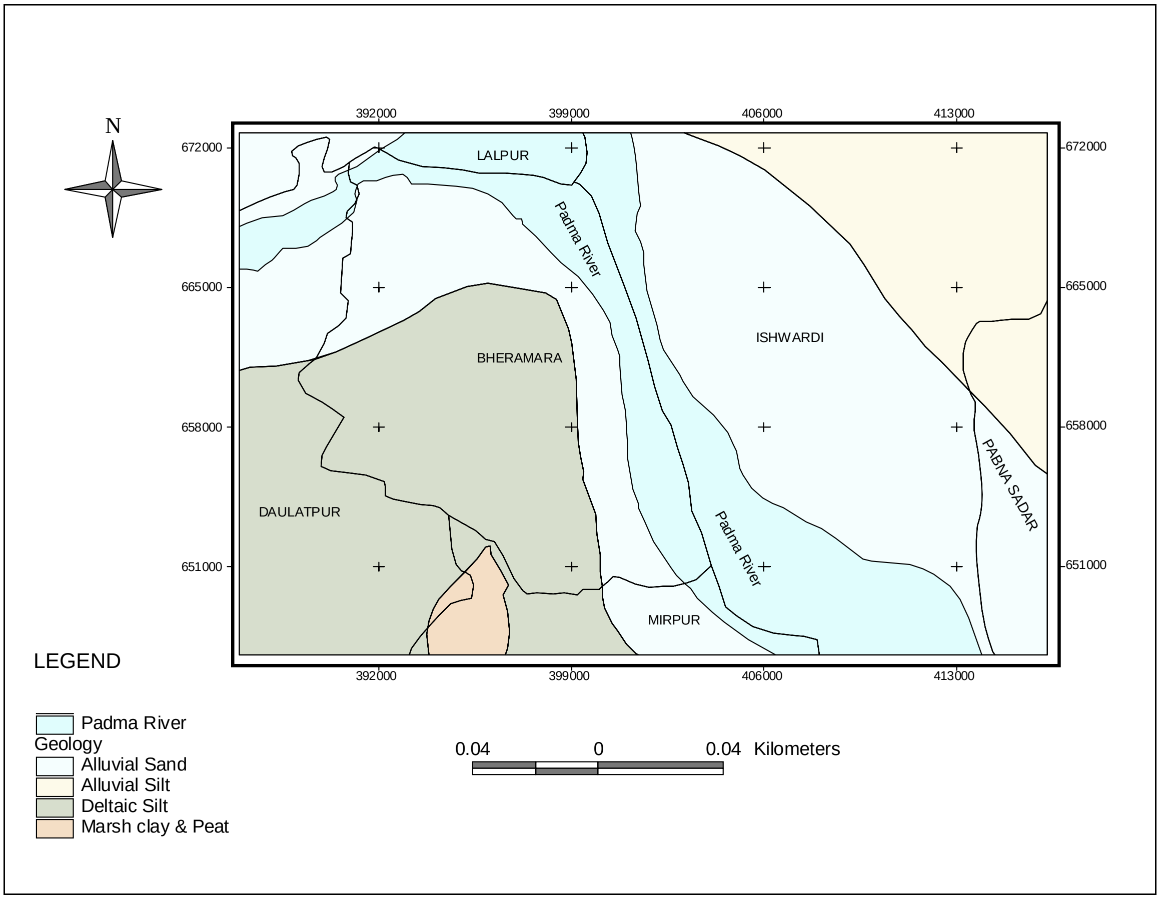


Figure 7. Surface geological map of the study area

The project site is situated on the point bar of the mighty Ganges -a meandering river. Typical fining upward sequence of a point bar is found in the drilling of bore holes at the project site.

3.2.5 River Systems and Hydrology

A unique river network drains the study area. The main river is the Padma or the Ganges which passes through the middle part of the study area. During monsoon heavy rainfall in the Bengal basin and surrounding areas initiates high flow of water through the Padma River. The elevation of water measured at SW 90 (Hardinge Bridge) in the wet season can be as high as 14 metres above PWD datum (Figure 8). The maximum elevation of water level generally occurs in the months of August or September in most of the years. During dry season (April or May) water level in the Padma River can be as low as 5 metres above PWD datum in most of the years.

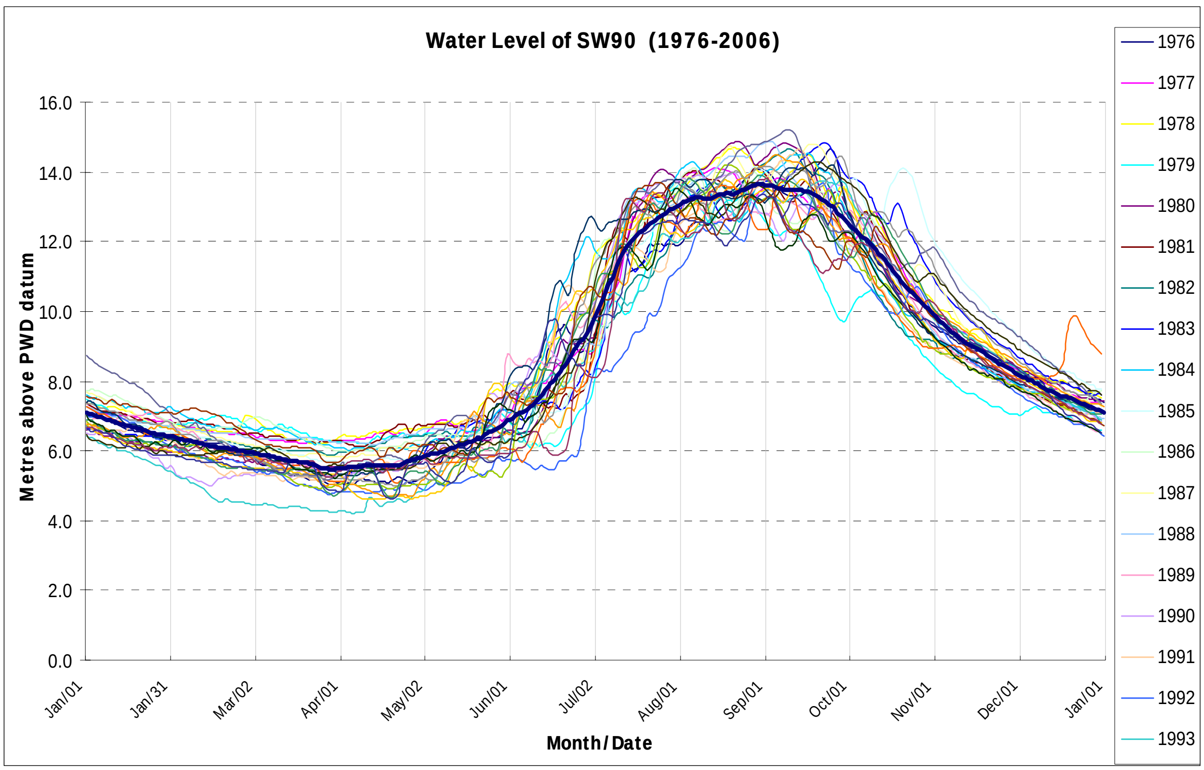


Figure 8. Padma River stage at Hardinge Bridge (SW 90)

The monthly maximum discharge of water through the river Padma varies between about 30000 to 70000 m^3/s (Figure 9). The maximum discharge in the river takes place in the wet season (August or September). The minimum discharge of water generally occurs in March and April and it varies from less than 500 m^3/s to 1000 m^3/s. The Padma is about 2 km wide in the study area. In this part the river gains water from surrounding aquifers from January to July and October to December (BWDB 1987). In August and September the river is influent.

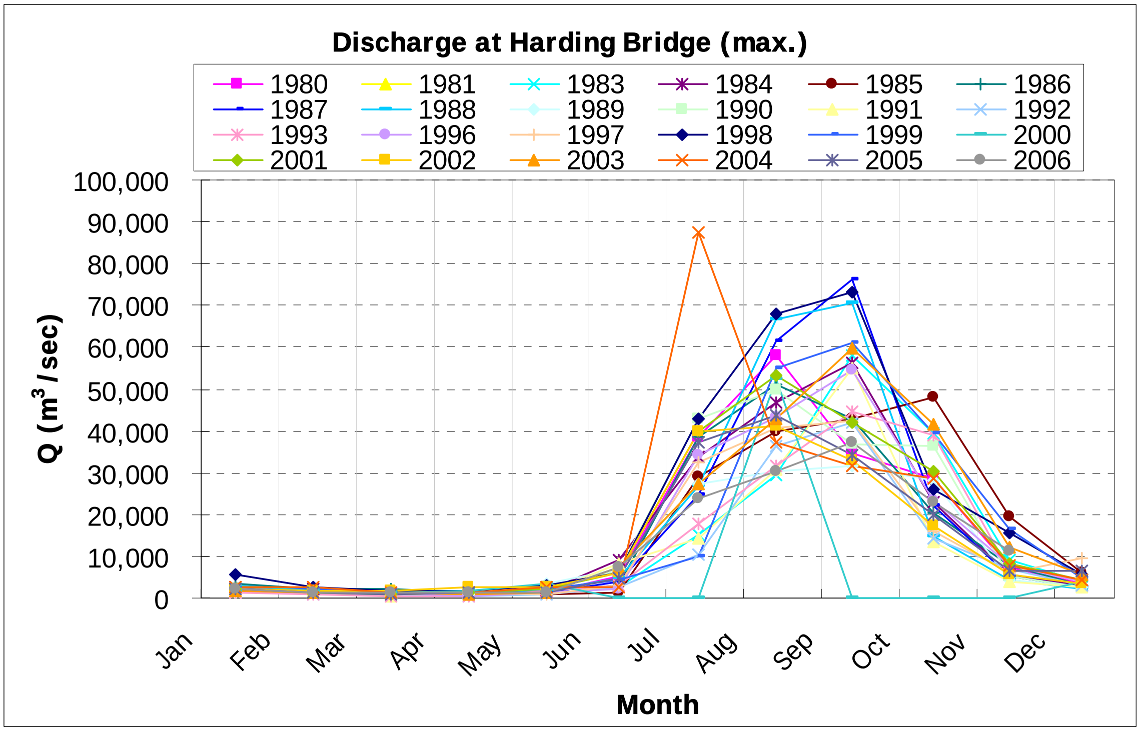


Figure 9. Monthly maximum discharge of Padma River at Hardinge Bridge

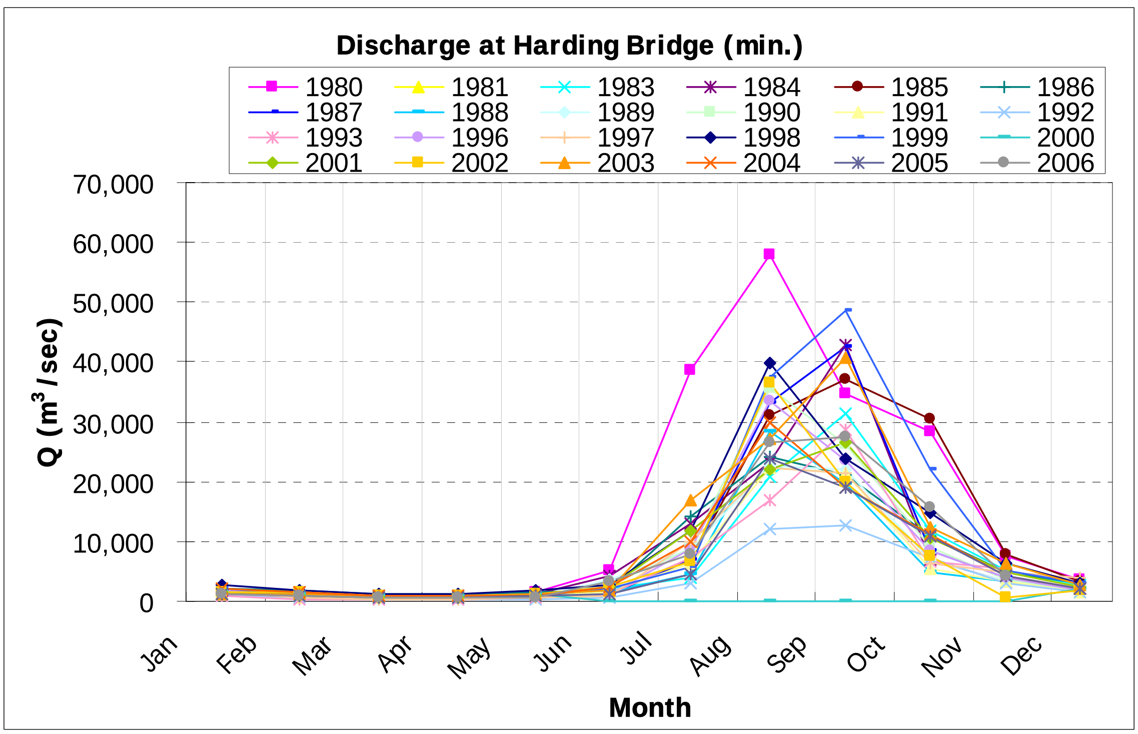


Figure 10. Monthly minimum discharge of Padma River at Hardinge Bridge

3.3 Hydrogeology

3.3.1 The Groundwater Reservoir

The study area is underlain by a good aquifer system in the context of a groundwater supply for irrigation and other purposes. Bore logs of the study area have been collected from different organisations to delineate the hydrostratigraphy of the study area. Information of deep aquifer has been revealed from the study of exploratory bore logs of about 330m depth in or around the study area. The aquifer system includes a surface aquitard, overlying the aquifers of main interest. Below the surface clays and silts are a series of sand beds which range from fine-grained to coarse-grained in nature. In general the entire sequence down to some 120 metres below ground level becomes coarser with depth. Below 120m, there are coarse sands, gravels and medium sands to a depth of about 200 metres. Little exploration has been undertaken at depths greater than 330m. The deep tubewells drilled by BADC extend to a depth of between 90 and 110 metres from the surface. In the context of the present study, the aquifer of main interest is the one composed of the fining upward sequences. Figure 11 shows the well location map of the study area. Figure 12 gives the geological cross section along A-A'.

The three layer aquifer model (UNDP, 1982) is the most commonly used conceptual model which has been applied to define the aquifer system of the study area (Table 1).

Table 1. The three layer aquifer model (after UNDP 1982)

Layer	Description	Lithology	Thickness (m)
1	Upper Clay and Silt	clay and silt	0-36
2	Composite aquifer	Very fine to fine sand	5-51
3	Main aquifer	Medium to coarse sand and gravel	75+

Upper Clay and Silt layer is an aquitard which lies on the surface of the study area. This layer is either absent or very thin (1-2m) in some parts adjacent to the Padma River. The thickness of the surface layer is variable ranging from less than 1 m to over 36 m. This layer comprises mainly silty clay and silt with some intercalations of fine sand and clay lenses. The whole system therefore would be expected to behave as an aquitard rather than as an aquiclude. This assessment is borne out by the rapidity of the water table reaction to rainfall events.

The Composite Aquifer is the uppermost aquifer composed mainly of very fine to fine sand and some time of medium sand with occasional clay layer. The thickness of this layer in the study area varies from 5 to 51m.

The Main Aquifer is the lowest aquifer considered in the present study. The aquifer appears to be fairly uniform over a wide lateral extent and to be composed mainly of medium grained sands with some coarse sands and gravels. Occasionally silty laminations are reported to occur. It is probable that, given the nature of the depositional environment, silty laminations are wide-spread occurrences. The effect of the silt layers may be to limit vertical flow within the aquifer, thereby inducing some horizontal flow. The bottom of this zone has not been encountered in any of the bore hole in the study area. The thickness of this layer is more than 75m in most part of the study area.

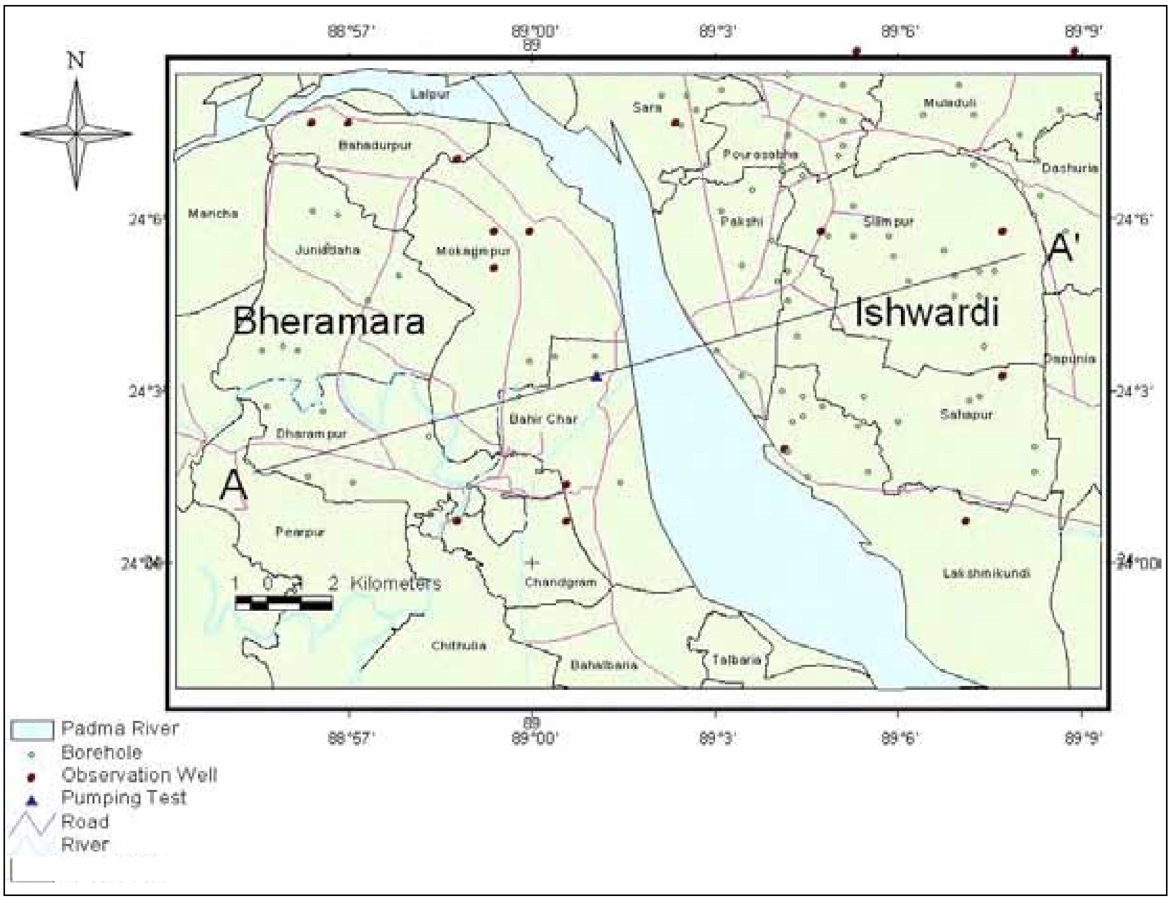


Figure 11. Borehole location map of the study area

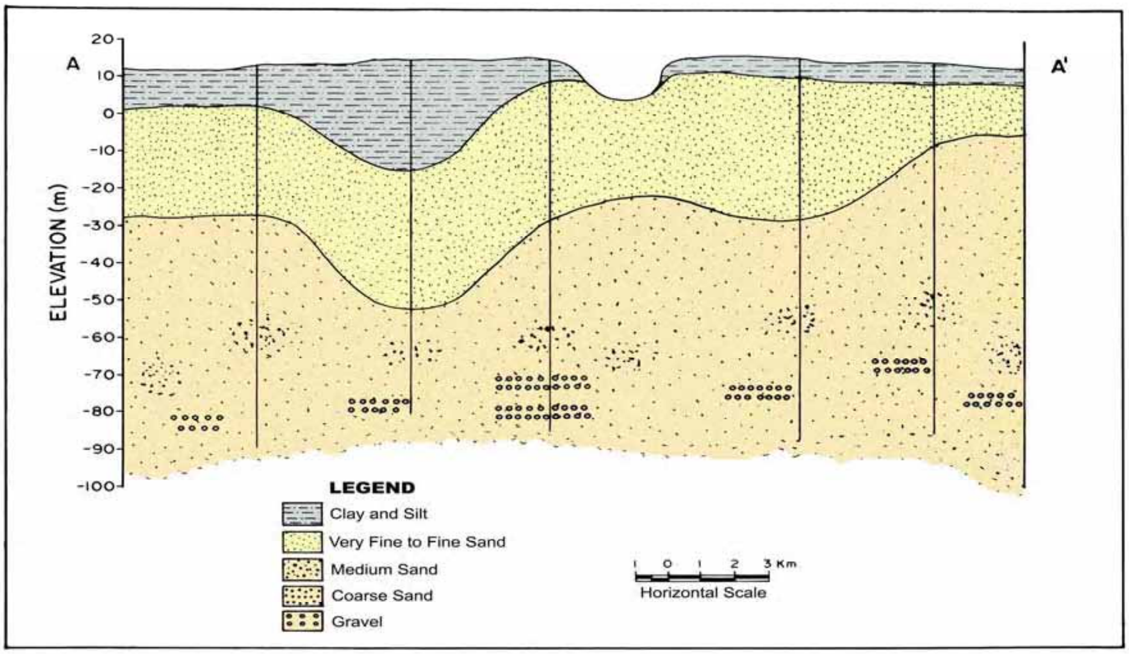


Figure 12. Geological cross-section along A-A'

3.3.2 Groundwater Movement

Water table contour maps for both dry and wet season have been drawn for the study area based on the water level monitoring data of observation wells. Observation wells may be dug well or piezometer. Dug wells are often shallow and in most cases do not represent the water level in the aquifer and therefore, dug well data were not used in preparing the water table contour maps.

In the dry season (April or May) water level elevation reaches to the minimum. Figure 13 gives the water table contour map of minimum elevation. The lowest elevation of water level generally occurs in wells nearer to the river. Groundwater in dry season moves towards the river.

In the wet season (August or September) groundwater level reaches to its maximum. Figure 14 shows the water table contour map of maximum elevation. The highest elevation of water table generally occurs in areas nearer to the river. This indicates that the aquifer is well connected with river.

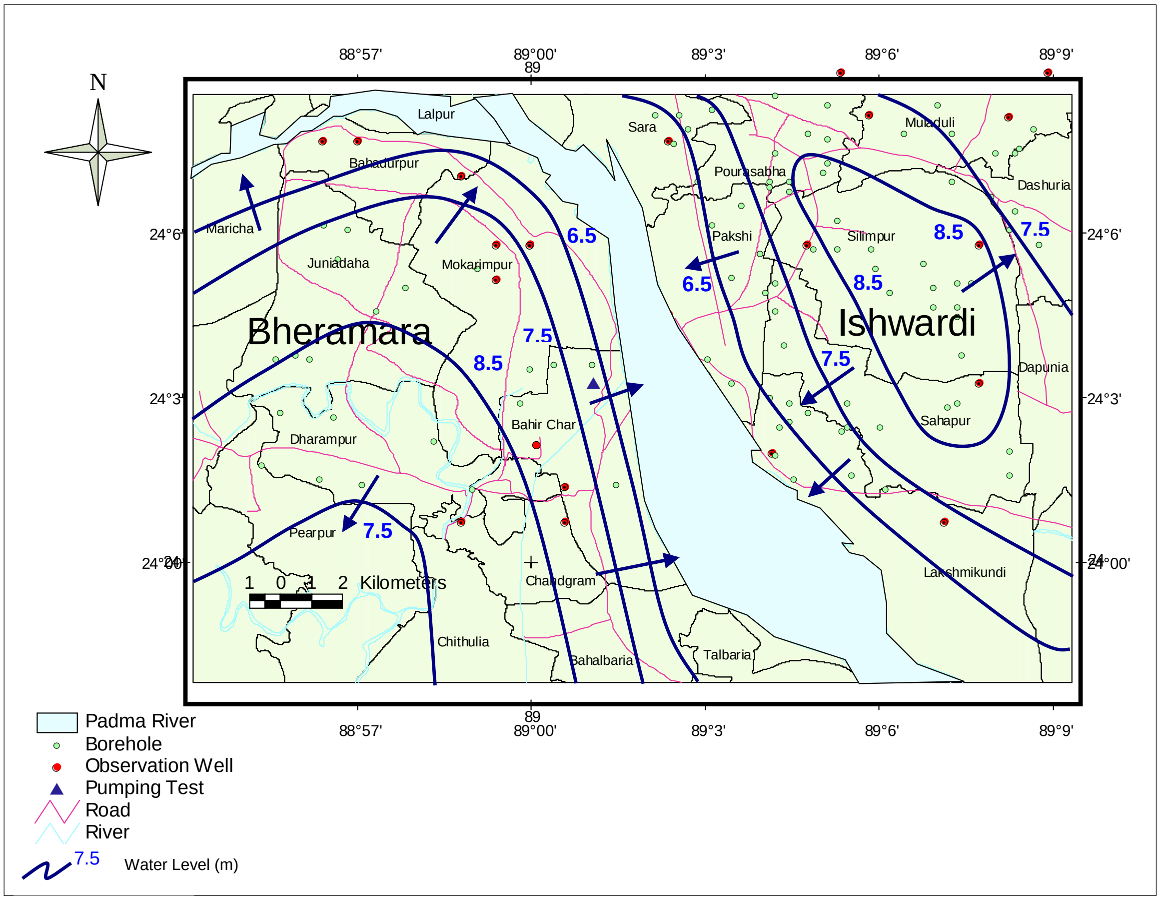


Figure 13. Water table contour map of minimum elevation

3.3.3 Groundwater Recharge and Evapotranspiration

Recharge means the replenishment of groundwater storage that has been depleted by withdrawal with tubewells and natural processes. The natural losses are due to outflows to rivers, canals, beels, haors and other depressed water bodies. The loss of water due to evaporation from water table and transpiration by plants also attribute to depletion of groundwater storage. Rainwater, floodwater, and irrigation return flow into the under-ground reservoir are the main sources of recharge to groundwater.

Recharge to groundwater depends on different physical settings, climatic conditions and hydraulic properties related to soil and aquifer. In the study area, during June to September, recharge occurs primarily through vertical percolation from relatively large amounts of rainfall and stored water within bunds around the paddy field and floodwater in places. However, during this period infiltration rate is lower in the non-cultivated, high lands and forests. Low topographic relief, slow drainage with large areas of relatively pervious soil and permeable underlying sediments are conducive to high recharge.

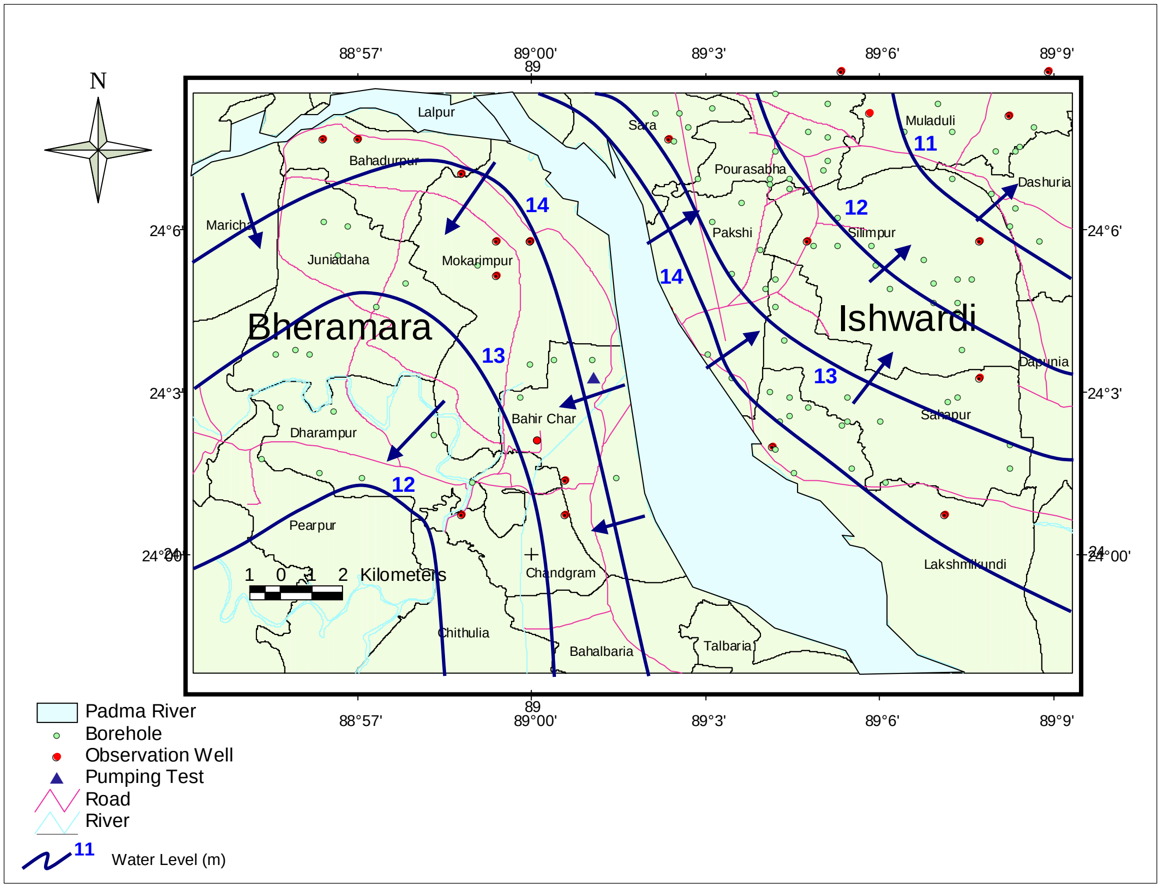


Figure 14. Water table contour map of maximum elevation

Rate of percolation at the start of the rainfall is high enough to bring the soil stratum to field capacity. After the field capacity of the soil is attained, water starts to percolate to the groundwater reservoir and the groundwater level starts to rise. Once the water table reaches the ground surface, recharge starts rejecting in places mainly during August and September when there is no space for further storage.

No specific and co-ordinated investigations have been carried out in the study area to define and quantify the individual processes of groundwater recharge. Much of the present understanding of the recharge process is based on studies elsewhere in Bangladesh and also on direct inference from existing monitoring data.

The development of the groundwater model for this study depended upon a preliminary understanding of the dominant modes of recharge. Existing data suggests that the groundwater reservoir of the study area is replenished or depleted by several distinct processes described below.

Rainfall and evapotranspiration process

Records of groundwater levels have .shown that the water table is very close to the land surface throughout the year and that there is a strong correlation between fluctuations in level and the highly seasonal rainfall pattern. In addition, the aquifer piezometry indicates that natural groundwater gradients across the study area are always very small which suggests that lateral movement of groundwater within the study area is consequently small and much less than the groundwater recharge rates inferred for the area. These factors strongly imply that a major proportion of recharge is derived from the vertical percolation of rainfall, while losses from the aquifer are most likely to result from direct evaporation or evapotranspiration from the water table.

Inundation due to river-overtopping

Numerous temporary or permanent surface-water bodies exist in the area. It is probable that they rest on impermeable silts and clays and are relatively insignificant in relation to the volumes of regional groundwater recharge from other sources. For this reason this possible mechanism of recharge has been ignored in the groundwater model.

The available well-monitoring data has shown that, during the monsoon season, groundwater levels rise above regional ground level in some part of the study area which coincides with the areas subject to regional seasonal river inundation.

Figure 5 shows the flood hazard map of the study area. No data are available regarding the depths of flooding across these areas or the rate of rise and fall of water levels as the rivers overtop their banks and subsequently recede. Comparison of field levels and embankment levels however, suggests that standing water depths may be as great as 2 metres in parts of the area, but are normally expected to be in the range of 0.5 to 1 metres. The significant extent and frequency of flooding represents a regionally important source of groundwater recharge.

Hydraulic continuity between the aquifer and rivers

The water table contour maps (Figure 13 and 14) show that the groundwater flow lines are influenced by the alignment of the River Padma. Fluctuations of groundwater levels are characteristically greater in the vicinity of the river than elsewhere and correspond closely, both in amplitude and elevation, to the fluctuating stage of the Padma River. The above factors strongly suggest that river leakage is important, at least locally, as a source of aquifer recharge. Bearing in mind the distribution of surface lithologies and the density of embankments and drainage lines traversing the study area it is possible that leakage between the aquifer and rivers is a widespread phenomenon.

Estimation of Recharge

The study of UNICEF (1993) estimated mean monthly recharge of Iswardi Upazila. This recharge rate is assumed to be valid for the whole study area. Table 2 gives the mean monthly recharge data of the study area.

Table 2. Mean Monthly Recharge Rate of the study area

Month	Recharge (mm)
January	10
February	12
March	23
April	59
May	92
June	102
July	102
August	82
September	49
October	31
November	12
December	10
Yearly Recharge	**584**

Estimation of evapotranspiration

A large number of more or less empirical methods have been developed over the last 50 years by numerous scientists and specialists worldwide to estimate evapotranspiration from different climatic variables. Penman method (Ponce 1989) is widely used method to evaluate potential evapotranspiration of any area using meteorological data. These data include mean monthly temperature, mean monthly net radiation, relative humidity and wind velocity.

Howard Humphre (1984) estimated mean monthly potential evapotranspiration of the study area based on modified Penman method. Table 3 gives the mean monthly potential evapotranspiration of the study area.

Table 3. Mean Monthly Evapotranspiration Rate of the study area.

Month	Potential Evapotranspiration (mm)
January	93.3
February	116.1
March	174.1
April	211
May	232.4
June	179.7
July	170.6
August	172.1
September	132.1
October	143.8
November	109.7
December	93.1
Yearly Evapotranspiration	**1850.3**

3.3.4 Hydrograph Analysis

Groundwater level observation well data have been collected from BWDB. These wells are either dug well or piezometer. Generally, water level data of these wells are collected at an interval of seven days. They provide very clearly the trend of water level in the study area. The fluctuation of water level in the study area is very much steady and regular. The lowest elevation of water level occurs during dry season particularly in the month of April or May. The groundwater level reaches to the highest elevation generally in the month of August or September. The fluctuation of water table varies between 4 to 7 metres in the study area. Higher fluctuation generally occurs in wells closer to the river Padma which indicates hydraulic connectivity between the river and the aquifer. Figure 15 to 20 give the hydrographs of the observation wells in the study area.

The regularity of hydrographs over a long period indicates that the effect of present groundwater development in the study area has not disturbed the natural water balance of the study area significantly. However, future groundwater development potential in the study area can be investigated using modelling technique.

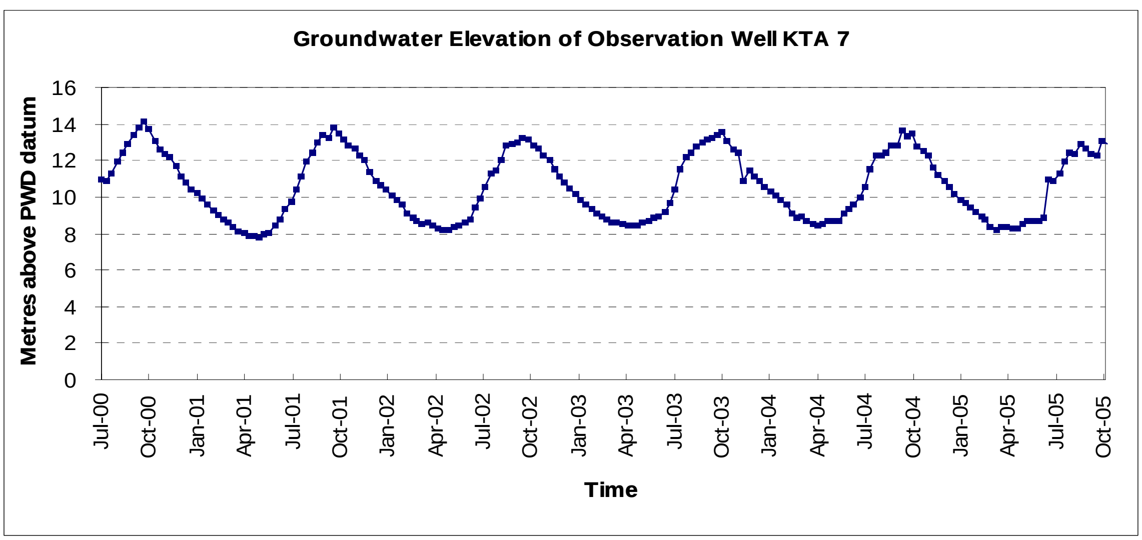
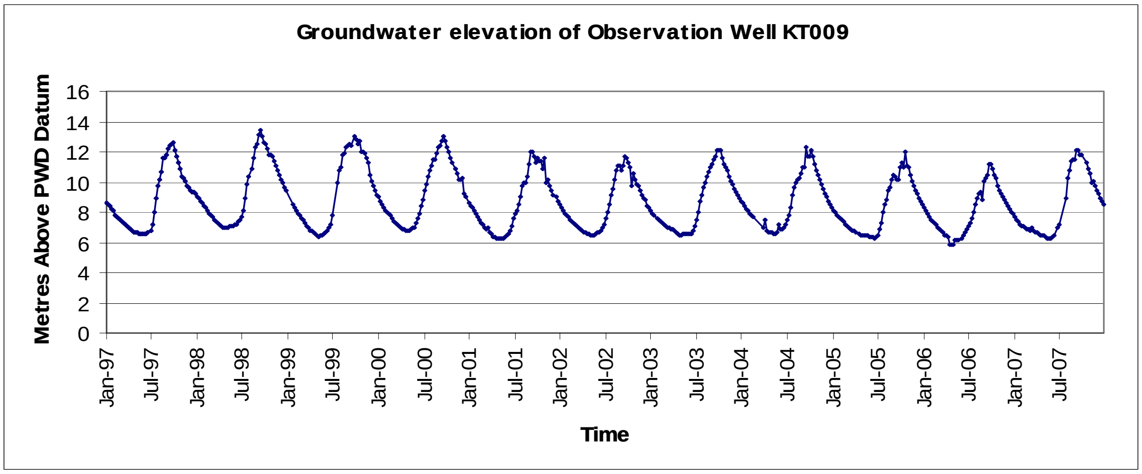


Figure 15. Groundwater level hydrograph of KTA-7 (Peizometer, latitude 24º 01′ 48″N and longitude 89º 00′01″E)



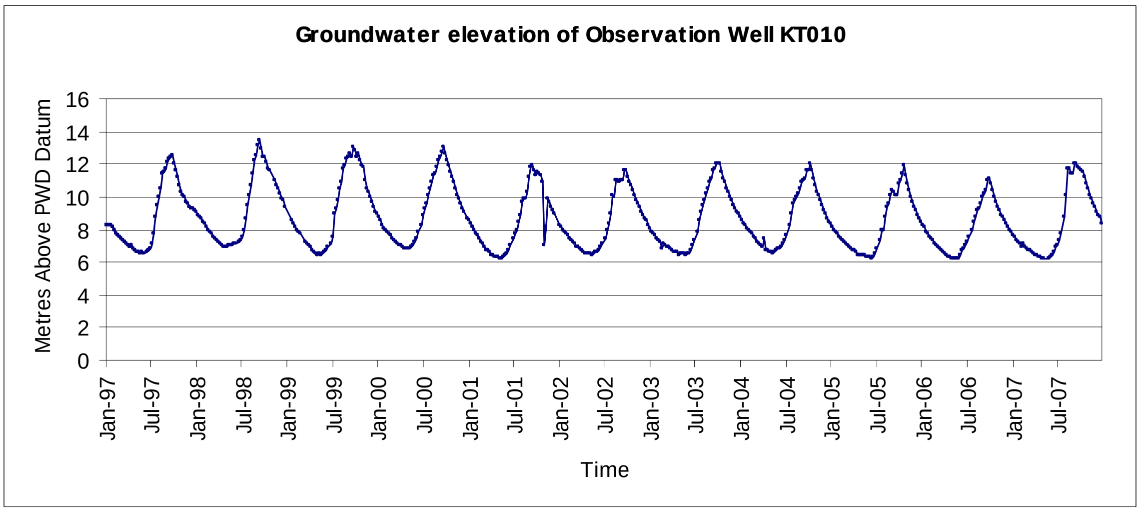
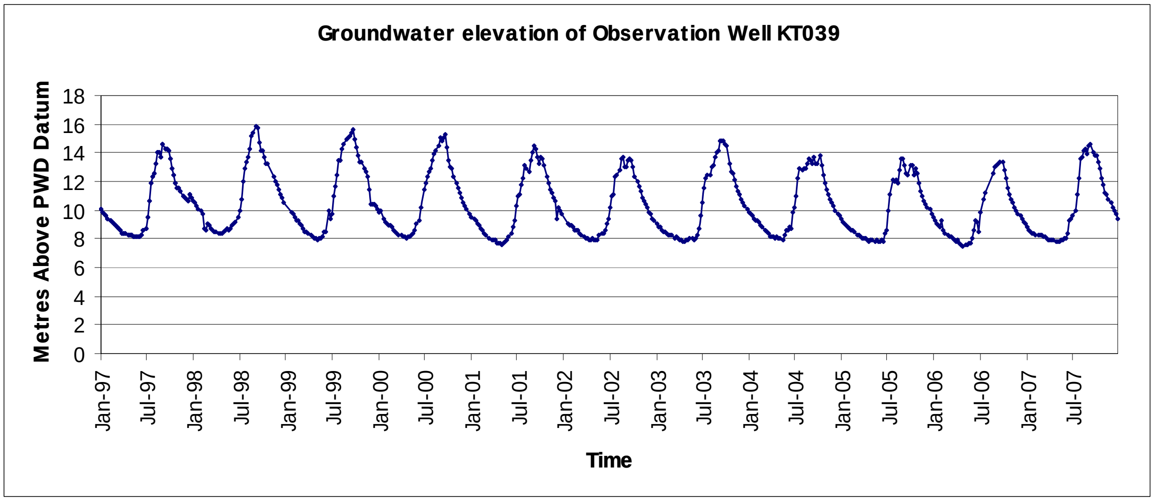


Figure 16. Groundwater level hydrograph of KT-09 (Dug Well, latitude 24º 05′ 48″N and longitude 89º 09′ 36″E) and KT-010 (Dug Well, latitude 24º 07′ 43″N and longitude 88º 58′ 55″E)



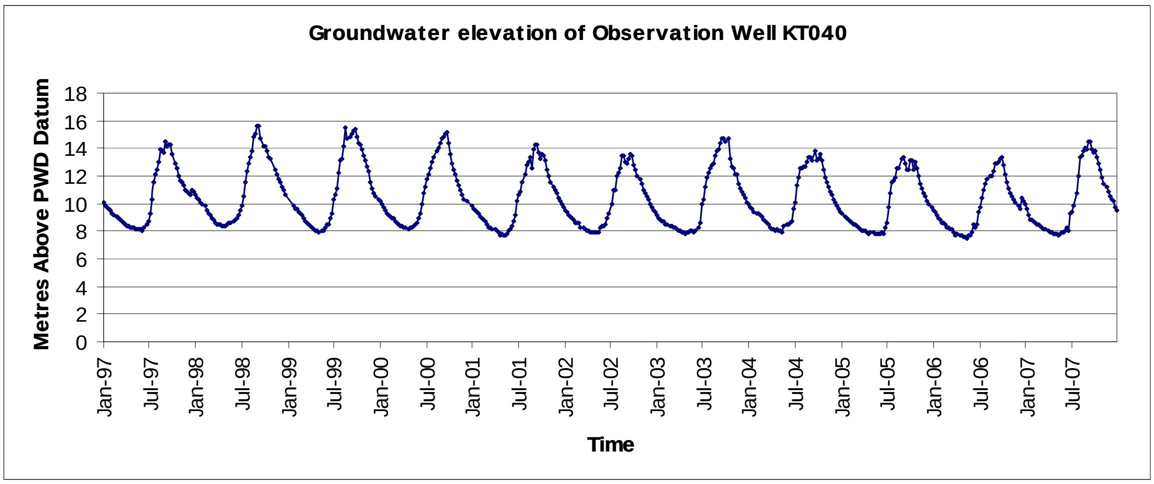


Figure 17. Groundwater level hydrograph of KT-39 (Peizometer, latitude 24º 04′ 30″N and longitude 89º 00′ 11″E) and KT-40 (Peizometer, latitude 24º 04′ 42″N and longitude 88º 59′ 02″E)

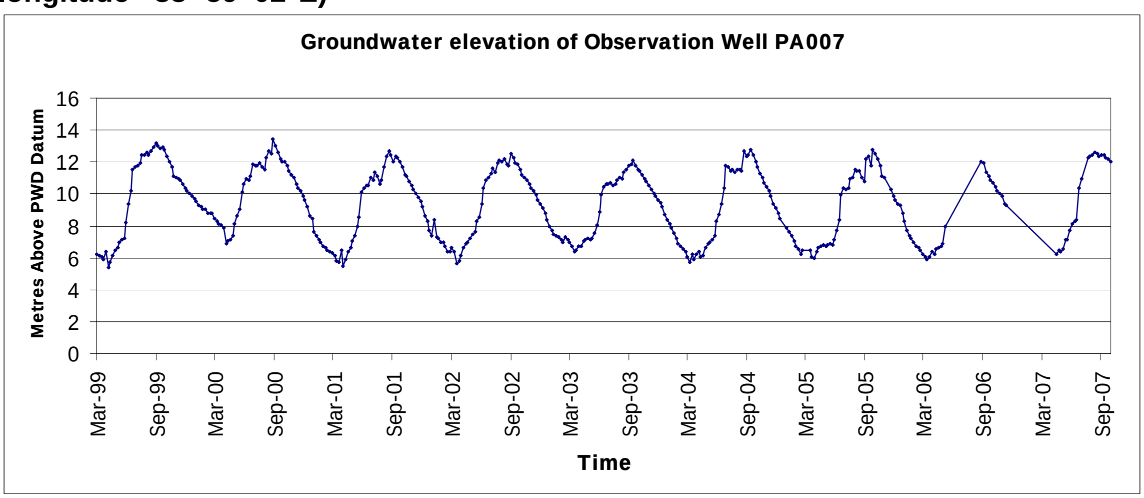


Figure 18. Groundwater level hydrograph of PA-007 (Peizometer, latitude 24º 07′ 36″N and longitude 89º 02′ 16″E)

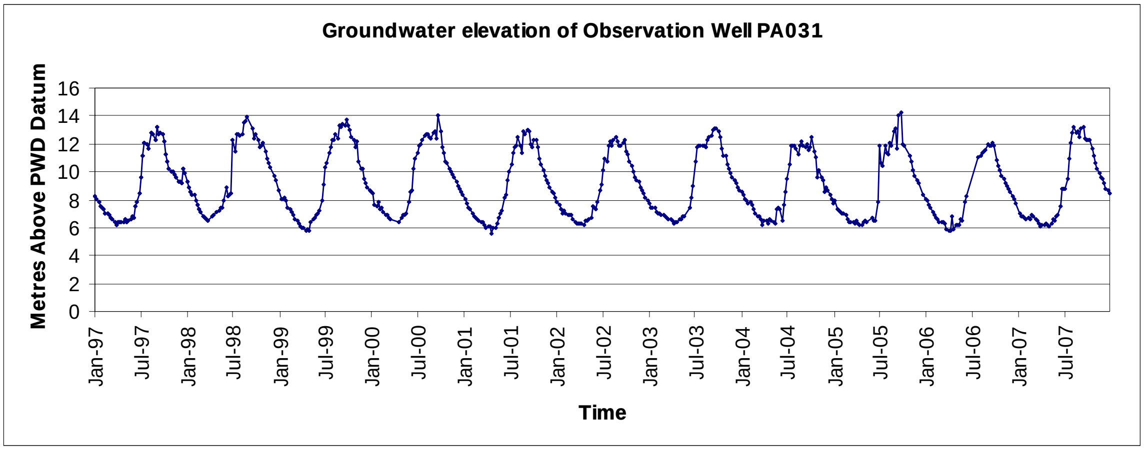


Figure 19. Groundwater level hydrograph of PA-031 (Dug Well, latitude 24º 06′ 14″N and longitude 89º 07′ 21″E)

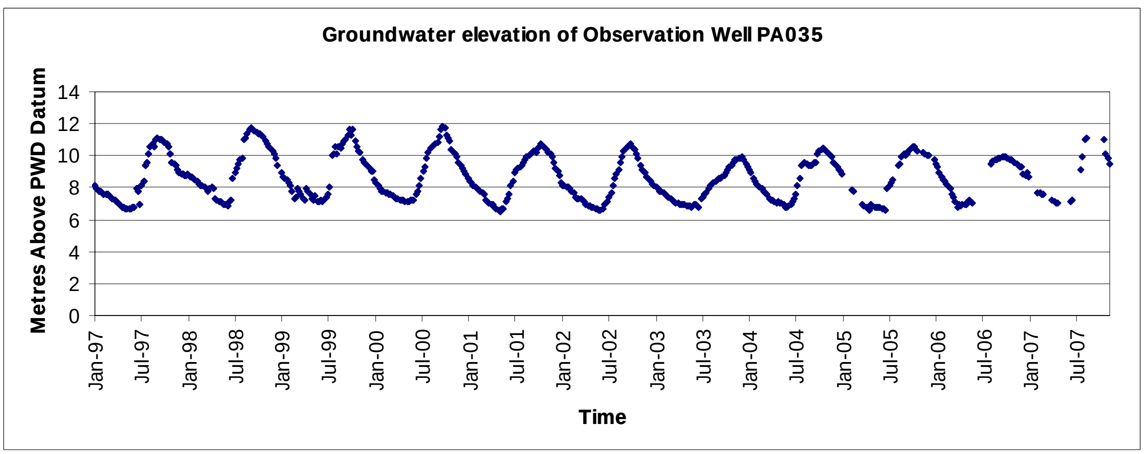


Figure 20. Groundwater level hydrograph of PA-035 (Dug Well, latitude 24º 08′ 05″N and longitude 89º 07′ 55″E)

3.3.4 Water Chemistry

Water chemistry data of the study area have been collected from different published and unpublished sources. Islam (2002) has reported the water chemistry data of different parts of Bheramara Upazila and also of the Padma River. The samples were collected three times from the same location in three years. Table 4 gives the water chemistry data of both groundwater and river water of the study area.

Table 4. Groundwater and river water chemistry data of the study area.

Source of Water sample	**HTW No 1**			**HTW No 2**			**HTW No 3**			**Padma Hardinge Bridge**		
Probable Location	Latitude 24.09°N Longitude 88.95°E			Latitude 24.03°N Longitude 88.92°E			Latitude 24.01°N Longitude 88.88°E			Latitude 24.07°N Longitude 89.04°E		
Time	1998	1999	2001	1998	1999	2001	1998	1999	2001	1998	1999	2001
EC (µS cm^{-1})	723	780	810	680	795	825	594	691	755	184	302	373
TDS (mg/l)	463	499	518	435	509	528	380	417	483	118	193	239
Temp (°C)	29.8	29.0	28.5	30.0	28.0	28.0	29.9	29.0	29.0	30.4	31.0	31.5
pH	7.6	7.1	7.0	8.4	7.8	7.6	8.2	7.8	7.4	8.2	8.1	8.1
TIC (mg/l)	107.8	108.9	106.3	98.5	102.4	101.2	101.2	109.2	107.7	21.5	36.6	33.3
TOC (mg/l)	2.0	2.1	2.2	2.0	2.0	2.0	1.1	1.2	1.1	3.8	3.8	3.9
TC (mg/l)	109.8	111.0	108.5	100.5	104.4	103.1	102.3	110.4	108.8	25.2	40.4	37.1
SAR	1.0	1.1	1.1	0.9	1.0	1.0	0.9	1.0	1.0	0.5	0.5	0.5
Hr as $CaCo_3$ (mg/l)	34.9	432.5	475.4	354.2	445.7	489.5	281.2	354.9	390.2	91.3	111.9	141.0
Na^+ mg/l	30.6	36.1	38.5	28.8	34.0	36.2	25.1	29.7	31.6	7.8	9.2	9.8
K^+ mg/l	3.7	5.2	6.4	3.5	4.9	6.0	3.0	4.3	5.3	6.5	8.9	9.1
Ca^{2+} mg/l	88.2	106.0	114.5	93.9	112.8	121.9	71.8	86.3	93.3	28.0	31.4	39.7
Mg^{2+} mg/l	29.9	40.8	46.1	29.2	39.9	45.1	24.8	33.9	38.3	5.2	8.2	10.2
Fe^{2+} mg/l	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.8	1.2	0.0	0.0	0.0
Mn^{2+} mg/l	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.2	0.2	0.0	0.0	0.0
Zn^{2+} mg/l	0.0	0.0	0.0	-	-	-	-	0.0	0.0	0.0	0.0	0.0
Cu^{2+} mg/l	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cl^- mg/l	29.2	42.3	50.1	27.4	39.8	47.1	24.0	34.8	41.2	2.4	3.5	4.1
HCO_3^- mg/l	410.3	450.9	461.5	435.4	491.3	502.1	339.7	385.2	411.3	127.2	150.8	168.3
SO_4^{2-} mg/l	13.4	33.7	44.0	0.9	1.2	1.7	10.3	18.3	23.2	9.7	15.2	20.9
PO_4^{3-} mg/l	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.2	0.0	0.0	0.0
B mg/l	0.1	0.2	0.2	0.3	0.4	0.4	0.3	0.4	0.5	0.0	0.0	0.0
F mg/l	0.3	0.3	0.3	0.1	0.1	0.1	0.2	0.2	0.3	0.2	0.2	0.2
Br^- mg/l	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NO_3^- mg/l	0.0	0.0	0.0	1.7	4.0	4.2	0.6	1.5	1.5	1.0	2.5	2.6

Water samples from three DTWs of an area near GK pump house and one sample from the project site have been analysed at the laboratory of Bangladesh University of Engineering and Technology (BUET). The results of the analysis are given in Table 5. The water chemistry data indicate that the groundwater is suitable for domestic and industrial uses.

Table 5. Water chemistry data of three wells of GK Pump Colony and project site.

Sample Nr	DW-1	DW-2	DW-3	Project site
Probable Location	Latitude 24.04°N Longitude 89.02°E			24002′59.4″ N 89001′00.5″ E
Well Type	DTW	DTW	DTW	DTW
Sampling Date	11/06/2008	11/06/2008	11/06/2008	18/09/2008
EC (µScm^{-1})	401	395	366	567
TDS (mg/l)	338	325	325	364
TSS (mg/l)	9	7	6	6
pH	6.6	6.7	6.7	7.48
TC (mg/l)	0	0	0	24
FC	0	0	0	6
Turbidity (NTU)	2.29	1.77	1.16	0.96
Hr As $CaCo_3$ (mg/l)	274	264	242	290
Alkalinity mgl^{-1}	287	296	265	266
Fe^{2+} mg/l	0.20	0.18	0.10	0.12
Mn^{2+} mg/l	0.171	0.169	0.248	0.505
Cl^- mg/l	17	15	13	15
SO_4^{2-} mg/l	12.8	12.9	11.7	18.4
NO_3^- mg/l	0.30	0.30	0.20	0.40
As	0.003	0.003	0.004	<0.001
F	0.65	0.67	0.67	0.56
SiO_2	40.2	36.7	30.8	37.6

4. AQUIFER TEST AT THE PROJECT SITE

4.1 Introduction

Pumping test in the proposed Bheramara Power Plant area was conducted for determining the aquifer properties of the study area. Hydrogeological field study includes drilling of test boreholes, electric logging, installation of tubewells, conducting pumping test and recording of all data. The analyses of the data provided basic information about the hydrogeological condition and aquifer properties of the study area. The purposes of pumping test were determining the aquifer type, hydraulic properties of the aquifer and hydraulic connectivity between aquifers. Groundwater modelling requires site specific realistic aquifer properties for constructing most reliable model and resulting predictions.

Three day long constant discharge pumping test was carried out without any interruption during the period from 10:00 hrs on September 21, 2008 till 10:00 hrs on September 24, 2008. Drawdown data were collected from the main well as well as 12 observation wells. Table 6 gives the location of wells and the distance of observation wells from main well. Figure 21 gives the layout of pumping well and observation wells in the study area.

Table 6 : Location of wells and distance of observation wells from main well.

Well Identification	Geographical coordinates		Distance and direction of OWs from PW-01
	Longitude	Latitude	
PW-01	E 89^{0}01′00.5″	N 24^{0}02′59.4″	--
TTW/OW-01	E 89^{0}00′59.9″	N 24^{0}02′59.4″	16.98 m west of PW-01
OW-02	E 89^{0}01′00″	N 24^{0}02′56″	74.35 m south of PW-01
OW-03	E 89^{0}01′03.4″	N 24^{0}02′59″	82.79 m east of PW-01
OW-04	E 89^{0}01′02.6″	N 24^{0}03′00.7″	71.51 m north of PW-01
OW-05	E 89^{0}00′55″	N 24^{0}02′57.5″	166.01 m west of PW-01
OW-06	E 89^{0}00′59.5″	N 24^{0}02′52.9″	201.90 m south of PW-01
OW-07	E 89^{0}01′07.7″	N 24^{0}02′59.1″	203.63 m east of PW-01
OW-08	E 89^{0}01′04.4″	N 24^{0}03′02.6″	147.75 north of PW-01
OW-09	E 89^{0}00′46.7″	N 24^{0}03′00.3″	390.94 m west of PW-01
OW-10	E 89^{0}00′57.7″	N 24^{0}02′45.7″	428.80 m south of PW-01
OW-11	E 89^{0}01′14.8″	N 24^{0}02′59.1″	404.10 m east of PW-01
OW-12	E 89^{0}01′07″	N 24^{0}03′10″	374.30 m north of PW-01

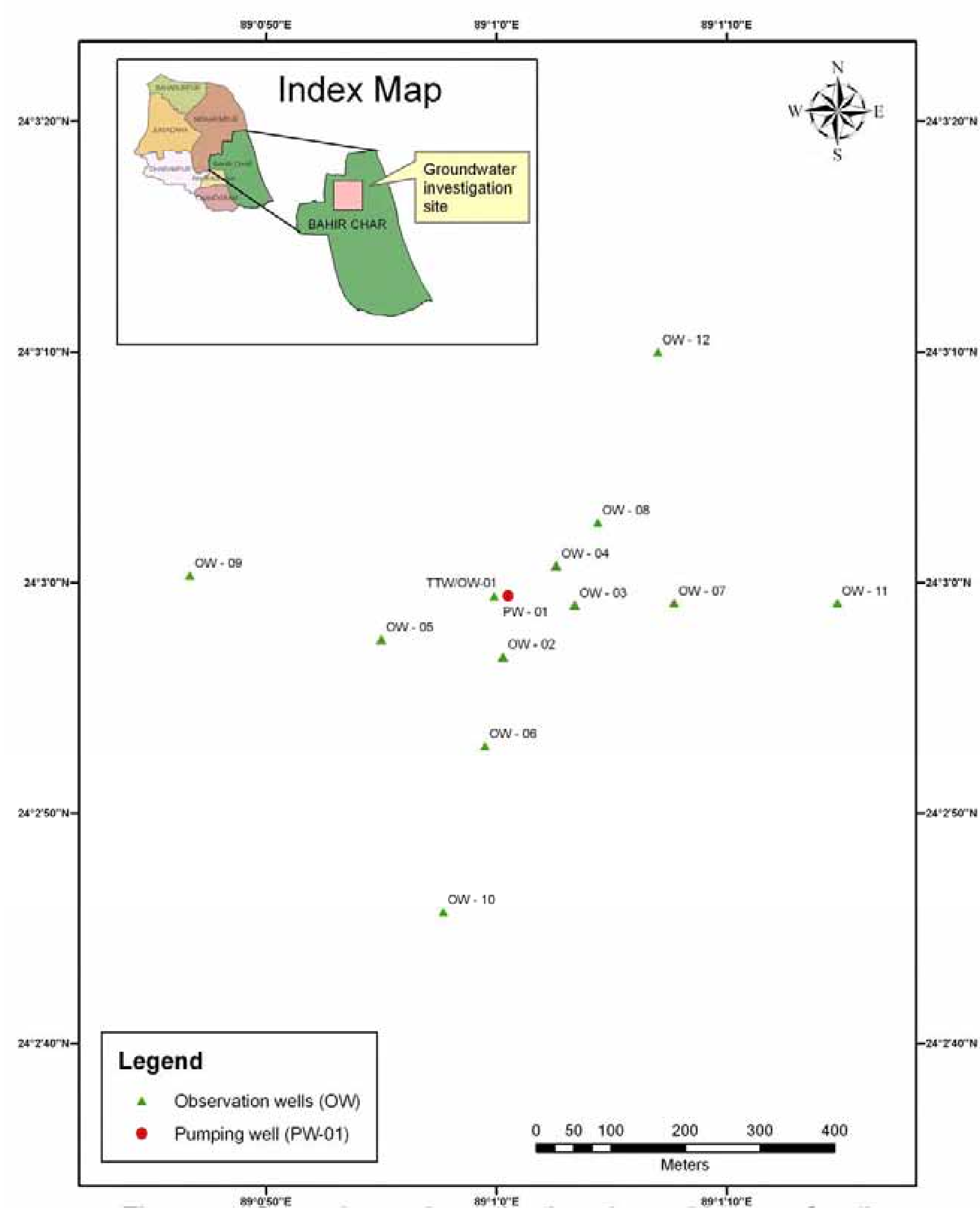


Figure 21. Groundwater investigation site and layout of wells

4.2 Analysis of Pumping Test Data

The geological cross-sections of the study area are given in Figure 22. In the study area only one sand aquifer exists up to a depth of about 100m which is overlain by an aquitard of clay and silty-clay of about 4 to 10m thickness. The groundwater table lies within few meters from the surface.

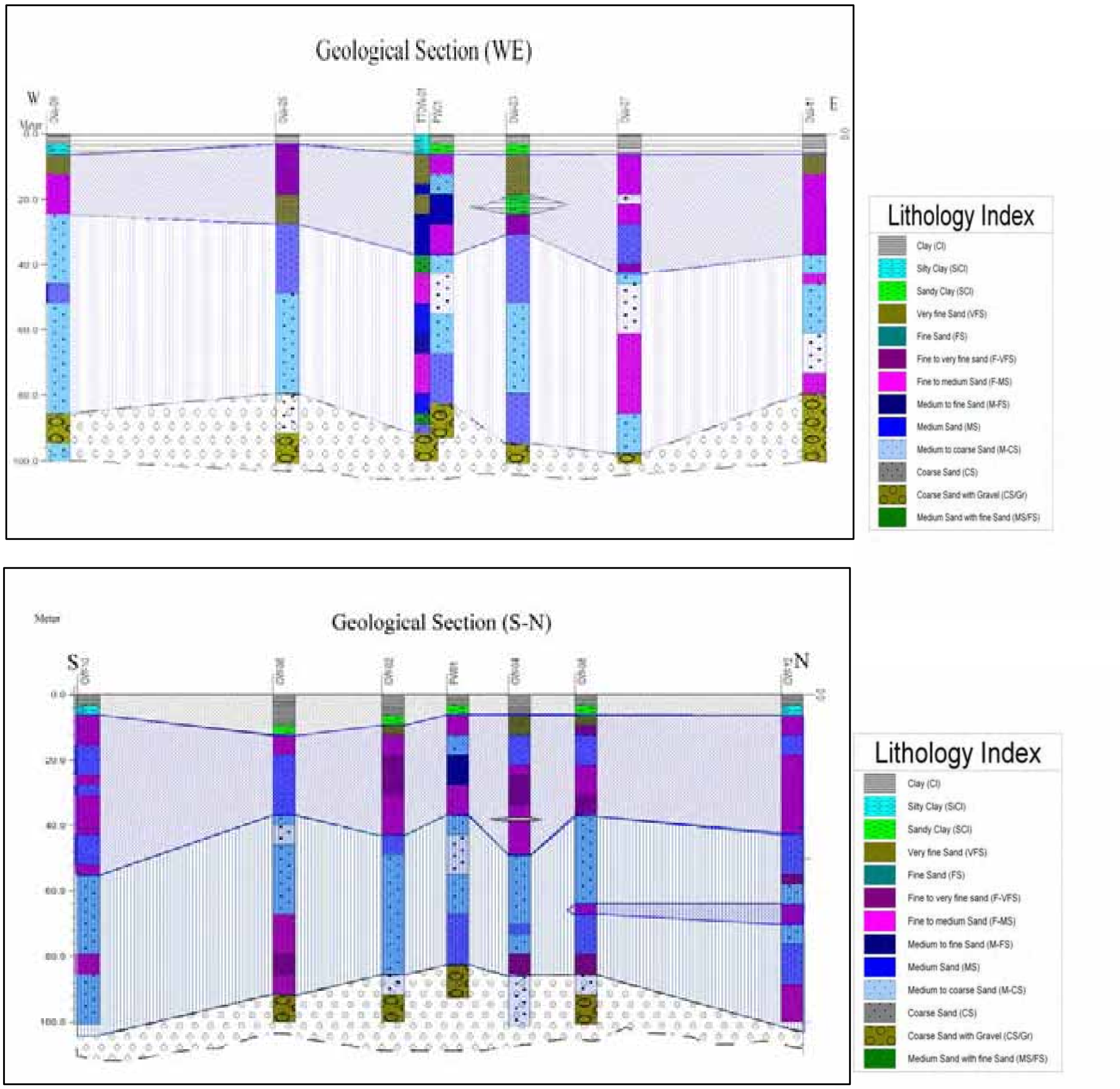


Figure 22. Geological cross-sections of the project site.

The time-drawdown curves on log-log paper obtained for different observation wells exhibit the characteristics of both typical S-shaped curve of unconfined aquifer and Theis-type-curve shaped curve of confined aquifer (Appendix I). The aquifer geometry as envisaged from the geological cross-sections (Figure 4-2) also shows that the aquifer can be either confined or unconfined.

Equation for confined aquifer

Theis (1935) derived a solution for unsteady flow to a fully penetrating well in a confined aquifer. The solution assumes a line source for the pumped well and therefore neglects wellbore storage.

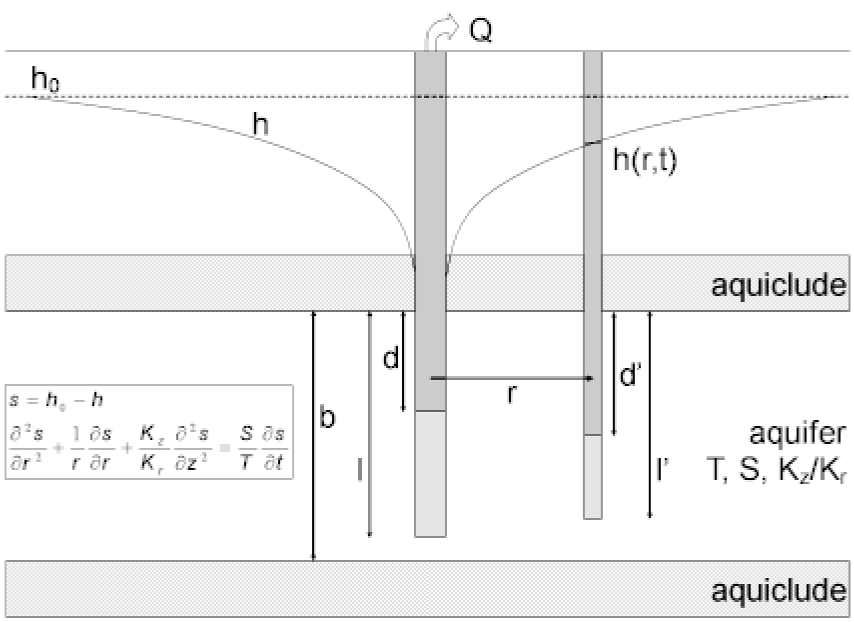


Figure 23. Confined aquifer

$$s = \frac{Q}{4\pi T}\int_u^\infty \frac{e^{-y}}{y}dy$$

$$u = \frac{r^2 S}{4Tt}$$

$$s_D = \frac{4\pi T}{Q} s$$

$$t_D = \frac{Tt}{r^2 S}$$

where

- Q is pumping rate [L^3/T]
- r is radial distance [L]
- s is drawdown [L]
- S is storativity [dimensionless]
- t is time [T]
- T is transmissivity [L^2/T]

Hydrogeologists commonly refer to the exponential integral in the drawdown equation as the Theis well function, abbreviated as *w(u)*. Therefore, the Theis drawdown equation in compact notation can be written as follows:

$$s = \frac{Q}{4\pi T} w(u)$$

Replacing the integral with a Taylor expansion series

$$T = \frac{Q}{4\pi s}\left[-0.5772 - \ln u + u - \frac{u^2}{2\times 2!} + \frac{u^3}{3\times 3!} - \frac{u^4}{4\times 4!} + \cdots\cdots\right]$$

Equation for unconfined aquifer

Neuman (1972, 1974) derived an analytical solution for unsteady flow to a fully or partially penetrating well in a homogeneous, anisotropic unconfined aquifer with delayed gravity response. The Neuman model assumes instantaneous drainage at the water table. Neuman (1974) derived an analytical solution for unsteady flow to a partially penetrating well in an unconfined aquifer with delayed gravity response

The equation is:

$$s = \frac{Q}{4\pi T}\int_0^\infty 4yJ_0(y\sqrt{\beta})\left[u_0(y) + \sum_{n=1}^{\infty} u_n(y)\right]dy$$

$$\beta = \frac{r^2 K_z}{b^2 K_r}$$

$$\sigma = \frac{S}{S_y}$$

$$t_s = \frac{Tt}{Sr^2}$$

$$s_D = \frac{4\pi T}{Q}s$$

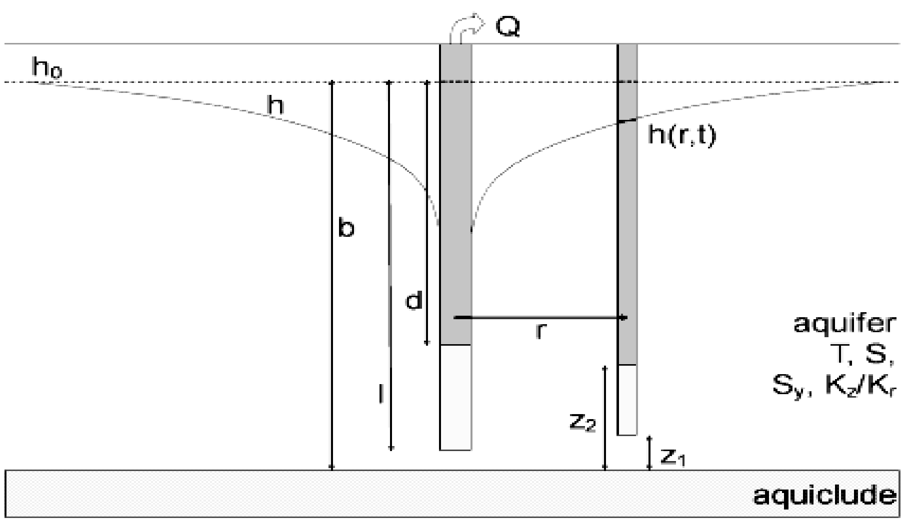


Figure 24. Unconfined Aquifer

where

b is aquifer thickness [L]

K_r is radial hydraulic conductivity [L/T]

K_z is vertical hydraulic conductivity [L/T]

Q is pumping rate [L^3/T]

r is radial distance [L]

s is drawdown [L]

S is storativity [dimensionless]

S_y is specific yield [dimensionless]

t is time [T]

T is transmissivity [L^2/T]

The drawdown in a piezometer is found using the following equations:

$$u_0(y) = \frac{[1-\exp(-t_s\beta(y^2-\gamma_0^2))]\cosh(\gamma_0 z_D)}{[y^2+(1+\sigma)\gamma_0^2-(y^2-\gamma_0^2)^2/\sigma]\cosh(\gamma_0)} \cdot \frac{\sinh(\gamma_0(1-d_D))-\sinh(\gamma_0(1-l_D))}{(l_D-d_D)\sinh(\gamma_0)}$$

$$u_n(y) = \frac{[1-\exp(-t_s\beta(y^2+\gamma_n^2))]\cos(\gamma_n z_D)}{[y^2-(1+\sigma)\gamma_n^2-(y^2+\gamma_n^2)^2/\sigma]\cos(\gamma_n)} \cdot \frac{\sin(\gamma_n(1-d_D))-\sin(\gamma_n(1-l_D))}{(l_D-d_D)\sin(\gamma_n)}$$

The drawdown in a partially penetrating observation well is found using the following equations:

$$u_0(y) = \frac{[1-\exp(-t_s\beta(y^2-\gamma_0^2))][\sinh(\gamma_0 z_{2D})-\sinh(\gamma_0 z_{1D})]}{[y^2+(1+\sigma)\gamma_0^2-(y^2-\gamma_0^2)^2/\sigma]\cosh(\gamma_0)} \cdot \frac{\sinh(\gamma_0(1-d_D))-\sinh(\gamma_0(1-l_D))}{(z_{2D}-z_{1D})(l_D-d_D)\sinh(\gamma_0)}$$

$$u_n(y) = \frac{[1-\exp(-t_s\beta(y^2+\gamma_n^2))][\sin(\gamma_0 z_{2D})-\sin(\gamma_0 z_{1D})]}{[y^2-(1+\sigma)\gamma_n^2-(y^2+\gamma_n^2)^2/\sigma]\cos(\gamma_n)} \cdot \frac{\sin(\gamma_n(1-d_D))-\sin(\gamma_n(1-l_D))}{(z_{2D}-z_{1D})(l_D-d_D)\sin(\gamma_n)}$$

The gamma terms are the roots of the following equations:

$$\sigma\gamma_0\sinh(\gamma_0)-(y^2-\gamma_0^2)\cosh(\gamma_0)=0 \qquad \gamma_0^2 < y^2$$

$$\sigma\gamma_n\sin(\gamma_n)+(y^2+\gamma_n^2)\cos(\gamma_n)=0 \qquad (2n-1)(\pi/2) < \gamma_n < n\pi \quad n \ge 1$$

where

d_D is dimensionless depth to top of pumping well screen (d/b)

J_0 is Bessel function of first kind, zero order

l_D is dimensionless depth to bottom of pumping well screen (l/b)

z_D is dimensionless elevation of piezometer opening above base of aquifer (z/b)

z_{1D} is dimensionless elevation of bottom of observation well screen above base of aquifer (z_1/b)

z_{2D} is dimensionless elevation of top of observation well screen above base of aquifer (z_2/b)

Subsequent work by Moench (1993, 1996) presented improved methods for evaluating the Neumann solution.

This method can be used to estimate aquifer transmissivity (T), storativity (S), specific yield (S_y), horizontal hydraulic conductivity (K_h) and vertical hydraulic conductivity (K_v).

4.3 Aquifer Properties

Aquifer properties of the project site have been determined by both Theis Confined type curve matching method and Neuman Unconfined type curve method. Table 7 gives the aquifer properties determined by using Theis confined type curve matching method.

Table 7. Estimated aquifer properties determined by using Theis confined type curve matching method.

Observation Well	T (m^2/d)	S	K (m/d)
OW-1	6063	0.001	60.6
OW-2	7509	0.007	75.1
OW-3	7509	0.006	75.1
OW-4	8537	0.004	85.4
OW-5	6894	0.007	68.9
OW-6	3058	0.004	30.6
OW-7	6894	0.007	68.9
OW-8	7195	0.019	72.0
OW-9	4495	0.009	45.0
OW-10	5110	0.028	51.1
OW-11	5810	0.006	58.1
OW-12	6063	0.007	60.6

Using Theis curve matching method it has been found that the transmissivity of the aquifer in the project site varies between 3058 m^2/d and 8537 m^2/d and average transmissivity of the project site is 6261 m^2/d. The storativity of the aquifer ranges from 0.001 to 0.028 and the average storativity of the project site 0.009. Hydraulic conductivity of the aquifer material estimated using this method ranges from 30.6 m/d to

85.4 m/d and average hydraulic conductivity of the aquifer in the project site is 62.6 m/d. Figure 25 illustrates the example of determining aquifer parameter using Theis curve matching method.

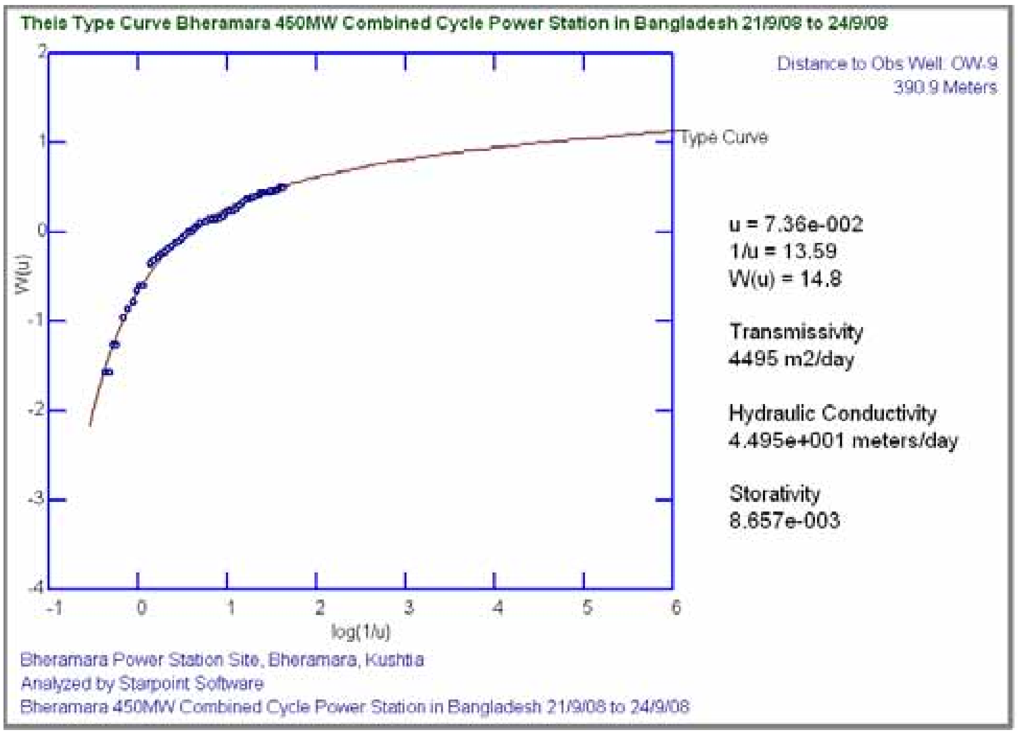


Figure 25. Time-drawdown data of OW-9 matched with Theis type curve

Table 8 summarises the aquifer properties determined from the analysis of pumping test data of all observation wells using Neuman curve matching technique. Early time-drawdown data and late time-drawdown data were matched separately with the Neuman Type Curve. The transmissivity of the test site estimated by Neuman curve fitting method varies between 2498 m^2/d and 6298 m^2/d. The average transmissivity measured using this method is 4456 m^2/d. The horizontal hydraulic conductivity (K_h) of the study area ranges from 15.9 m/d to 63 m/d and the average is 42.5 m/d. The vertical hydraulic conductivity (K_v) of the aquifer at the project site ranges from 1.1 m/d to 8.7 m/d and the average is 4.9 m/d. The storativity (S) of the aquifer in the project site varies between 0.003 and 0.022 and the average is 0.007. The specific yield of the aquifer determined by this method varies between 0.02 and 0.40 and the average is 0.09.

Table 8: Aquifer properties determined from pumping test data using Neuman Curve fitting method.

Obs. Well	Early				Late				Average		
	T (m^2/d)	S	Kh (m/d)	Kv (m/d)	T (m^2/d)	Sy	Kh (m/d)	Kv (m/d)	T (m^2/d)	Kh (m/d)	Kv (m/d)
OW-1	2498	0.008	25.0	8.7	2498	0.40	25.0	8.66	2498	25.0	8.7
OW-2	4929	0.005	49.3	8.9	3168	0.16	31.7	5.73	4049	15.9	7.3
OW-3	4929	0.003	49.3	7.2	3168	0.14	31.7	4.62	4049	40.5	5.9
OW-4	4605	0.003	46.1	9.0	3391	0.12	33.9	6.63	3998	40.0	7.8
OW-5	5275	0.004	52.8	7.7	4302	0.04	43.0	6.24	4789	47.9	7.0
OW-6	3755	0.003	37.6	9.2	4019	0.02	40.2	0.10	3887	38.9	4.7
OW-7	4451	0.004	44.5	4.3	4605	0.02	46.1	4.44	4528	45.3	4.4
OW-8	7667	0.011	76.7	3.5	4929	0.04	49.3	2.26	6298	63.0	2.9
OW-9	2333	0.005	23.3	6.1	4451	0.02	44.5	1.17	3392	33.9	3.6
OW-10	5275	0.022	52.8	1.2	5099	0.04	51.0	1.11	5187	51.9	1.1
OW-11	6692	0.005	66.9	4.1	4764	0.02	47.6	2.92	5728	57.3	3.5
OW-12	5841	0.005	58.4	1.7	4302	0.02	43.0	1.23	5072	50.7	1.4

Figure 26 gives an example of matching of the data of observation well OW-2. The aquifer in the project site comprises mostly of fine sand, medium sand, coarse sand and gravel. The average specific yield of fine sand is about 0.2 and for coarse sand is 0.27 (Fetter 1990). The average specific yield obtained by using this method is 0.09 which is obviously lower than the real values. One drawback of using Neuman equation for determining specific yield is that unreasonably low Sy values are often obtained (Van der Kamp 1985).

The average transmissivity of the aquifer estimated by the Theis method and Neuman methods are 6261 m^2/d and 4456 m^2/d, respectively. These values are well acceptable for the study area. As the aquifer appears to be unconfined, aquifer properties determined by Neuman method have been accepted for this study. It could be mentioned here that the bottom of the aquifer has not been encountered in the project site during drilling. The effective thickness of the aquifer is presumably much more greater and transmissivity for the full thickness of the aquifer may exceed 10000 m^2/d. Howard Humphre (1984) estimated transmissivities of KT-2 (Amguri, Meherpur, Kushtia) and KT-6 (Darmaehali, Gangi, Kushtia) which are 9800 m^2/d and 5700 m^2/d, respectively.

The hydraulic conductivity of unconsolidated fine sand ranges from 2×10^{-7} to 2×10^{-4} m/s and that of gravel ranges from 3×10^{-4} to 3×10^{-2} m/s (Domenico and Schwartz 1990). In the project area the average horizontal hydraulic conductivity (K_h) of the aquifer is found to be 42.5 m/d (≈ 5×10^{-4} m/s). This value is acceptable because this value is well within the range of fine sand to gravel by which the aquifer is composed. The estimated average Kv of the aquifer is 4.9 m/d and average storativity is 0.007.

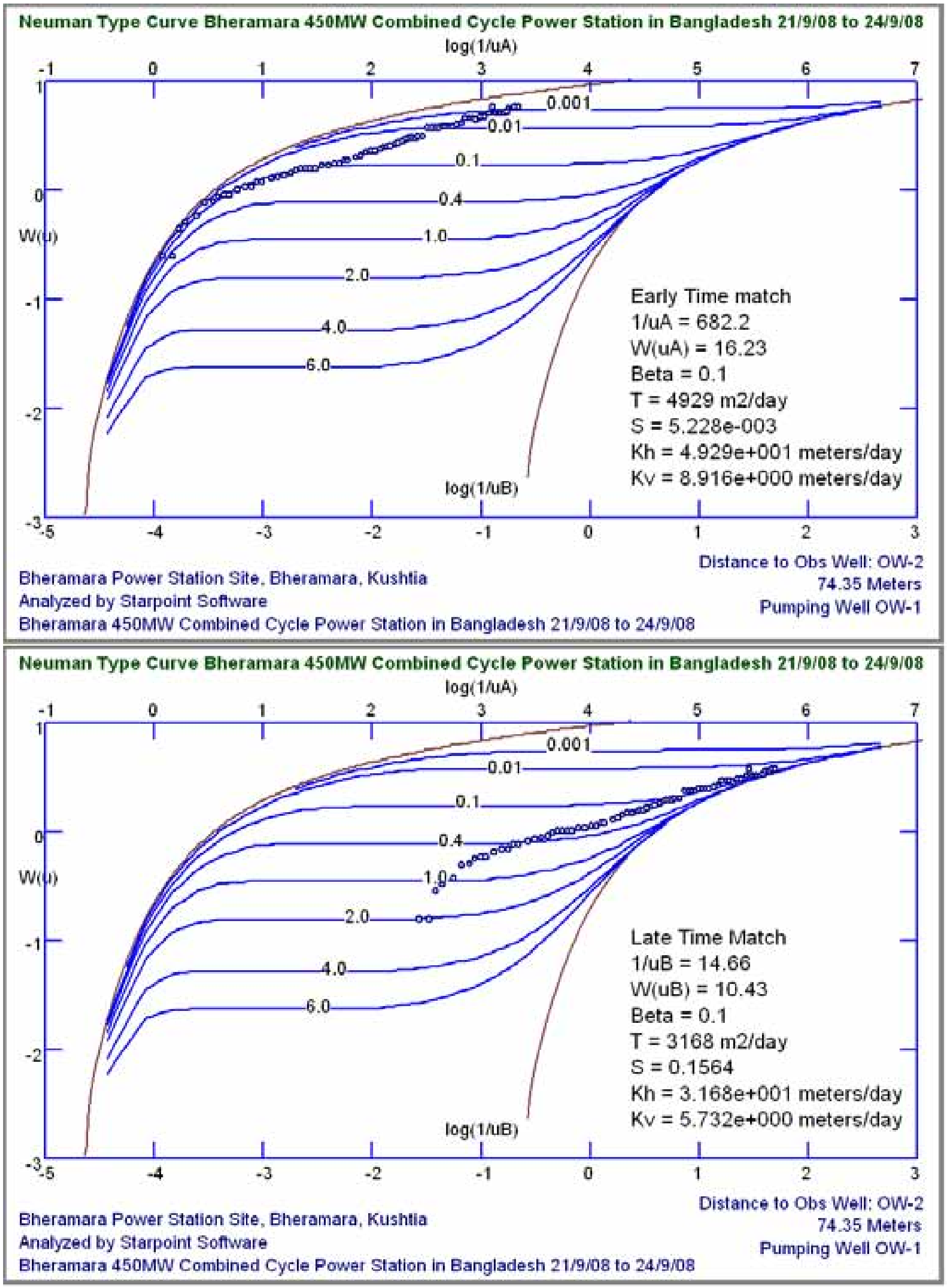


Figure 26. Analysing time-drawdown data of OW-2 using Neuman Curve Matching Technique

5.0 EXISTING AND FUTURE GROUNDWATER ABSTRACTION

5.1 Introduction

The ultimate purpose of the model is to evaluate the extent to which groundwater resource of the study area can support the withdrawal of water at a rate 1300 m^3/h continuously from subsurface aquifer. Groundwater is currently abstracted on a wide scale throughout the study area for agricultural use and also for domestic and industrial purposes. Available data indicate that abstraction for irrigation water overshadows that for other uses and is likely to become even more dominant as the development of irrigated agriculture becomes more widespread. This study has therefore involved an evaluation of both the present and future dry season irrigation and an estimate of resulting water requirements as irrigated agriculture in the Study Area approaches full development.

This chapter firstly reviews the existing level of groundwater abstraction and secondly, an assessment of likely scale of future demand on groundwater as irrigated agriculture is increased.

5.2 Existing Groundwater Abstractions

Groundwater abstraction in the study area can be classified into following types:

a. Irrigation

(i) Deep Tubewells (DTWs) : generally 100m depth, designed and equipped with turbine pumps to deliver approximately 55 l/s (2 cusec).

(ii) Shallow Tubewells (STWs) : generally 40-50m depth, designed and equipped with surface mounted centrifugal pumps (operate by suction lift) to deliver approximately 15 l/s (0.5 cusec).

b. Rural Water Supply

(i) Hand dug wells: Traditional form of groundwater abstraction but are rapidly being replaced by Hand pump tubewells.

(ii) Hand pumps Tubewells (HTWs)

c. Municipal and industrial

A small number of wells constructed by municipal authorities to provide water in urban or suburban areas.

The rate at which groundwater abstraction occurs in the study area has been derived from the analysis of the number of tubewells known to exist. Bangladesh Agricultural Development Corporation (BADC) has been conducting survey and monitoring of irrigation equipment since 1999. The recent survey report (BADC 2005) showed that there are 12 DTWs and 1049 STWs operate at Bheramara Upazila during dry season for Boro cultivation. At Iswardi Upazila of Pabna district 75 DTWs and 525 STWs operates during dry season for irrigation. Low Lift Pumps (LLPs) are used for pumping surface water from canals or ponds. Table 11 gives the number of DTWs, STWs and LLPs in the study area and the area irrigated by that equipment. It has been observed that the source of most of the water used for irrigation is groundwater.

Table 9. Number of DTWs , STWs and LLPs in the study area (BADC 2005).

District	Upazila	DTWs		STWs		LLPs		Total area (ha) irrigated by all equipment
		No.	Area Irrigated (ha)	No.	Area Irrigated (ha)	No.	Area Irrigated (ha)	
Kushtia	Bheramara	12	247	1049	1627	8	13	1887
Pabna	Iswardi	75	2133	525	3750	15	140	6023

In terms of the volume of water pumped, actual groundwater abstraction from the study area is considerably less than the installed capacity might imply because irrigation pumping only occurs during a fraction of the year. Unfortunately, no reliable or consistent information exists regarding either the normal season for irrigation pumping or the average daily pumping period. Previous investigations estimated seasonal pumping periods of between 450 hours/year (IECO, 1980) and 900 hours/year (UNDP 1982).

By assuming that each well is capable of delivering its design yield of 15 and 55 l/s for STW and DTW, respectively, the annual abstraction has been calculated. The scope of the present study has not permitted a detailed determination of actual tubewell pumping calendars to be obtained which is necessary precursor to convert installed capacity into actual abstractions. Therefore a conservative approach has had to be taken in view of the wide range of unknowns and hence a seasonal pumping period of 1050 hours/year has been used. In this study five months of pumping season and a daily pumping duration of 7 hours has been adopted.

Water withdrawn each day for domestic and municipal purposes has been estimated from the number of people living in the study area. It has been estimated that each person in rural area uses about 40 litres of water per day. By multiplying the number of people with estimated consumption of water per day by person abstraction for domestic and municipal uses has been estimated. According to the population census of 2001 (BBS 2007) the total population of Iswardi and Bheramara Upazila was 292938 and 175677, respectively. The present national growth rate of population in Bangladesh is 1.07% per year (BBS 2007). Table 12 gives present abstraction of groundwater in the study area.

Table 10. Present abstraction of groundwater for irrigation, domestic and municipal purposes

Upazila	No of DTWs	Groundwater Abstraction by DTWs (m^3/yr)	No of STWs	Groundwater Abstraction by STWs (m^3/yr)	Estimated present Population	Groundwater Abstraction Domestic & Municipal Uses (m^3/yr)	Total Groundwater Abstraction (m^3/yr)
Bheramara	12	2494800	1049	59478300	189265	2763272	64736372
Iswardi	75	15592500	525	29767500	315596	4607702	49967702

5.3 Future Groundwater Abstractions

Net Cultivable Area (NCA) of Bheramara and Iswardi are 9735 ha and 14079 ha, respectively. Only 1887 ha of land of Bheramara and 6023 ha of land of Iswardi are presently cultivated in dry season. The left over cultivable land remain fallow in dry season.

It is assumed that the increase of groundwater abstraction for irrigation takes place at a rate of 2.5% per year until it reaches to a saturation point at which all the cultivable land is irrigated groundwater. The abstraction of water for domestic and municipal purposes also increased with the increase in population. The national growth rate of population has been considered for calculating the annual increase in groundwater abstraction. For each year, the rate of abstraction of groundwater for domestic purposes increased by 1.07% in the model. Table 13 gives the projected future abstraction of groundwater in two Upazilas.

Table 11. Projected abstraction of groundwater for irrigation, domestic and municipal purposes.

Year	Bheramara, Kushtia			Iswardi, Pabna		
	Groundwater Abstraction for irrigation (m^3/yr)	Groundwater Abstraction Domestic and Municipal Uses (m^3/yr)	Total Groundwater Abstraction (m^3/yr)	Groundwater Abstraction for irrigation (m^3/yr)	Groundwater Abstraction Domestic and Municipal Uses (m^3/yr)	Total Groundwater Abstraction (m^3/yr)
1st	61973100	2763272	64736372	45360000	4607702	49967702
2nd	63522428	2792839	66315266	46494000	4657005	51151005
3rd	65110488	2822722	67933210	47656350	4706835	52363185
4th	66738250	2852925	69591176	48847759	4757198	53604957
5th	68406707	2883452	71290158	50068953	4808100	54877053
6th	70116874	2914305	73031179	51320677	4859547	56180223
7th	71869796	2945488	74815284	52603693	4911544	57515237
8th	73666541	2977004	76643546	53918786	4964097	58882883
9th	75508205	3008858	78517063	55266755	5017213	60283969
10th	77395910	3041053	80436963	56648424	5070897	61719322
11th	79330807	3073592	82404400	58064635	5125156	63189791
12th	81314078	3106480	84420558	59516251	5179995	64696246
13th	83346930	3139719	86486649	61004157	5235421	66239578
14th	85430603	3173314	88603917	62529261	5291440	67820701
15th	87566368	3207269	90773637	64092493	5348058	69440551
16th	89755527	3241586	92997114	65694805	5405283	71100088
17th	91999415	3276271	95275687	67337175	5463119	72800294
18th	94299401	3311328	97610728	69020604	5521575	74542179
19th	96656886	3346759	100003644	70746119	5580655	76326775
20th	99073308	3382569	102455877	72514772	5640368	78155141

6.0 GROUNDWATER FLOW MODEL

6.1 Introduction

Groundwater models are representation of a real system or processes that approximately simulates the relevant excitation-response relation of the real world system and offer a quantitative evaluation of groundwater resources through a correct mathematical and physical framework (Bear and Bachmat 1991). They describe the groundwater flow and transport processes using mathematical equations based on certain simplifying assumptions. These assumptions typically involve the direction of flow, geometry of the aquifer, the heterogeneity or anisotropy of sediments or bedrock within the aquifer, the contaminant transport mechanisms and chemical reactions.

The basis for modelling three dimensional groundwater flow forms the integrated modelling package MODFLOW (Harbaugh and McDonald 1996). MODFLOW was originally developed by the U.S. Geological Survey (McDonald and Harbaugh, 1988). The MODFLOW model uses the block-centred finite-difference approximation to simulate transient, or time-varying, flow in three dimensions in a heterogeneous and anisotropic porous medium. Steady-state conditions can also be simulated. The principal axes of hydraulic conductivity must be aligned with the coordinate directions, and water of constant density is assumed. Wells, rivers, drains, evapotranspiration, and recharge can be simulated and are represented as head dependent source or sink terms in which the head outside the model is user specified. Layered aquifers can be represented in the so-called quasi-three-dimensional approximation. Nodes in this approximation can change from being confined to unconfined, and vice versa, as the computation progresses.

MODFLOW is a generalised tool with comprehensive applicability range usable to accommodate the hydrological conditions and related problems of the study area. Aquifer hydraulic parameters, boundary conditions, initial conditions, and stresses are required model input. The input is from text files with the data laid out in a prescribed order and format. The input data must correspond to the specified grid structure. The primary model output is the head at each model node.

6.2 Mathematical and Conceptual Basis of the Model

Groundwater modeling begins with a conceptual understanding of the physical problem. The next step in modeling is translating the physical system into mathematical terms. In general, the results are the familiar groundwater flow equation and transport equations. The governing flow equation for three-dimensional saturated flow in saturated porous media is:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-Q=S_s\frac{\partial h}{\partial t}$$

where,

Kxx, Kyy, Kzz	=	hydraulic conductivity along the x,y,z axes which are assumed to be parallel to the major axes of hydraulic conductivity;
h	=	piezometric head;
Q	=	volumetric flux per unit volume representing source/sink terms;
Ss	=	specific storage coefficient defined as the volume of water released from storage per unit change in head per unit volume of porous material.

Conceptual Model

The conceptual model was developed using data from regional geologic reports and site-specific data. Figure 29 is a schematic three dimensional section illustrating the flow model conceptualization. The model comprises three layers. The Upper Clay and Silt layer comprises clay and silt and its thickness varies from 0 and 36m in the study area. Recharge from rainfall and surface water bodies infiltrates through this layer. Evapotranspiration from the area by which water is lost from the aquifer system also occurs from this layer. This Upper Clay and Silt layer is fully cut by the Padma River. Below this layer is the Composite aquifer. The thickness of this aquifer varies from 5 to 51m in the modeled area. The bottom of the Padma River cuts this layer and therefore, the river is well connected with this aquifer. The third layer is the Main aquifer the bottom of which has not been encountered by any bore hole in the study area. The Main aquifer is extended throughout the whole study area.

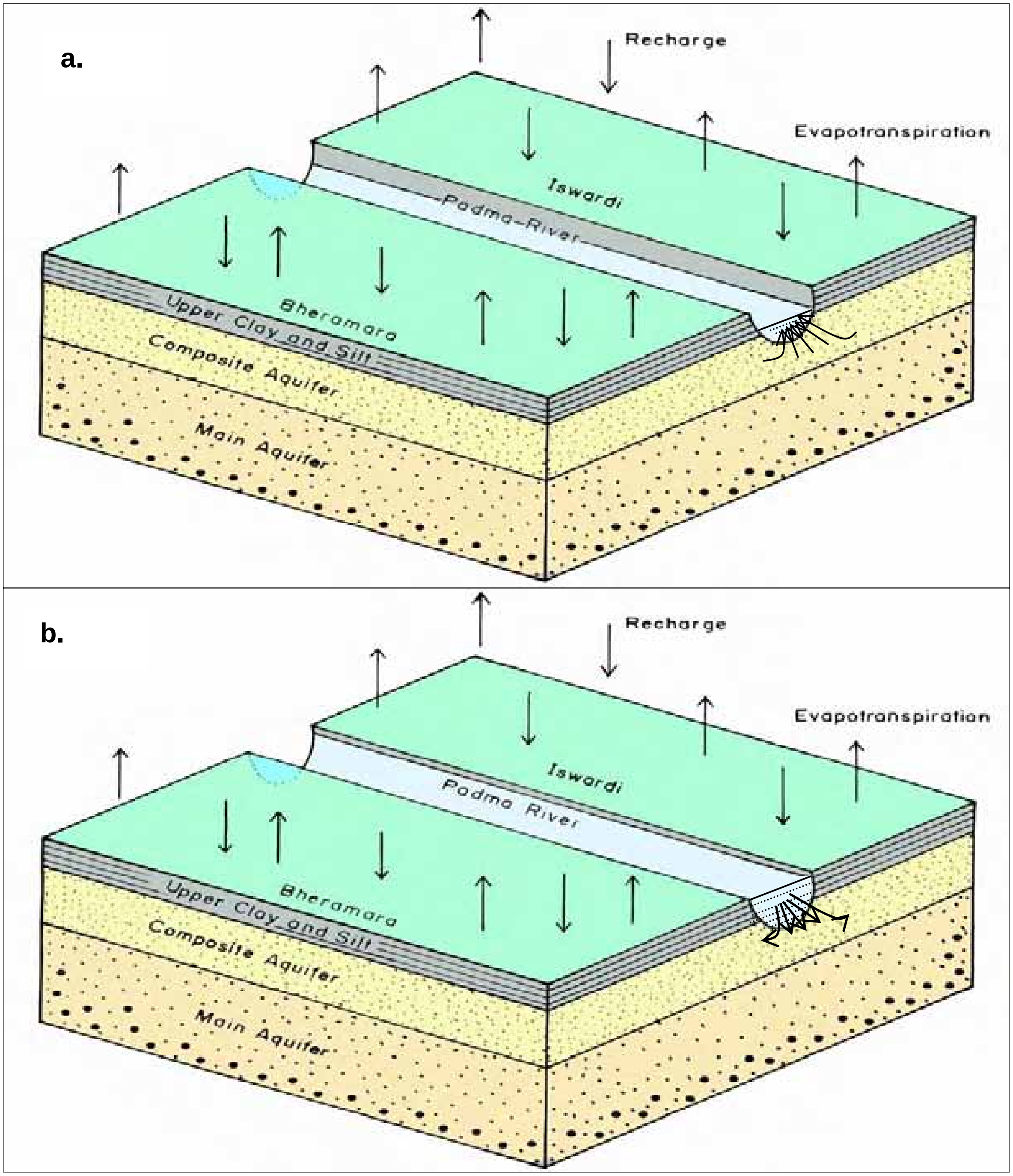


Figure 27. Conceptual model of the study area. (a) At low river stage condition the aquifer loses water. (b) At high river stage condition the aquifer gains water.

Figure 29 shows that the aquifers receive water from the river during wet season when the river stage is higher than the groundwater level of the surrounding aquifer. This influent condition of the river contributes highly in recharging the aquifer when huge monsoonal rain water flows through the river. But in dry season river stage falls down to a level which is lower than the surrounding aquifer. This effluent condition of the river results in the loss of groundwater from the aquifer to the river.

6.3 Selection of the Model Area

In construction of the model, the first stage was to define the modelled area and boundary conditions in accordance with natural physical features or limits. The flow pattern in the study area has been examined while setting the boundaries of the modelled area. Physical boundaries and the regional groundwater divide are often used as the boundary of the modelled area. However, in this study it was not convenient to use the physical boundaries of the system as the project site is far away from them.

In transient simulation boundaries may be arbitrarily set far from the area of interest (centre of the grid) as long as the stresses to the system will not reach the boundaries during the simulation. This type of boundary is known as distant boundary (Anderson and Woessner, 1992). In the present study distant boundaries were selected in the north, south, east and west of the modelled area.

Impermeable rock typically forms the lower boundary of the modelled area. But in the study area the bottom of the aquifer has not been encountered in any bore hole. Taking conservative view the bottom of the modelled area was set at -100m in spite of the fact that the bottom is deeper.

6.4 Model Geometry and Boundary Conditions

Groundwater model development includes creation of a conceptual model including definition of model grid, model layers and their respective hydrogeologic parameters, model boundaries and boundary conditions, and model sources and sinks. The conceptual model is then converted to a finite difference, transient, multi-layer model using the USGS MODFLOW 2000 software.

Model Grid

The model covered an entire area defined by BTM coordinates of 389318 to 412008 East and 653525 to 670026 North. The area of about 22.7 × 16.5 km^2 was divided into coarse grid of 80 rows and 100 columns. The model grid consists of 8000 active cells, spaced at about 206 m along rows and about 227m along the columns, covering an area of about 374 km^2 (Figure 30). All kinds of data related to hydrogeological parameters and aquifer geometry were used to build the model grid network. The model parameters were needed to be defined for each of the 8000 active square cells. In addition, the time variant parameters such as recharge, abstraction and boundary conditions were needed to be specified for monthly time steps.

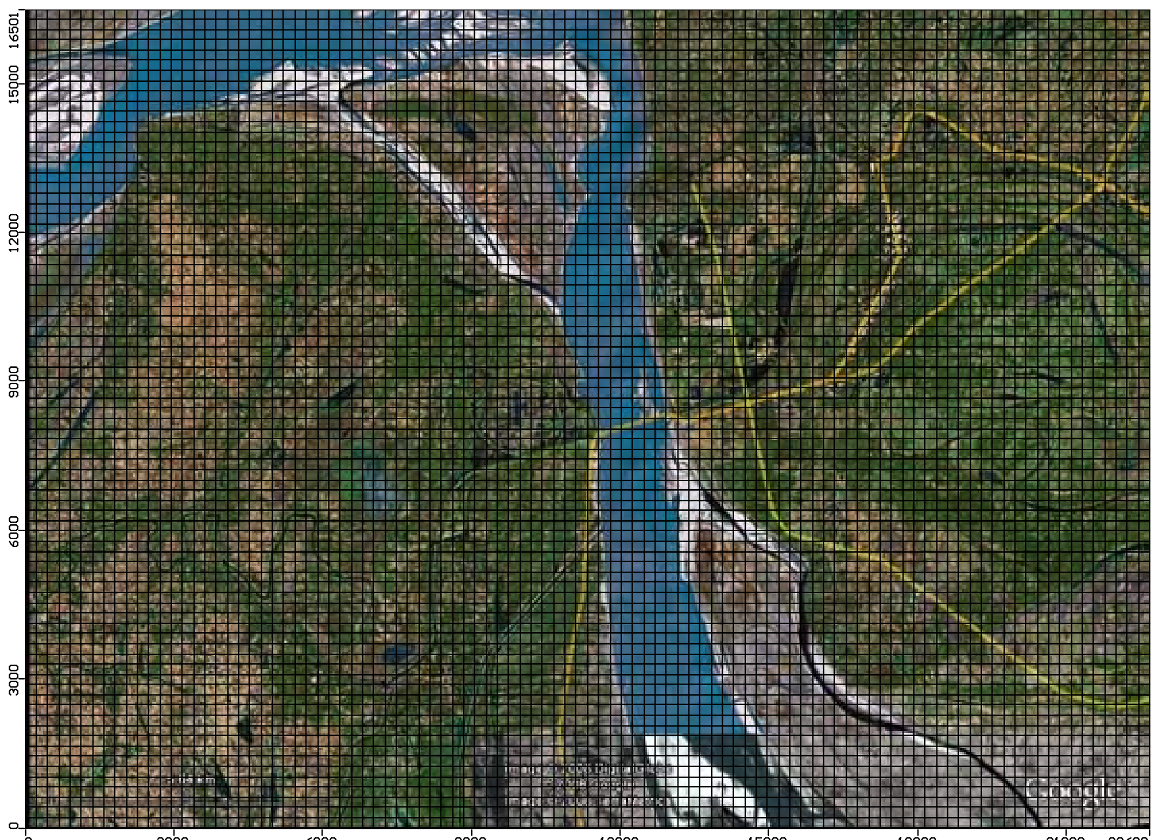


Figure 28. Model grid.

Three layers are included in the model. Layer 1 comprises low permeability clays and silts. Layer 2 comprises more permeable very fine sand to fine sand. Layer 3 comprises medium to coarse sand and gravel. Different hydrogeological parameters were assigned for each of the modelled layer (Table 14). Parameters that have been incorporated to the model are: mean horizontal and vertical permeability of each layer, storage-coefficients, specific yield and porosity of each layer. Domenico (1972) gives the ranges of values for Ss for different lithologies. Heath (1983) gives the values of hydraulic conductivities for different lithologies. Morris and Johnson (1967) and also Fetter (2001) give the values of specific yield for different lithologies. Johnson and Morris (1962) give the values of porosity for different lithologies. Domenico & Schwartz (1990) gives the values of effective porosity for different lithologies. Figure 31 gives the three dimensional view of the modelled area.

Table 12. Hydrogeological parameter settings for the model.

Layer	Lithology	Thickness (m)	Kx m/d	Ky m/d	Kz m/d	Ss (1/m)	Sy (%)	Effective porosity (%)	Total porosity (%)
1	Clay and silt	0-36	1	1	0.1	0.0001	0.03	0.06	0.5
2	Very fine to fine sand	5-51	10	10	1	0.0001	0.18	0.18	0.2
3	Medium to coarse sand and gravel	75 +	45	45	4.5	0.007	0.25	0.27	0.3

Explanation: Kx = Hydraulic conductivity in the x direction, Ky = Hydraulic conductivity in the y direction, Kz = Hydraulic conductivity in the z direction, Sy = Specific yield, Ss = Specific storage.

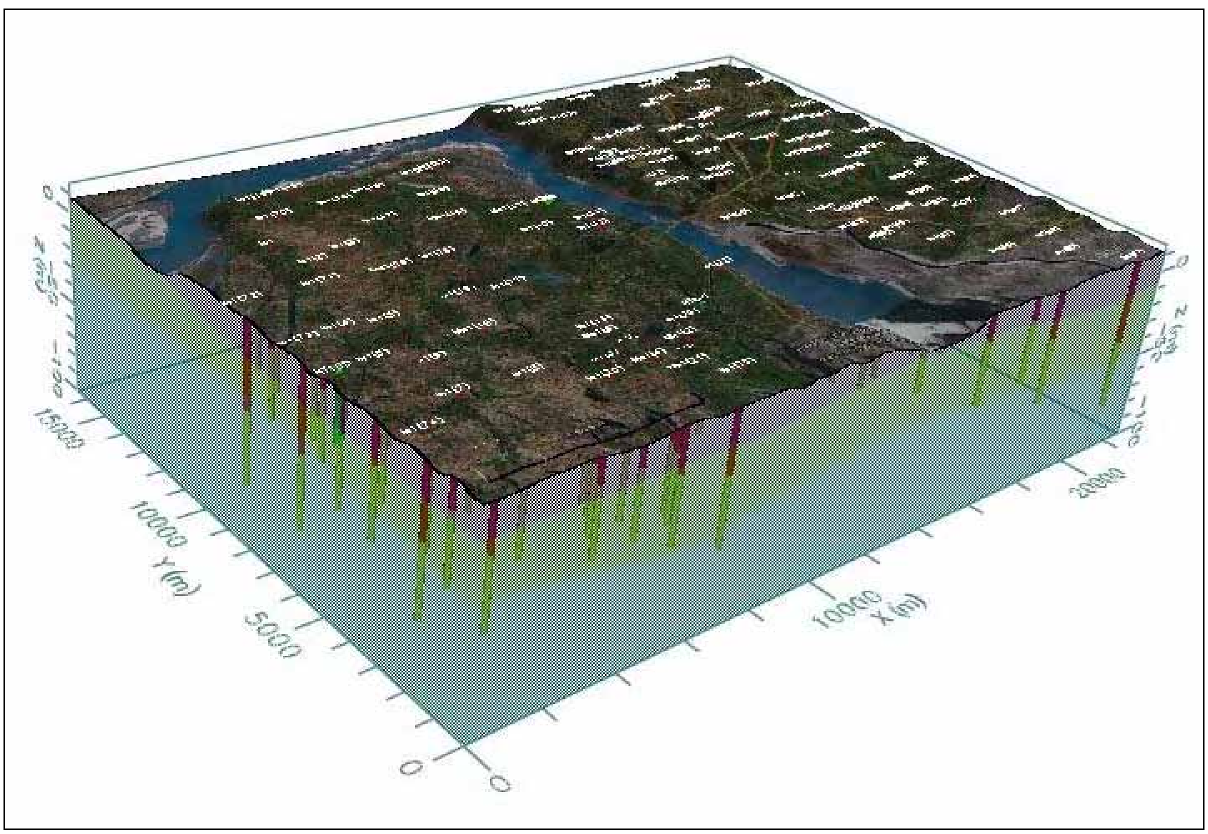


Figure 29. 3D view of the study area.

Boundary Conditions

Every model requires an appropriate set of boundary conditions to represent the system's relationship with the surrounding systems. In the case of a groundwater flow model, boundary conditions will describe the exchange of flow between the model and the external system. Boundary conditions may be of head controlled, gradient controlled or flow (water flux) controlled.

The river boundary condition is used to simulate the influence of a surface water body on the groundwater flow. Rivers may either contribute water to the groundwater system, or act as groundwater discharge zones depending on the hydraulic gradient between the surface water body and the groundwater system. The Padma River has a distinct influence on the water balance of the study area. The river boundary was set up along its tract in the north and middle part of the study area. Monthly average river stage at Hardinge Bridge (SW 90) was considered to develop the transient flow model with a time step of one month. Width, length and depth of the channels were implicated to the model. River stage data was also incorporated to the model.

Recharge estimates have been derived directly from the UNICEF (1993) Upazila base estimation. Evapotranspiration estimates made by Howard Humphre (1984) for the study area were incorporated in the model. These data were imported to the model as MODFLOW package file for the top layer only.

For flow modelling dynamic equilibrium conditions were adopted using monthly time steps. Thus average quantity of recharge, evapotranspiration and abstraction were incorporated in the model for each time steps. These parameters vary seasonally for changes in weather conditions. Groundwater abstraction has been specified for individual modelled layers and grid cells. In the study area, the rate of abstraction from tubewells for urban and irrigation use are specified for individual cells.

Municipal and domestic wells pumps water throughout the whole year whereas irrigation wells pump water only in dry season.

6.5 Calibration and Sensitivity Analysis

It is unlikely to find all well-defined parameters associated with the simulated water balance components. Uncertainties with the simulated results may arise through a lack of data, imprecision of data and the extrapolation of data defined on the field scale to the regional scale of the model. So, it becomes necessary for the model to undergo a process of calibration, which involves the continuous comparison of the model response with the equivalent known response of the real aquifer system. The close understanding of the modeller with the real aquifer is significant for better approximation of the real system to the model system. By cross matching the hydrographs of the observation wells the model is calibrated to represent the present ground water conditions. Figure 32 and 33 give the matching of modelled water table with the observed water table in the study area.

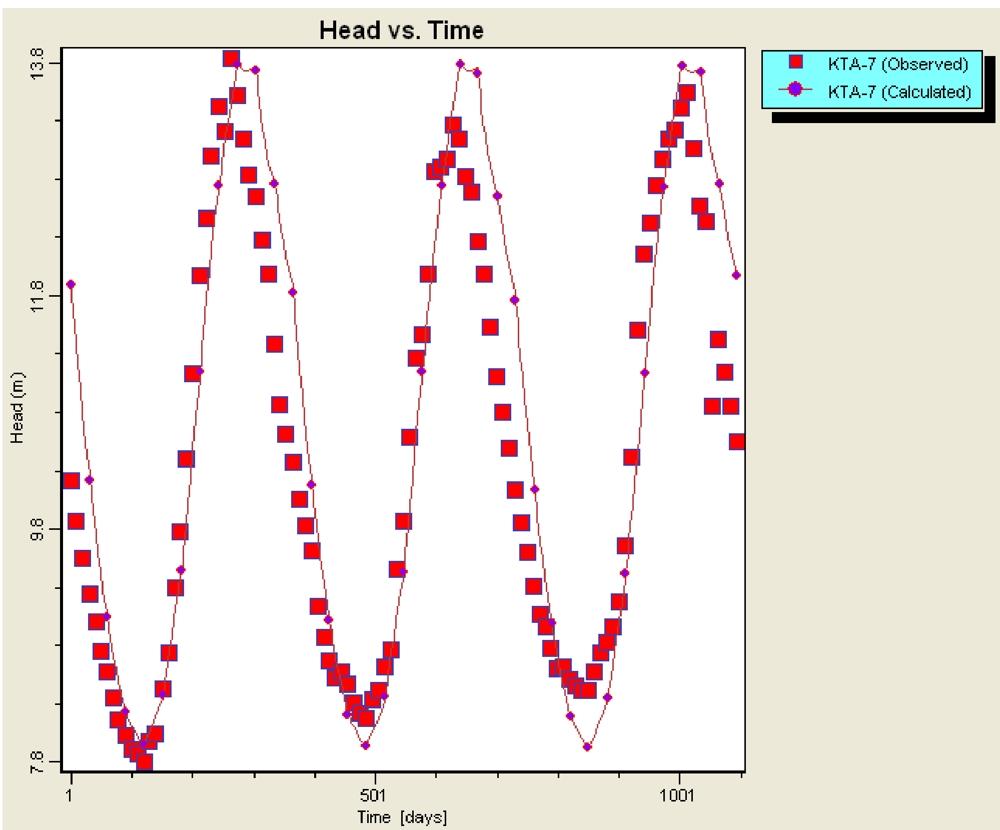


Figure 30. Matching of observed and calculated hydrographs of KTA -7.

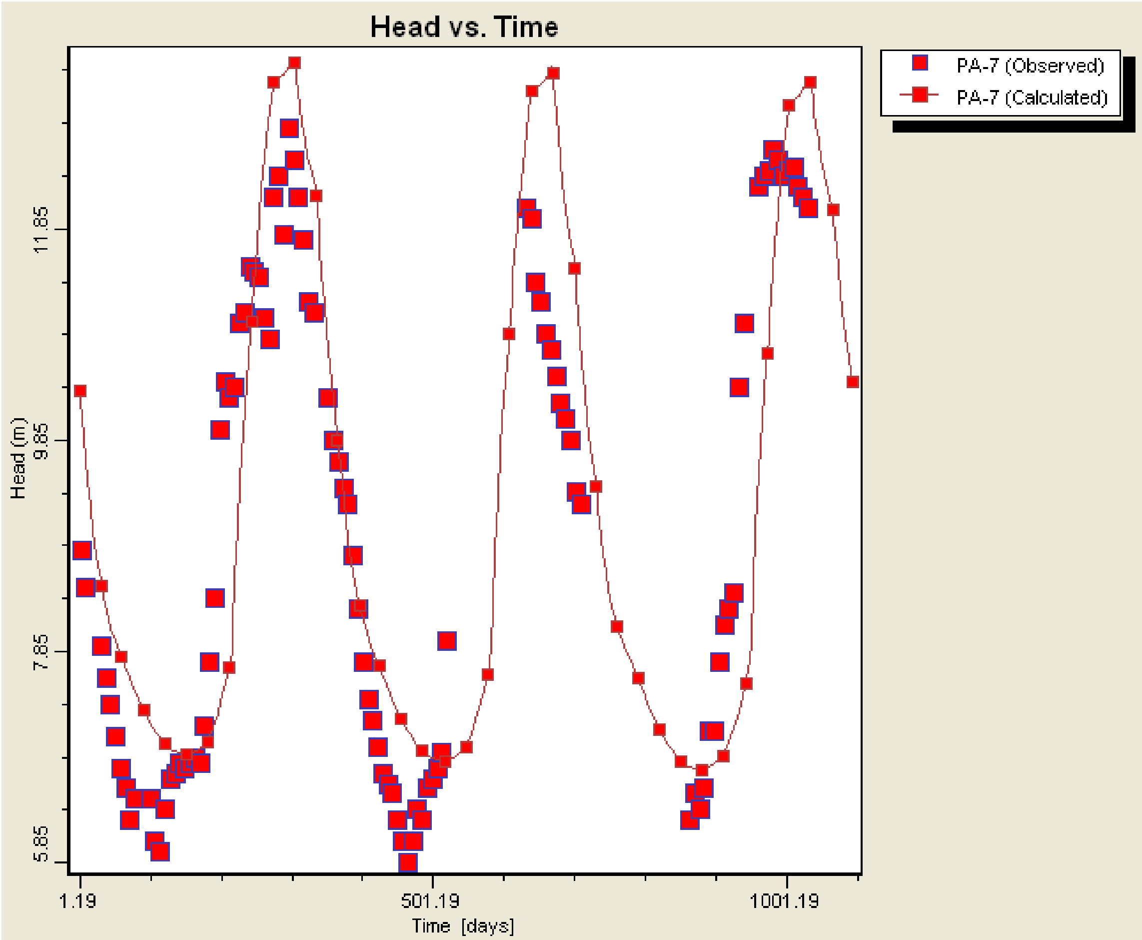


Figure 31. Matching of observed and calculated hydrographs of PA -7.

For calibrating the model adjustment of model input data such as storage parameter and recharge was made.

A sensitivity analysis is the process of varying model input parameters over a reasonable range and observing the relative change in model response. Typically, the observed change in hydraulic head is noted. Model sensitivity analysis was conducted by changing storage parameters and hydraulic conductivity. It has been observed that model is very much sensitive to storage parameter. Hydraulic conductivity also very slightly influences the model response. Appendix III gives the detail of sensitivity analysis.

7.0 MODEL PREDICTION AND WELL LAYOUT

7.1 Introduction

The main objective of this study is to predict the consequence of pumping water from the project site at the rate of 31200 m^3/day. After calibration the model was run to predict the results of groundwater abstraction by the pumping wells located at the proposed site of the power plant on the bank of the River Padma. Two different well layouts were considered for prediction purposes. The model was run for 20 years. Abstraction of water was increased by introducing new wells after each run to maintain predicted future water demand.

7.2 Arrangement of Wells

Well layout is very important while planning well field for groundwater abstraction. The size and shape of the catchment of a well field depends on the well layout. First objective is to minimise the effects on existing wells. The second objective in planning the well layout is to maximise the use of river water by inducing lower head at the bottom of the river. Interference of wells depends on the distance between production wells. The higher the space among the pumping wells, the lower the well interference. In closely spaced wells drawdown in wells will be higher which may cause higher pumping cost, higher cost for well construction and higher possibility of well failure around the project site. Ten wells with a discharge if 3120 m^3/day were introduced at the project site in the modelled area. The wells were arranged in two ways (Figure 32):

First Scenario: wells are set in a line over a distance of 1km.

Second scenario: wells are kept in cluster over a distance of about 400m.

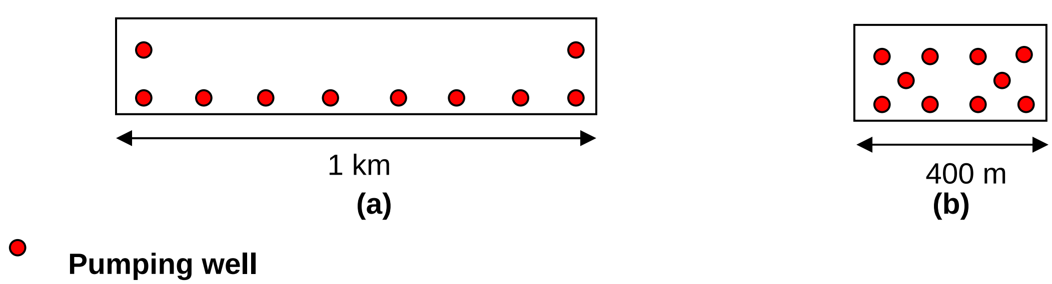


Figure 32. Arrangement of wells (a) in line and (b) in cluster.

7.3 Model Prediction

First scenario

For wells arranged in line the model is run for 20 years. Figure 33 shows the modelled groundwater level of dry season (May) after 20 years of pumping.

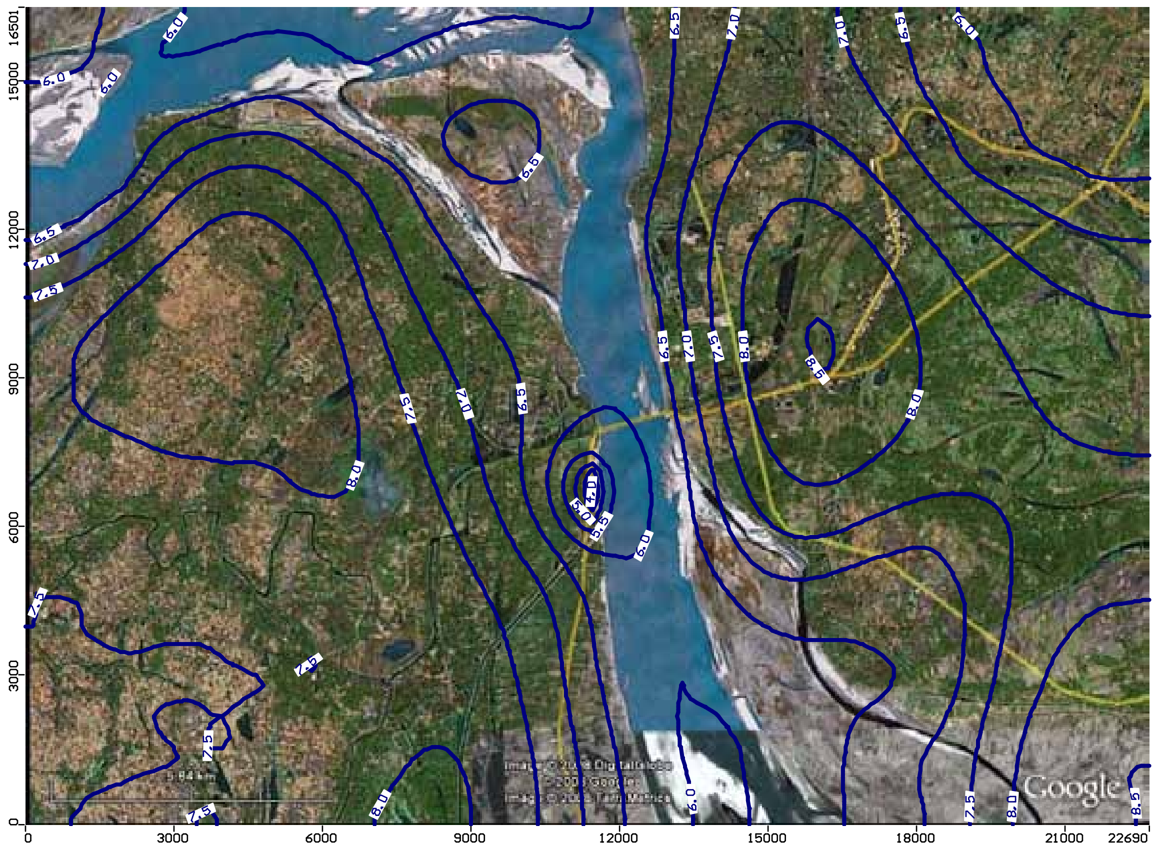


Figure 33. Modelled dry season (May) water table contour map after 20 years of pumping (wells arranged in line).

The modelled minimum elevation of groundwater table occurs in the month of May. The River Padma is effluent in the dry season. However, due to lowering of the head, water from the river bed may pass into the aquifer in areas adjacent to the pumping wells. It has been observed that the cone of depression is asymmetric and it is extended to the eastern side. In about 1 km^2 area surrounding the pumping wells of the proposed power plant water level may decline by 1 to 3 m from the existing water level. Figure 34 gives the zoomed view of the project site for dry season. Figure 35 shows the head equipotential lines in the cross-sections for dry season.

Figure 34. Zoomed in modelled dry season (May) water table contour map after 20 years of pumping (wells arranged in line).

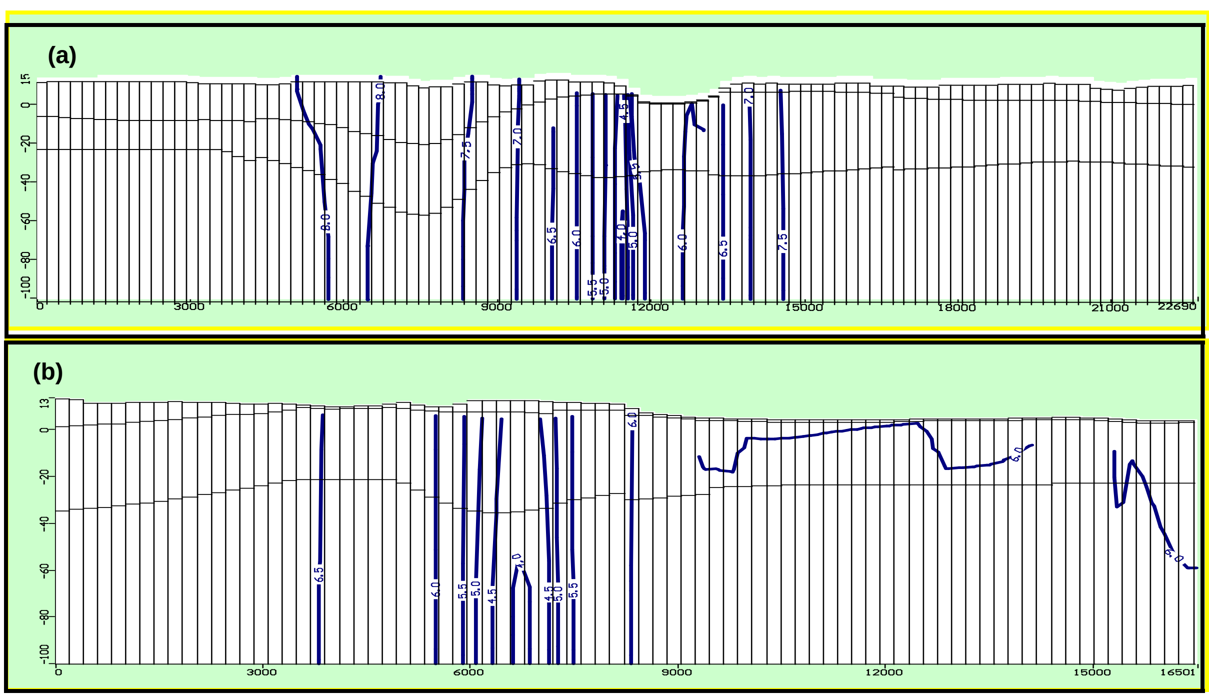


Figure 35. Modelled head equipotential line of dry season (May) in cross-sections (a) X-direction and (b) Y-direction (wells arranged in line).

The modelled maximum elevation of groundwater table occurs in the month of September (Figure 36). It has been found that the Padma River lying in the eastern side of the project site acts as a recharge boundary for the aquifer system in the wet season. The aquifers system is fully recharged in the wet season. Figure 37 gives the zoomed view of the project site for wet season. Figure 38 shows the head equipotential lines in the cross-sections for wet season.

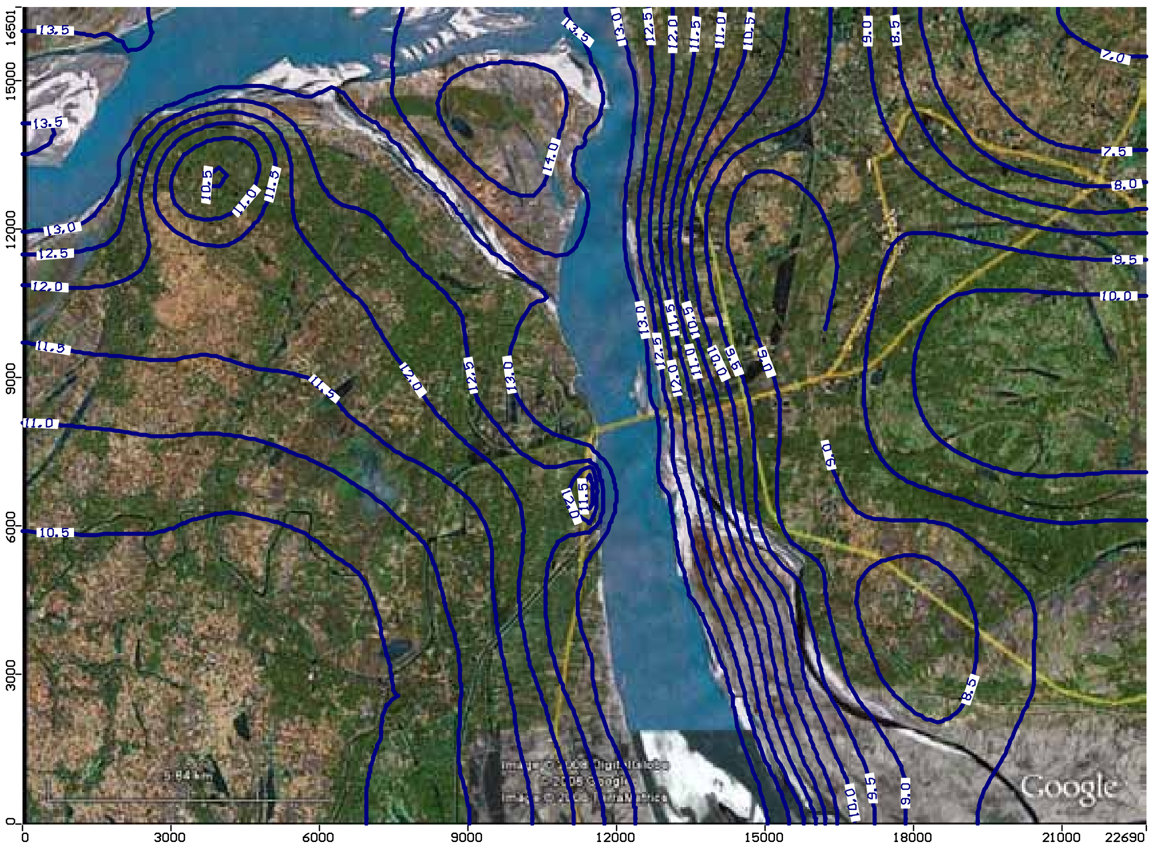


Figure 36. Modelled wet season (September) water table contour map after 20 years of pumping (wells arranged in line).

Figure 37. Zoomed in modelled wet season (September) water table contour map after 20 years of pumping (wells arranged in line).

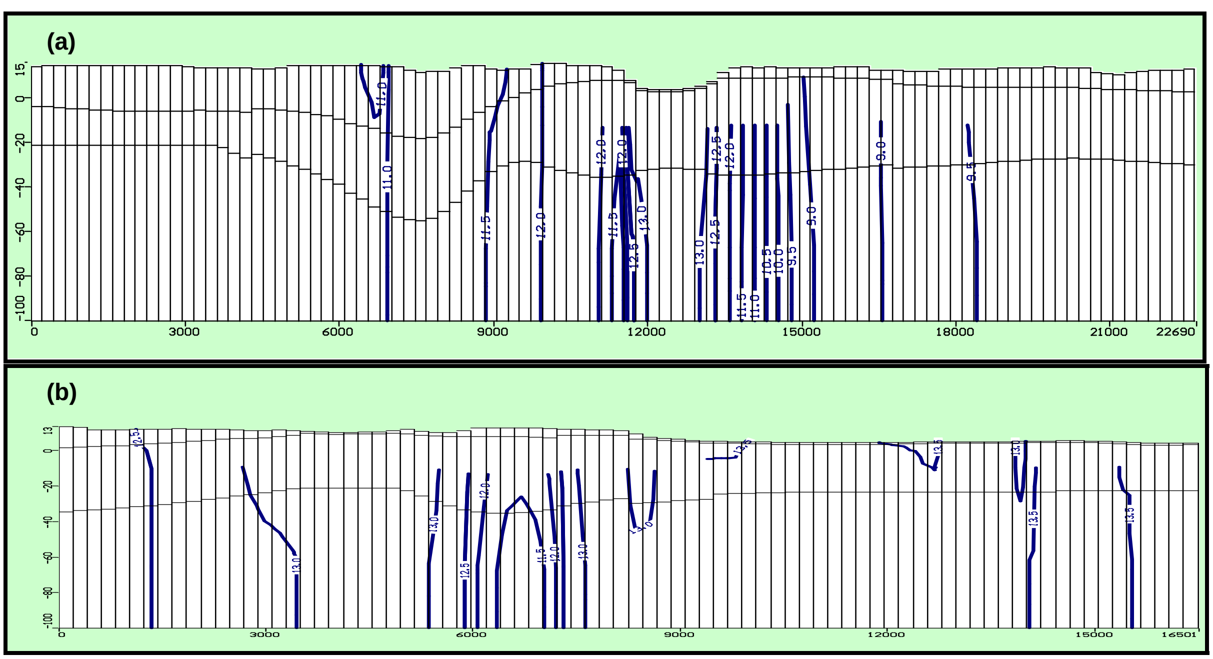


Figure 38. Modelled head equipotential line of wet season (September) in cross-sections (a) X-direction and (b) Y-direction (wells arranged in line).

Second scenario

For wells arranged in cluster the model is again run for 20 years. Figure 39 shows the modelled groundwater level of dry season (May) after 20 years of pumping. The modelled minimum elevation of groundwater table occurs in the month of May.

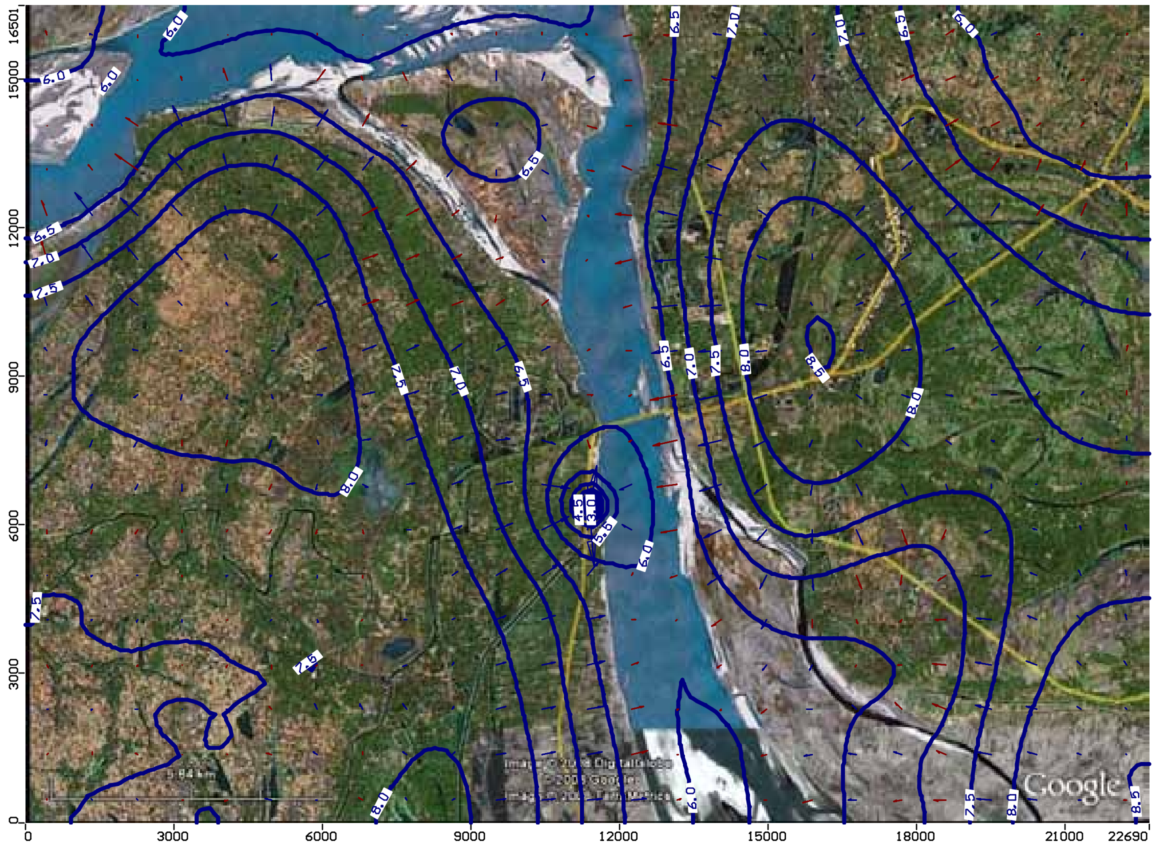


Figure 39. Modelled dry season (May) water table contour map after 20 years of pumping (wells arranged in cluster).

As the wells are arranged in cluster drawdown is higher in the vicinity of the pumping wells in comparison to first scenario. Figure 40 gives the zoomed view of the water table contour map of the project site. The cone of depression is asymmetric and it is extended to the eastern side of the project site. In about 1 km^2 area surrounding the pumping well of the proposed power plant water level may decline by 1 to 4 m from the existing water level. Figure 41 gives the head equipotential lines in the cross-sections for dry season.

Figure 40. Zoomed in modelled dry season (May) water table contour map after 20 years of pumping (wells arranged in cluster).

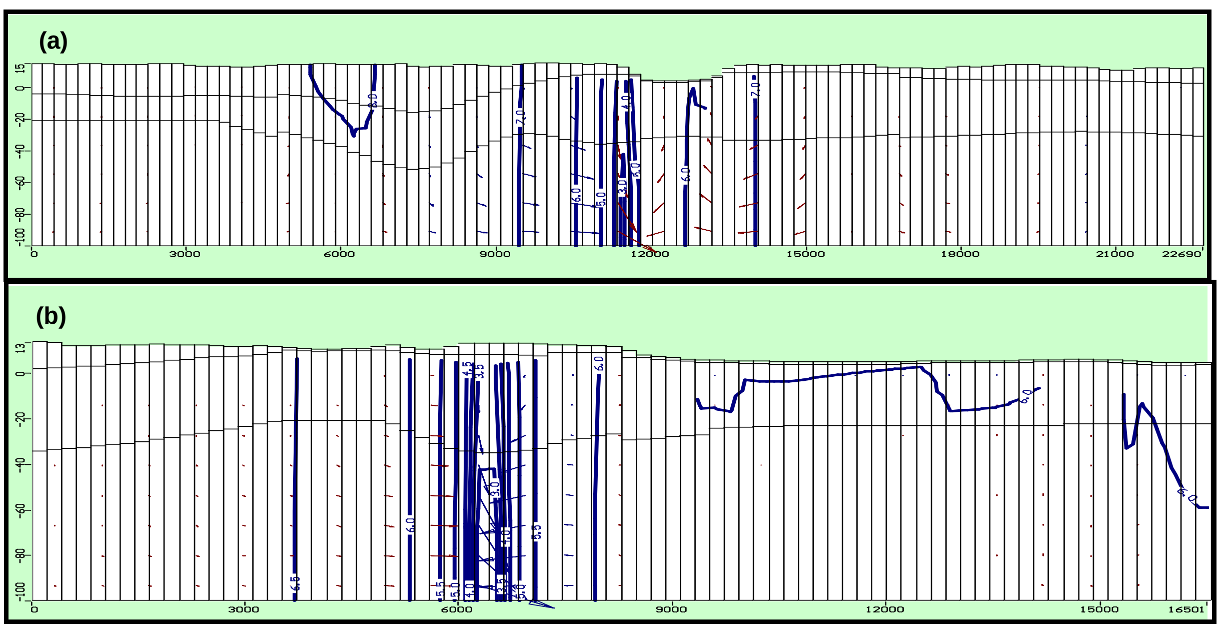


Figure 41. Modelled head equipotential line of dry season (May) in cross-sections (a) X-direction and (b) Y-direction (wells arranged in cluster).

The modelled maximum elevation of groundwater table occurs in the month of September (Figure 42). Figure 43 gives the zoomed view of the project site for wet season. Figure 44 shows the head equipotential lines in the cross-sections for wet season.

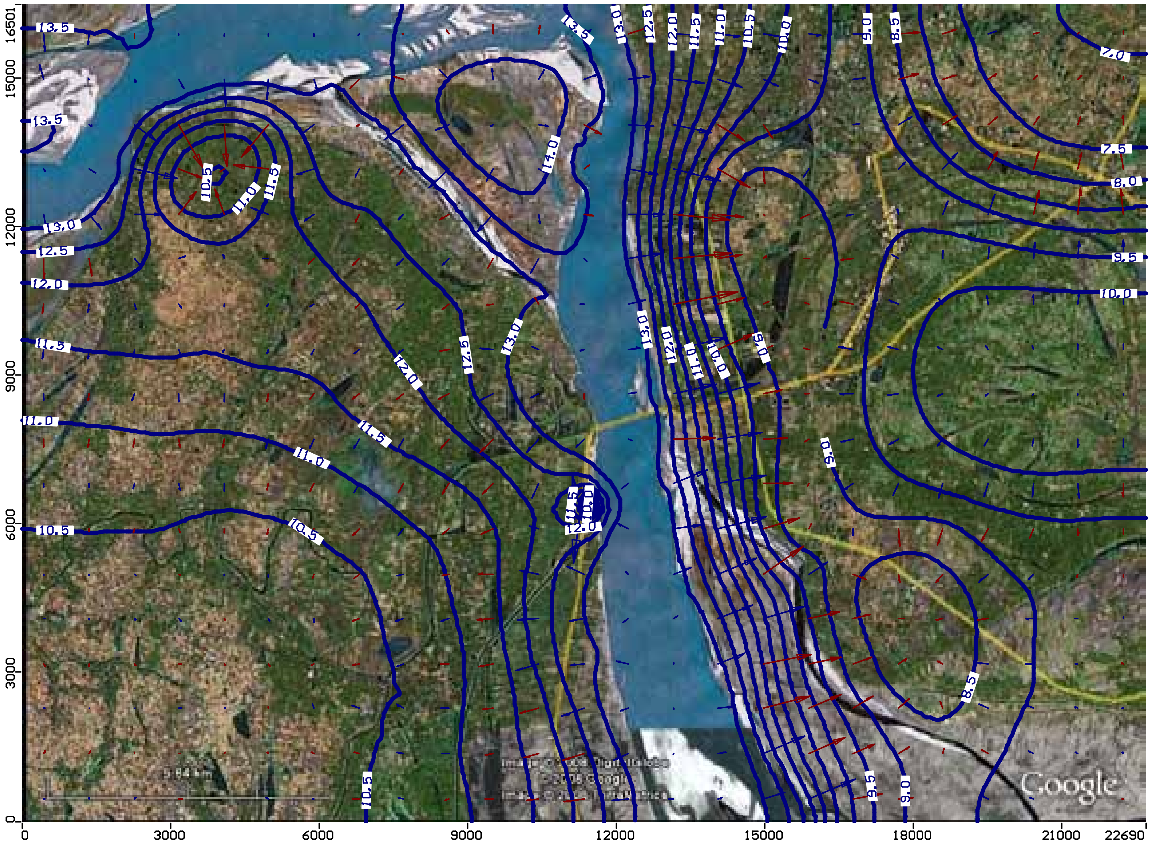


Figure 42. Modelled wet season (September) water table contour map after 20 years of pumping (wells arranged in cluster).

The MODFLOW results generated through this modeling effort reflect only assumed conditions based on site data, collected data or literature values. The model predicted that the minimum groundwater elevation in the dry season occurs in the month of May. During the dry season the Padma River gains water from surrounding aquifer. In spite of lowering of the water table in the pumping well in the proposed power station and surrounding areas, the pumping well are able to withdraw adequate quantity of water from the aquifer. The maximum elevation of water level occurs in September or October. In the wet season the Padma River recharges the aquifer. The pumping well in the proposed power plant will get plenty of water supplies from the river and water level in the pumping well will rise substantially.

Figure 43. Zoomed in modelled wet season (September) water table contour map after 20 years of pumping (wells arranged in cluster).

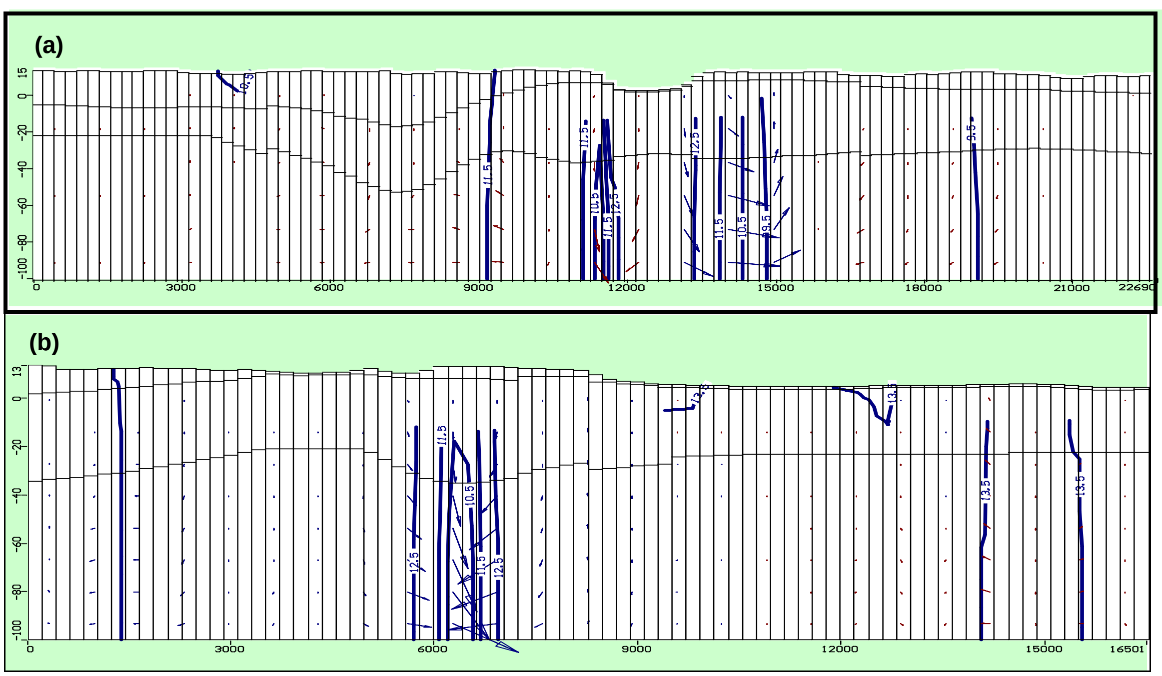


Figure 44. Modelled head equipotential line of wet season (September) in cross-sections (a) X-direction and (b) Y-direction (wells arranged in cluster).

In the **first scenario** the space among the wells was higher than the second scenario. The interference of wells which depend on the spacing among the wells was also lower.

The advantages of the first scenario in which wells are arranged in a line of about 1 km parallel to the Padma River are:

- Well interference is lower and the drawdown in wells is also lower
- The cone of depression is comparatively flatter and elongated in the direction of the river
- Possibility of harnessing river water is higher
- The extent of effected area is lower

If the spaces among the wells can be increased (e.g., the wells are arranged in a line of about 1.5 km) the advantages will also increase.

The disadvantages of the first scenario are:

- Requires large area on the bank of the Padma River
- The cost of construction and maintaining of the pipeline is higher

In the **second scenario** the space among the wells was lower than the first scenario.

The advantages of second scenario in which wells are arranged in cluster on the bank of the Padma River are:

- Requires small area on the bank of the Padma River
- The cost of construction and maintaining of the pipeline is lower

The disadvantages of the second scenario are:

- Well interference is higher and the drawdown in wells is also higher
- The cone of depression is comparatively steeper and circular
- Possibility of harnessing river water is lower
- The extent of effected area could be higher

Taking into consideration of the pros and cons of the two scenarios it is suggested that the first scenario in which wells are arranged in a line of about 1 km parallel to the Padma River would be more acceptable than the second scenario.

8.0 SURVEY OF EXISTING WELLS AND WATER BODIES NEAR PROJECT SITE

8.1 Introduction

Withdrawal of water from the aquifer at the project site may cause lowering of groundwater table in the surrounding area particularly in dry months of the year. This may cause failure of tubewells operating in suction mode in the neighbourhood. Generally, suction mode tubewells fails when water table decline to >7.5m. It is therefore, important to get a clear idea about the probable extent of the tubewell failure and to determine possible remedial measures. Surface water bodies which are well connected with the underlying aquifer may also dry up with the decline of groundwater table in the area.

8.2 Field Survey of Wells and Water Bodies

Field survey for tubewells and water bodies was conducted using GPS and maps of Bahir Char union and surrounding areas. All the localities in each Mauza (or JL) have been visited and the number and type of tubewells have been recorded. Hand tubewell (HTWs) operates in suction mode and consists of # 6 pump head, 38.1mm dia well pipes and filters. The foot valve and piston assembly are located into the # 6 pump head which is mounted at top of the ground level. HTW is the most common and low cost tubewell technology in Bangladesh. These wells are widely used to procure potable water for domestic uses. They generally work through out the whole year and their rate of discharge is about 0.3 l/s. The depth of HTWs generally ranges from 8 to16m. Shallow Tube Wells (STWs) are generally used for the withdrawal of water for irrigation. They also operate by suction lift. Rate of discharge of STWs is about 15 l/s. The depth of STWs varies from 40 to 50m. Deep Tubewells (DTWs) pump water for irrigation and the pumps operate by force lift. The depth of DTWs varies from 90 to 100m. Different types of water bodies are present in study area. They range from small ditches to canal or lake. The connection of the water bodies with the underlying aquifer is very poor as they remain above water table throughout the whole year.

Figure 45 shows the distribution of HTWs and major water bodies in the study area. Table 13 gives the number of tubewells in different parts of Bahir Char and surrounding areas. The number of population and house hold data of each locality were collected from Bangladesh Bureau of Statistics (BBS, 2007). Present population of each locality was estimated using national population growth rate of 1.07%.

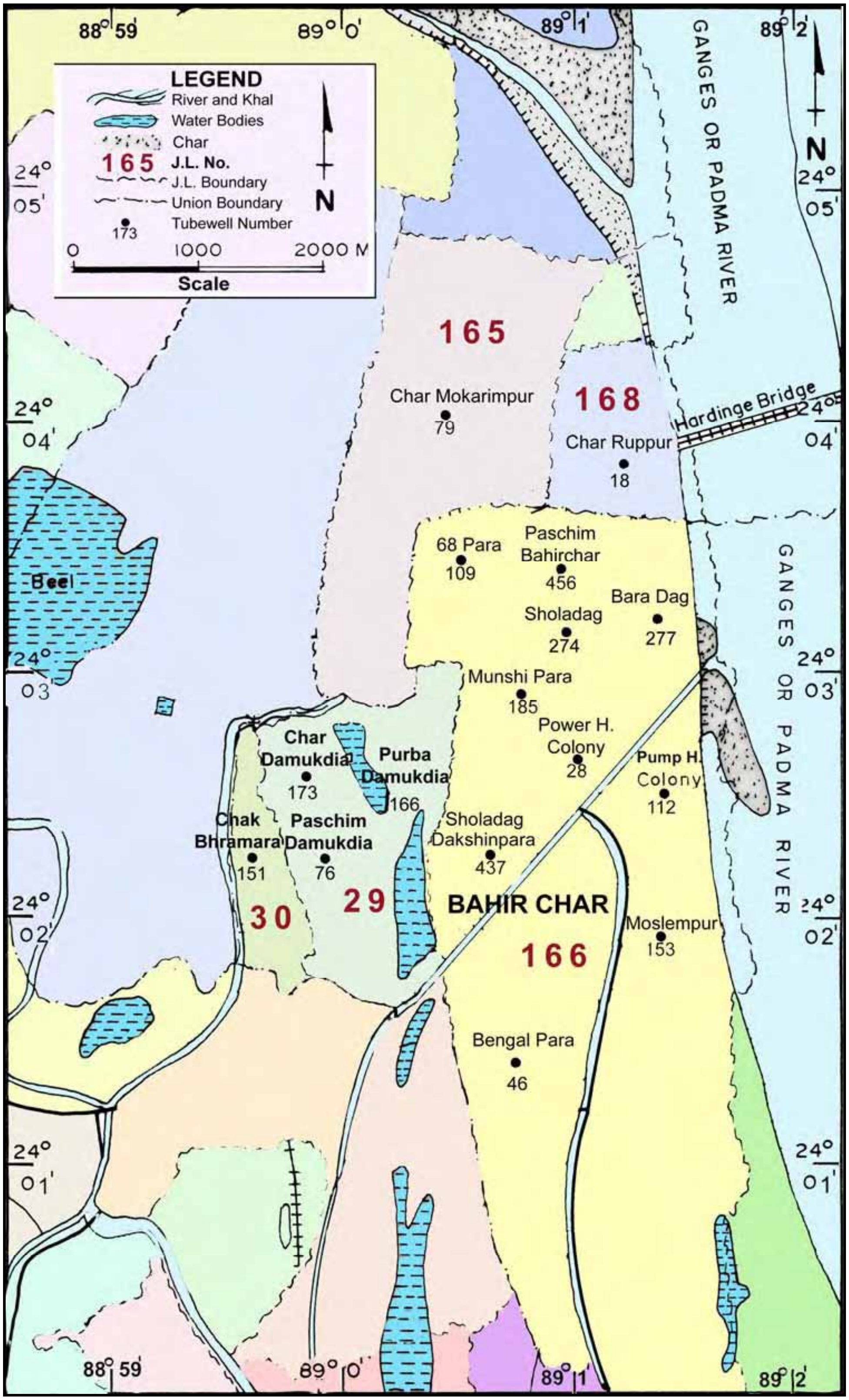


Figure 45. Number of tubewells and major water bodies at different location of Bahir Char union and surrounding areas.

Table 13. Number of existing tubewells, water bodies, house hold and population of Bahir Char union and surrounding areas

JL No.	Geo code	Locality	Area Km^2	House Hold	Population 2001	Estimated Present Population	HTWs	STWs	DTWs	Water Bodies
30	**213**	**Chak Bheramara**	**0.81**	**196**	**929**	**1001**	**151**	**4**	**1**	**11**
165	**307**	**Char Mokarimpur**	**4.04**	**122**	**492**	**530**	**79**	**9**	**1**	**13**
168	**331**	**Char Ruppur**	**1.28**	**28**	**346**	**373**	**18**	**6**	**1**	**17**
29	**355**	**Damukdia**	**2.97**	**647**	**3095**	**3334**	**415**	**8**	**2**	**14**
	355	Char Damukdia		181	936	1008	173	3	1	4
	355	Purba Damukdia		365	1705	1837	166	3		5
	355	Paschim Damukdia		101	454	489	76	2	1	3
166	**902**	**Pashchim Bahirchar**	**12.88**	**3412**	**16889**	**18195**	**2077**	**5**	**5**	**53**
	902	Power House colony		175	767	826	28			1
	902	Bara Dag		279	1420	1530	277	1	1	4
	902	68 para		141	694	748	109		1	3
	902	Moslempur		444	2218	2390	153	1		3
	902	Munshi Para		241	1174	1265	185			4
	902	Sholadag Dakshinpara		552	2716	2926	437	1		8
	902	Sholadag		551	2712	2922	274			9
	902	Paschim Bahirchar		856	4334	4669	456	2		13
	902	Pump House Colony		70	353	380	112		3	6
	902	Bengal Para		103	501	540	46			2

8.3 Effected Wells and Water Bodies

Table 14 gives the estimated number of wells that may become inactive by the lowering of water table due to pumping water at the project site. Figure 46 gives the probable shapes of the effected area for a linear layout of 12 pumping wells at the project site.

Table 14. Estimated number of effected wells and water bodies

Width of Effected Area (km)	Effected Area (km^2)	Number of Effected Wells			Water Bodies
		HTWs	STWs	DTWs	
0.5	0.9	260	0	0	3
1	2.6	670	5	0	22
1.5	5.0	1055	11	0	53
2	8.3	1818	17	0	68

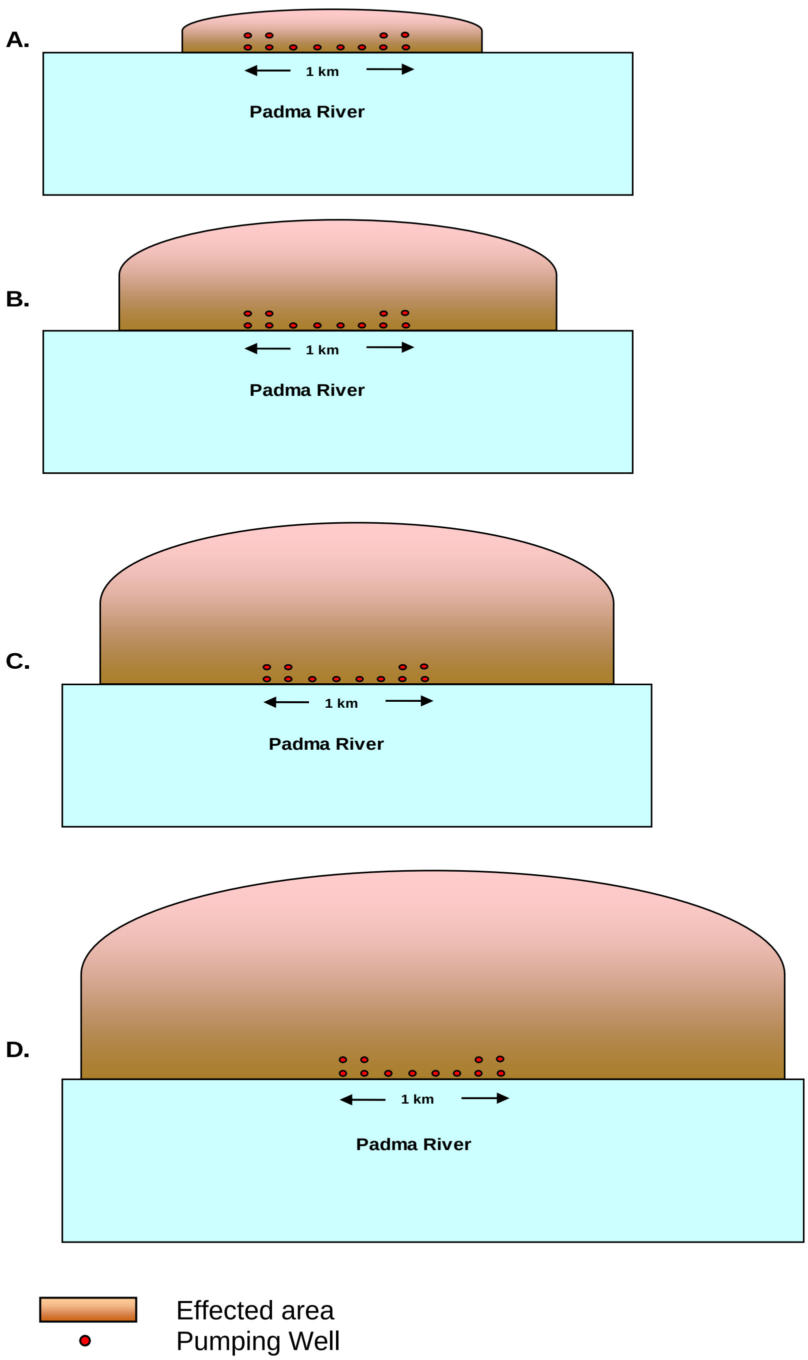


Figure 46. For a linear layout of 12 pumping wells at the project site probable shapes of the effected area. A. when the effected area is 500m wide, B. when the effected area is 1 km wide, C. when the effected area is 1.5 km wide and D. when the effected area is 2 km wide.

8.4 Remedial Measures

If the water level decline >7.5m from the surface, HTWs will not be able to pump water from the aquifer. Present tubewells will need replacement with the following types:

1. Half-Cylinder hand tubewell

This well is suitable for areas where water level goes beyond the suction limit (static water level > 7.5 m) for certain period of time in each year. In such cases, the cylinder of the pump is lowered along with the foot valve and piston assembly up to 1-3 m below ground surface through the casing pipe so that the pump can be operational for the whole year. This type of option tubewell is known as Half-Cylinder (sometimes Semi Deep-set pump) tubewell. The suction depth of this tubewell is **15m**.

2. Deep set hand tubewell (DSHTW)

Deep set hand tubewell (DSHTW) operates in force mode and can abstract water from a depth beyond the suction limit i.e., **30 - 37m** below ground level depending upon the type of DSHTW. For DSHTW, 76 mm dia housing/ casing pipe length is extended up to a certain depth depending on the water table and piston assembly of the pump is set at that level by connecting a pump-rod to the handle. The piston remains in submerged condition below water table.

Usually two types of DSHTWs are used, which are Tara-II (also known as Tara Super) and Tara Dev. They are more cost-effective than other pumps and are safe from bacteriological contamination since all underground parts are made of non-corrosive materials like PVC or stainless steel.

9. REFERENCES

Abu Bakr and Jackson 1964. Geological Map of Pakistan.

Anderson M.P., and Woessener W.W. 1992. Applied Groundwater Modeling. Simulation of Flow and Transport, Academic Press INC California. pp 381.

BADC (2005) Survey Report on Irrigation Equipment and Irrigated Area in Boro 2004, Survey and Monitoring Project For Minor Irrigation, Sech Bhaban, Dhaka, pp 183.

BBS 2007. Bangladesh Bureau of Statistics, Statistical Year Book of Kustia, 2007.

Bear, J., and Bachmat Yehuda, 1991. Introduction to modelling of transport phenomena in porous media. Kluwer Academic Publishers, Netherlands, pp. 553.

BWDB 1987. Regeneration Studied of the Ganges, BWDB Water Supply Paper No. 487, pp10.

Domenico, P.A. 1972. Concepts and Models in Groundwater Hydrology, Mc-Graw Hill, N.Y., 405 p.

Domenico, P.A. and F.W. Schwartz, 1990. *Physical and Chemical Hydrogeology*, John Wiley & Sons, New York, 824 p.

Fetter, C.W., 2001. Applied Hydrogeology (4th ed.), Prentice-Hall, Upper Saddle River, New Jersey, 598p.

Hantush, M.S., 1961a. Drawdown around a partially penetrating well, Jour. of the Hyd. Div., Proc. of the Am. Soc. of Civil Eng., vol. 87, no. HY4, pp. 83-98.

Hantush, M.S., 1961b. Aquifer tests on partially penetrating wells, Jour. of the Hyd. Div., Proc. of the Am. Soc. of Civil Eng., vol. 87, no. HY5, pp. 171-194.

Harbaugh, A.W., and McDonald, M.G. 1996. User's documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite difference groundwater flow model. U.S. Geol. Survey Open-File Report 96-485.

Heath, R.C., 1983. Basic Groundwater Hydrology, USGS, Water Supply Paper 2220, 84 p.

Howard Hamphre (1984) Groundwater Evaluation and Monitoring, Southwest Rural Development Project, prepared for BADC by Howard Humphre, Consuling Engineers, UK. pp 73.

IECO (1980) South West Regional Planning Study, Final Report.

Islam M.S. 2002. Studies on Hydrogeoenvironmental Changes in Southwestern Bangladesh after Commissioning the Farakka Barrage, Unpublished M.Phil. Thesis, Dhaka University, pp-204

Johnson A.I., and Morris, D.A., 1962. Physical and hydrologic properties of water bearing deposits from core holes in the Las Banos Kettleman City area, California, Denver, Colorado, USGS Open file report.

Kruseman, G.P. and N.A. DeRidder, 1990. *Analysis and Evaluation of Pumping Test Data (2nd ed.)*, Publication 47, Intern. Inst. for Land Reclamation and Improvement, Wageningen, The Netherlands, 370p.

McDonald, M. G., and A. W. Harbaugh, 1988. A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model. U.S. Geological Survey TWI 6-A1, 1988.

Moench, A.F., 1993. Computation of type curves for flow to partially penetrating wells in water-table aquifers, Ground Water, vol. 31, no. 6, pp. 966-971.

Moench, A.F., 1996. Flow to a well in a water-table aquifer: an improved Laplace transform solution, Ground Water, vol. 34, no. 4, pp. 593-596.

Morris, D.A., and Johnson, L.A., 1967. Summary of Physical properties of rock and soil materials as analyzed by the Hydrologic Laboratory of the U.S. Geological Survey 1948-1960. USGS, Water Supply Paper 2338, 41 p.

Neuman, S.P., 1974. Effect of partial penetration on flow in unconfined aquifers considering delayed gravity response, Water Resources Research, vol. 10, no. 2, pp. 303-312.

Neuman, S.P., 1972. Theory of flow in unconfined aquifers considering delayed gravity response of the water table, Water Resources Research, vol. 8, no. 4, pp. 1031-1045.

Ponce V.M,, 1989. Engineering Hydrology : Principle and Practices, Prentice Hall, pp 45-47.

Theis, C.V., 1935. The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage, Am. Geophys. Union Trans., vol. 16, pp. 519-524.

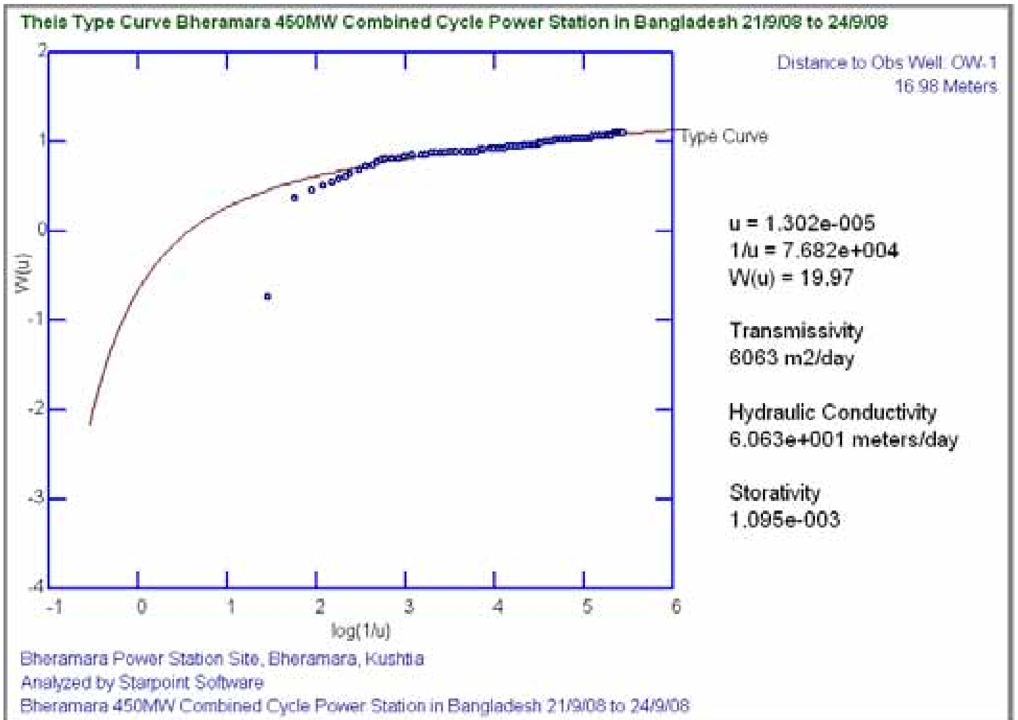
UNDP 1982, The Hydrogeological Conditions of Bangladesh; United Nations Ground Water Survey Technical Report, New York.

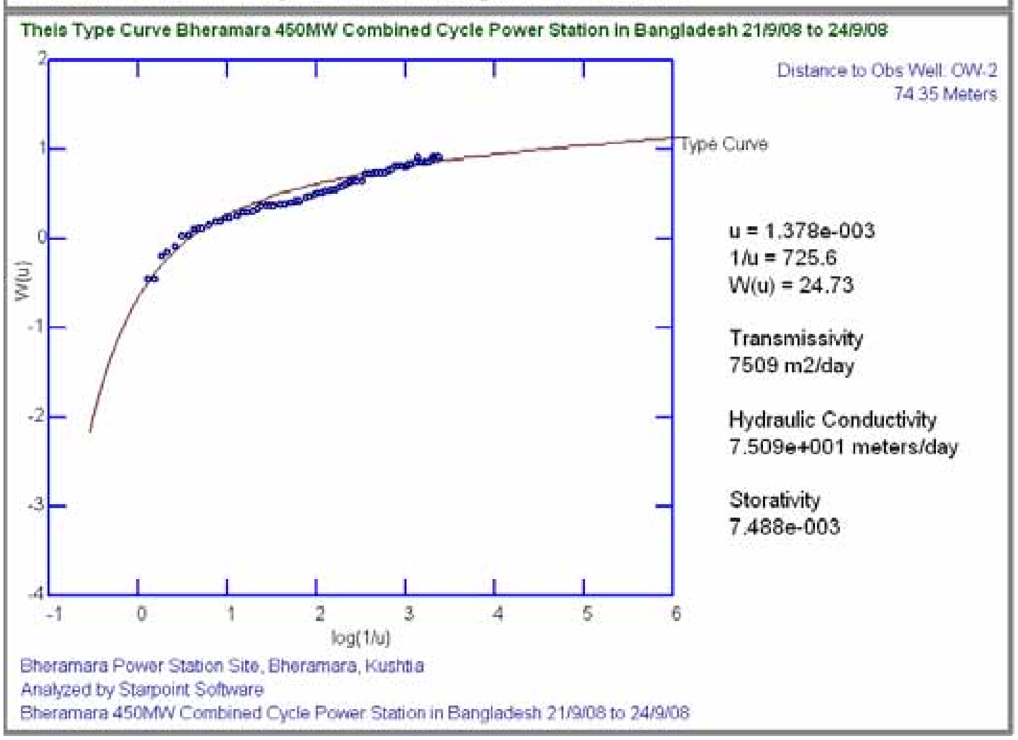
UNICEF 1993. The Study to Forecast Declining Groundwater Level in Bangladesh Final Report, 4, Dhaka.

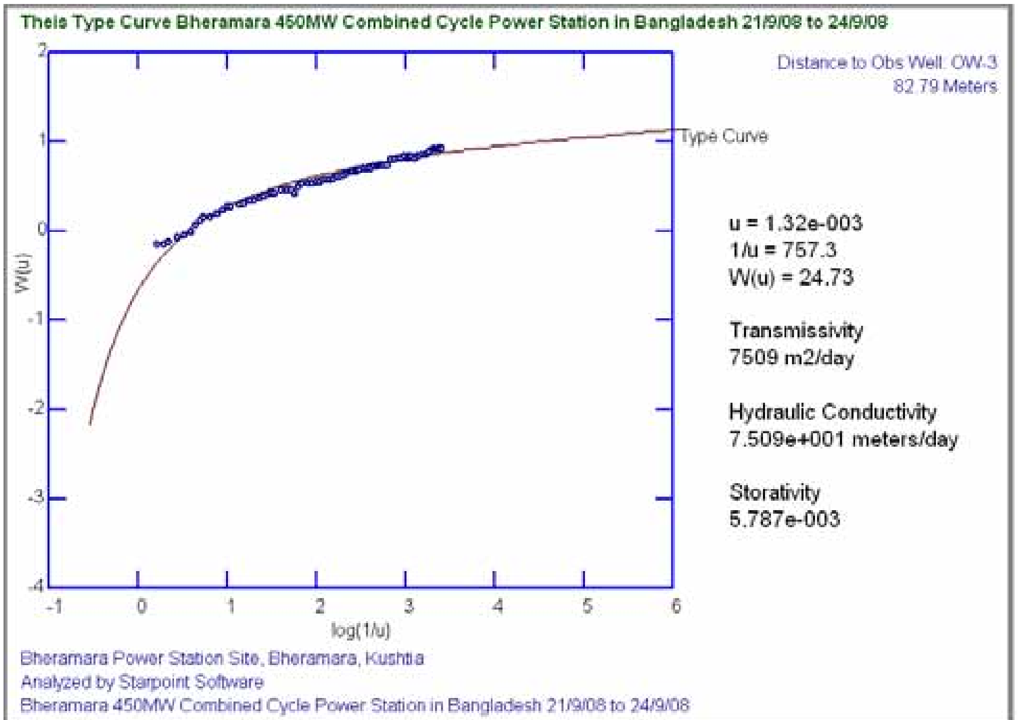
Van der Kamp G. 1985. Brief quantitative guidelines for the design and analysis of pumping test. In: Hydrology in the service of man. Mem. 18th Congress Intern. Asso Hydrogeol. Cambridge, pp 1978-206.

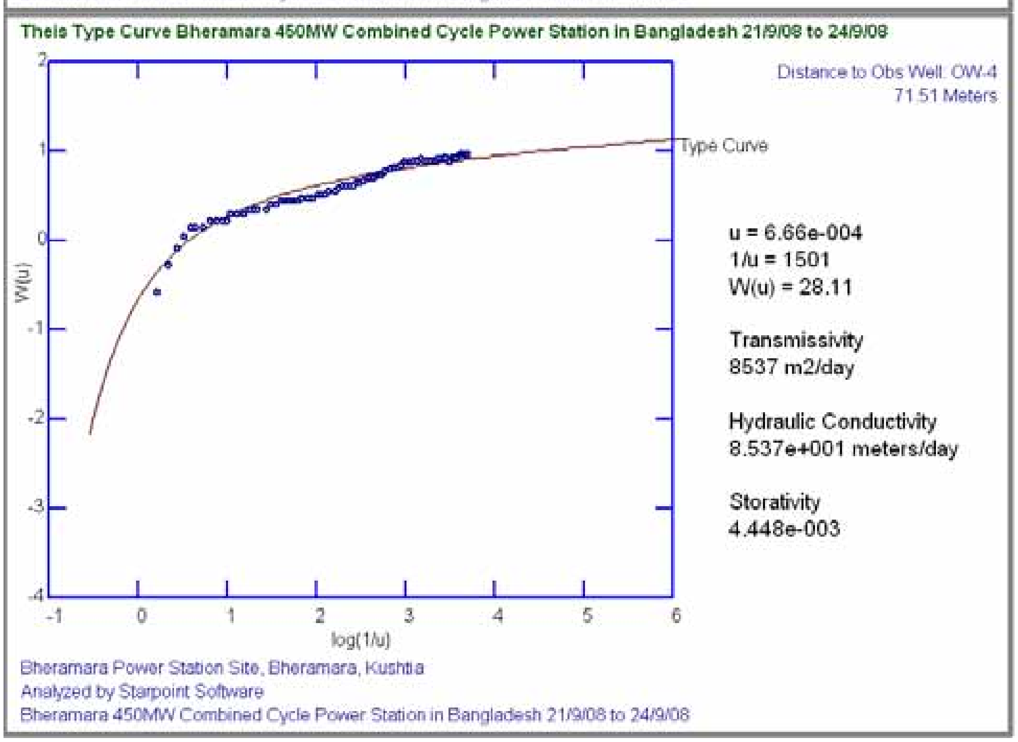
APPENDIX I : Analysis of Pumping Test Data

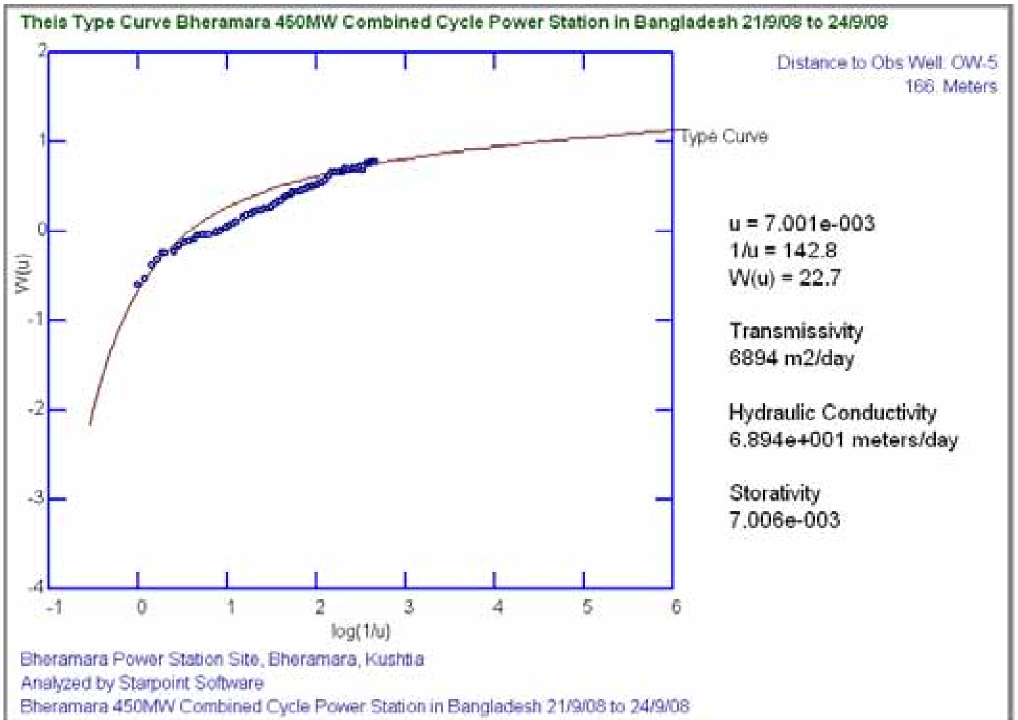
Appendix I : a. Theis Curve Matching

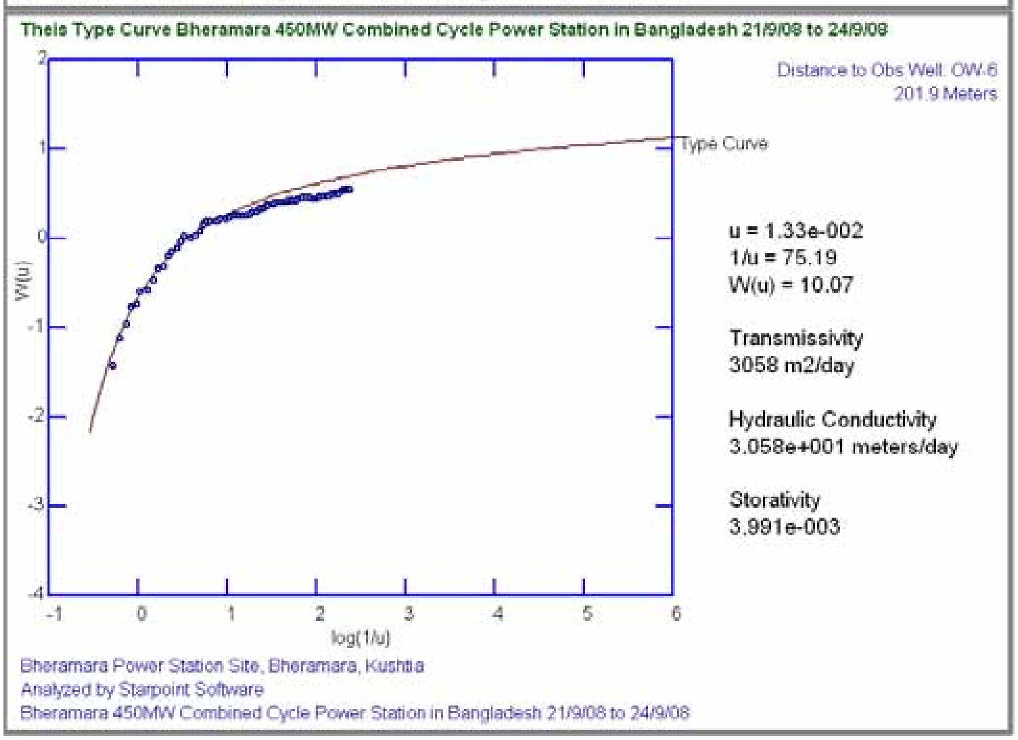


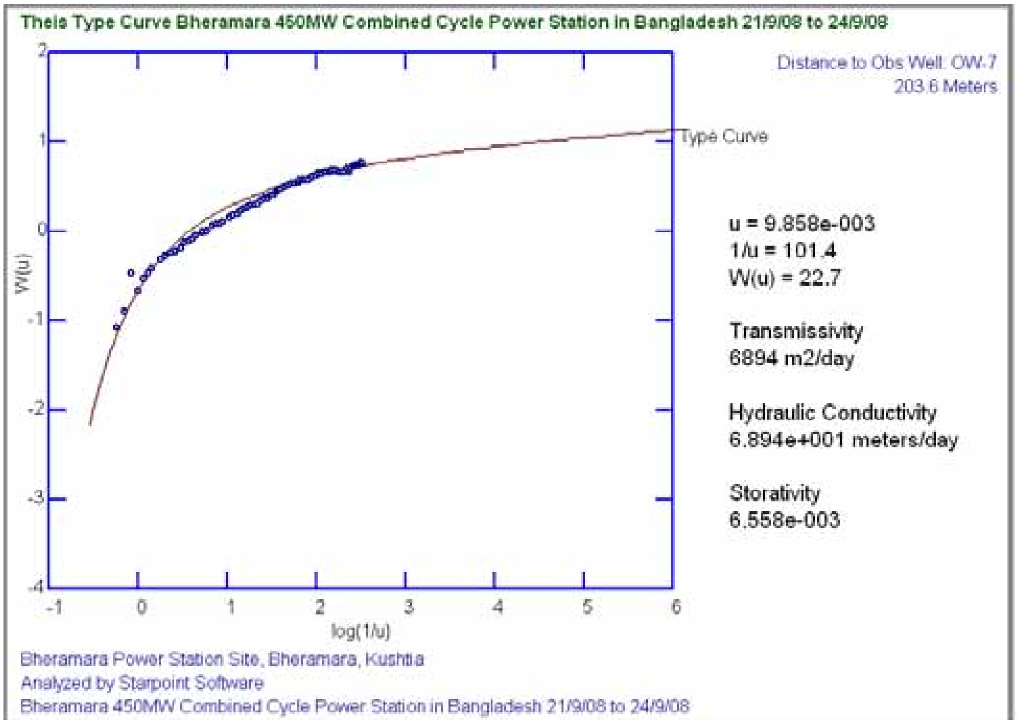


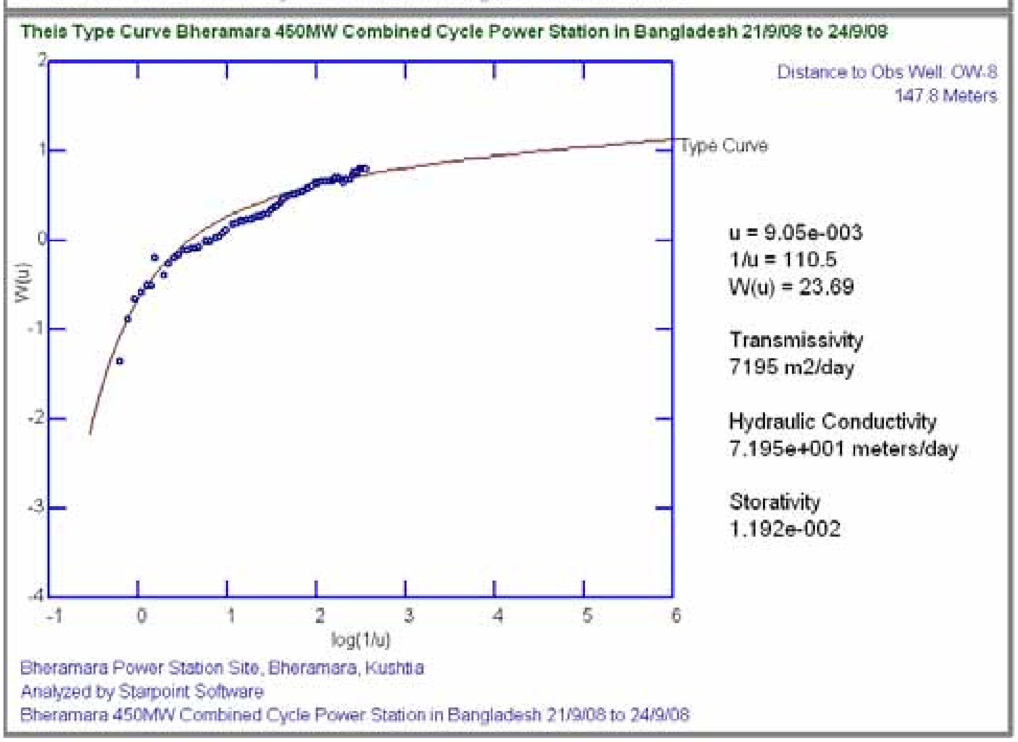

Theis Type Curve Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
Distance to Obs Well: OW-3
82.79 Meters
Type Curve
u = 1.32e-003
1/u = 757.3
W(u) = 24.73
Transmissivity
7509 m2/day
Hydraulic Conductivity
7.509e+001 meters/day
Storativity
5.787e-003
W(u)
log(1/u)
Bheramara Power Station Site, Bheramara, Kushtia
Analyzed by Starpoint Software
Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08

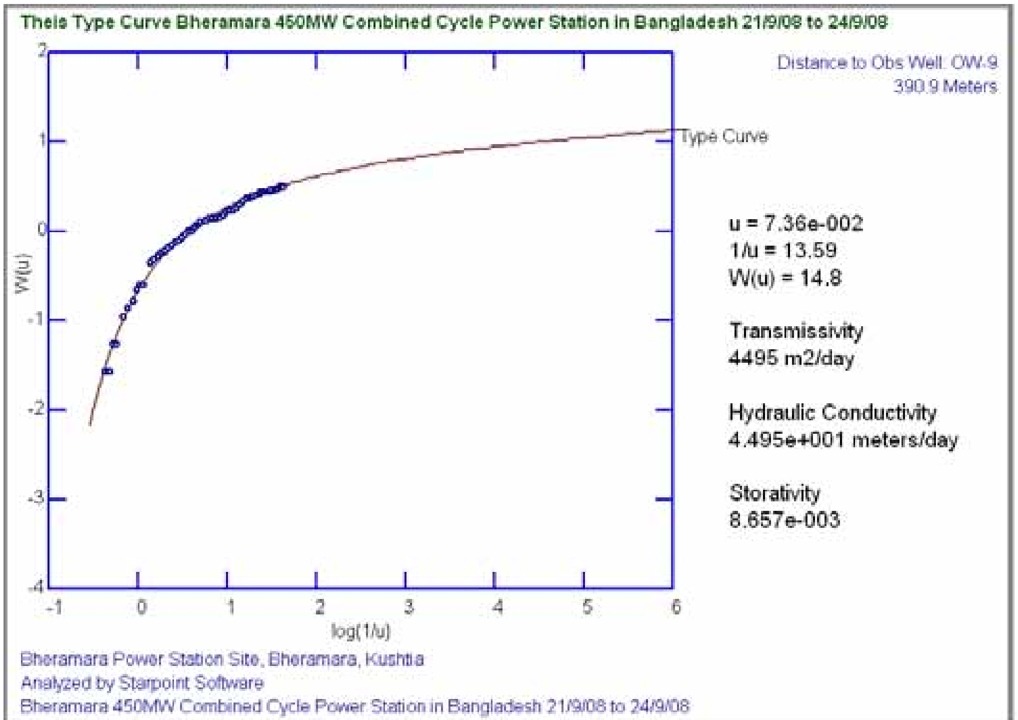

Theis Type Curve Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
Distance to Obs Well: OW-4
71.51 Meters
Type Curve
u = 6.66e-004
1/u = 1501
W(u) = 28.11
Transmissivity
8537 m2/day
Hydraulic Conductivity
8.537e+001 meters/day
Storativity
4.448e-003
W(u)
log(1/u)
Bheramara Power Station Site, Bheramara, Kushtia
Analyzed by Starpoint Software
Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08

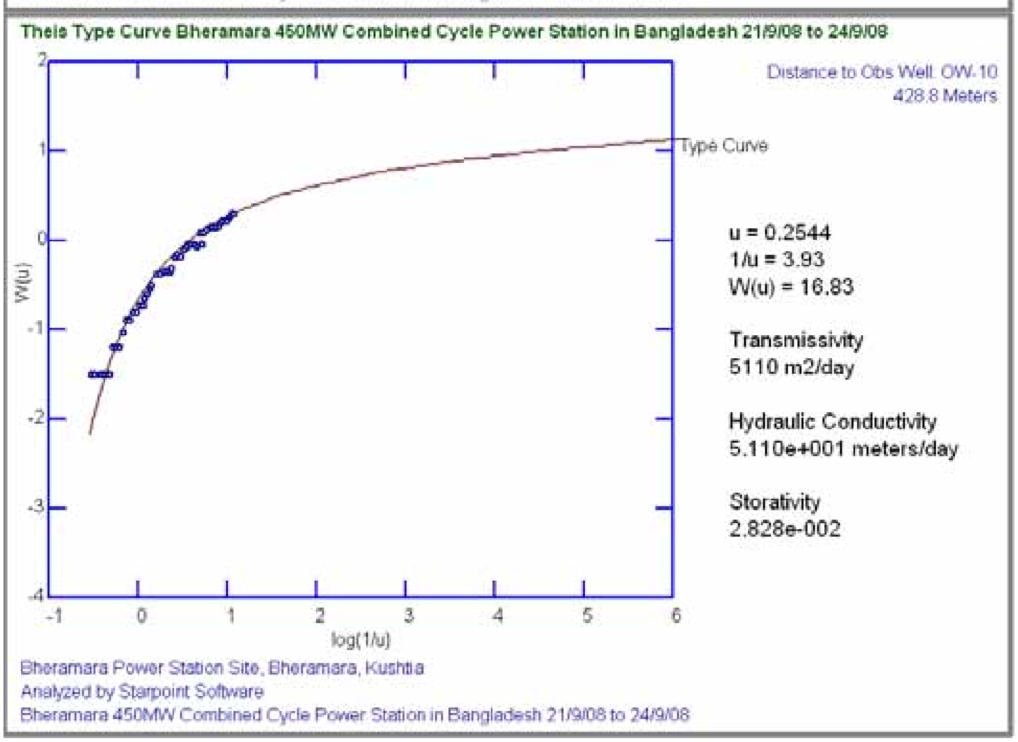

Theis Type Curve Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
Distance to Obs Well: OW-5
166. Meters
Type Curve
u = 7.001e-003
1/u = 142.8
W(u) = 22.7
Transmissivity
6894 m2/day
Hydraulic Conductivity
6.894e+001 meters/day
Storativity
7.006e-003
W(u)
log(1/u)
Bheramara Power Station Site, Bheramara, Kushtia
Analyzed by Starpoint Software
Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08

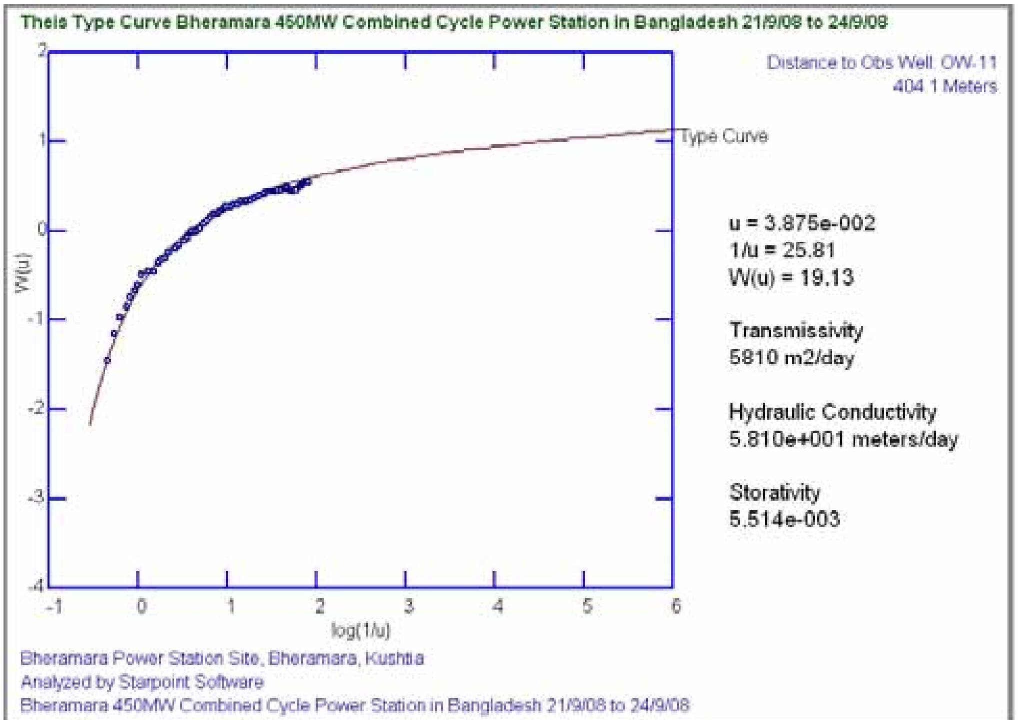

Theis Type Curve Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
Distance to Obs Well: OW-6
201.9 Meters
Type Curve
u = 1.33e-002
1/u = 75.19
W(u) = 10.07
Transmissivity
3058 m2/day
Hydraulic Conductivity
3.058e+001 meters/day
Storativity
3.991e-003
W(u)
log(1/u)
Bheramara Power Station Site, Bheramara, Kushtia
Analyzed by Starpoint Software
Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08

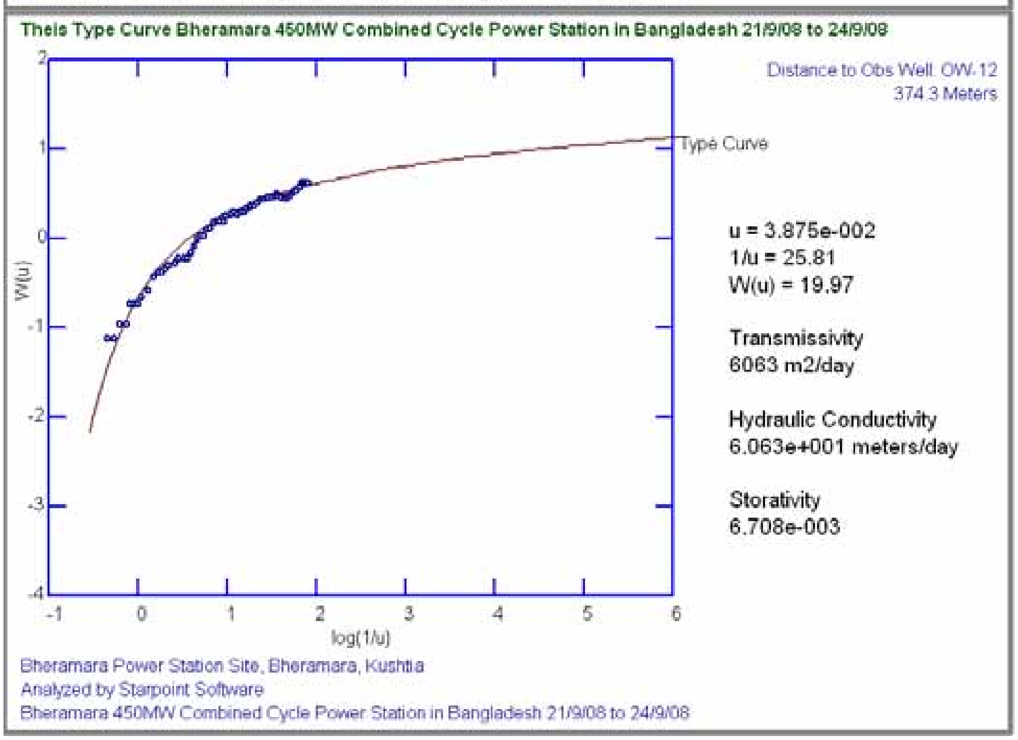

Theis Type Curve Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
Distance to Obs Well: OW-7
203.6 Meters
Type Curve
u = 9.858e-003
1/u = 101.4
W(u) = 22.7
Transmissivity
6894 m2/day
Hydraulic Conductivity
6.894e+001 meters/day
Storativity
6.558e-003
W(u)
log(1/u)
Bheramara Power Station Site, Bheramara, Kushtia
Analyzed by Starpoint Software
Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08


Theis Type Curve Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
Distance to Obs Well: OW-8
147.8 Meters
Type Curve
u = 9.05e-003
1/u = 110.5
W(u) = 23.69
Transmissivity
7195 m2/day
Hydraulic Conductivity
7.195e+001 meters/day
Storativity
1.192e-002
W(u)
log(1/u)
Bheramara Power Station Site, Bheramara, Kushtia
Analyzed by Starpoint Software
Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08

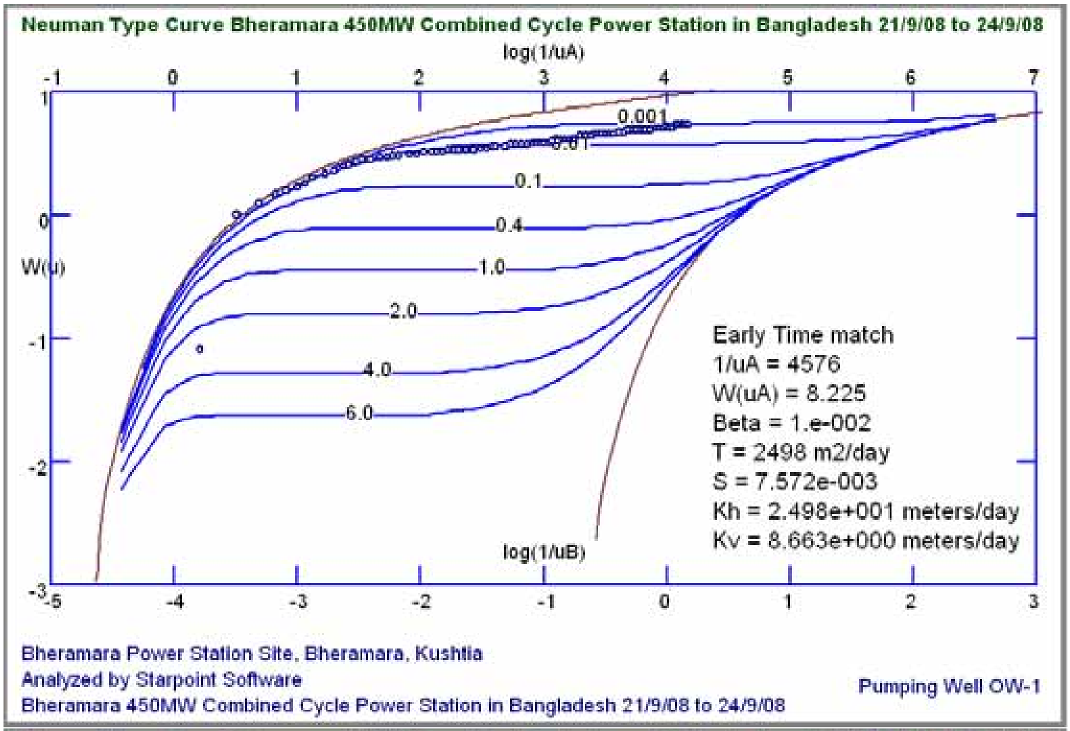

Theis Type Curve Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
Distance to Obs Well: OW-9
390.9 Meters
Type Curve
u = 7.36e-002
1/u = 13.59
W(u) = 14.8
Transmissivity
4495 m2/day
Hydraulic Conductivity
4.495e+001 meters/day
Storativity
8.657e-003
W(u)
log(1/u)
Bheramara Power Station Site, Bheramara, Kushtia
Analyzed by Starpoint Software
Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08

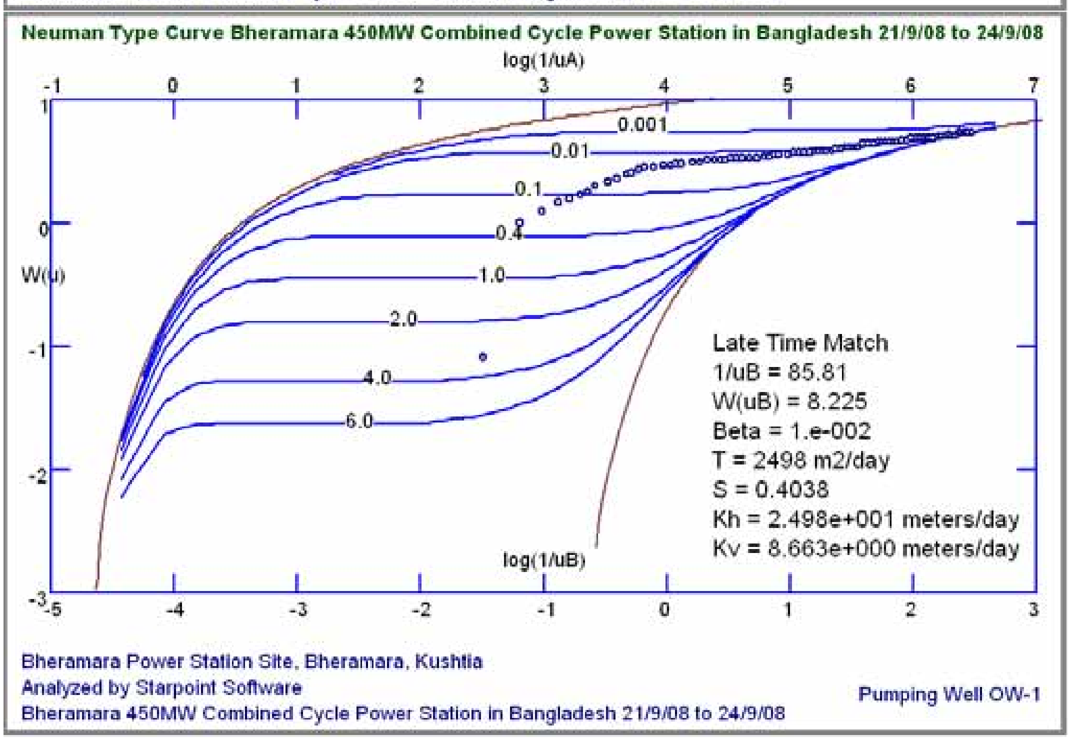

Theis Type Curve Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
Distance to Obs Well: OW-10
428.8 Meters
Type Curve
u = 0.2544
1/u = 3.93
W(u) = 16.83
Transmissivity
5110 m2/day
Hydraulic Conductivity
5.110e+001 meters/day
Storativity
2.828e-002
W(u)
log(1/u)
Bheramara Power Station Site, Bheramara, Kushtia
Analyzed by Starpoint Software
Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08

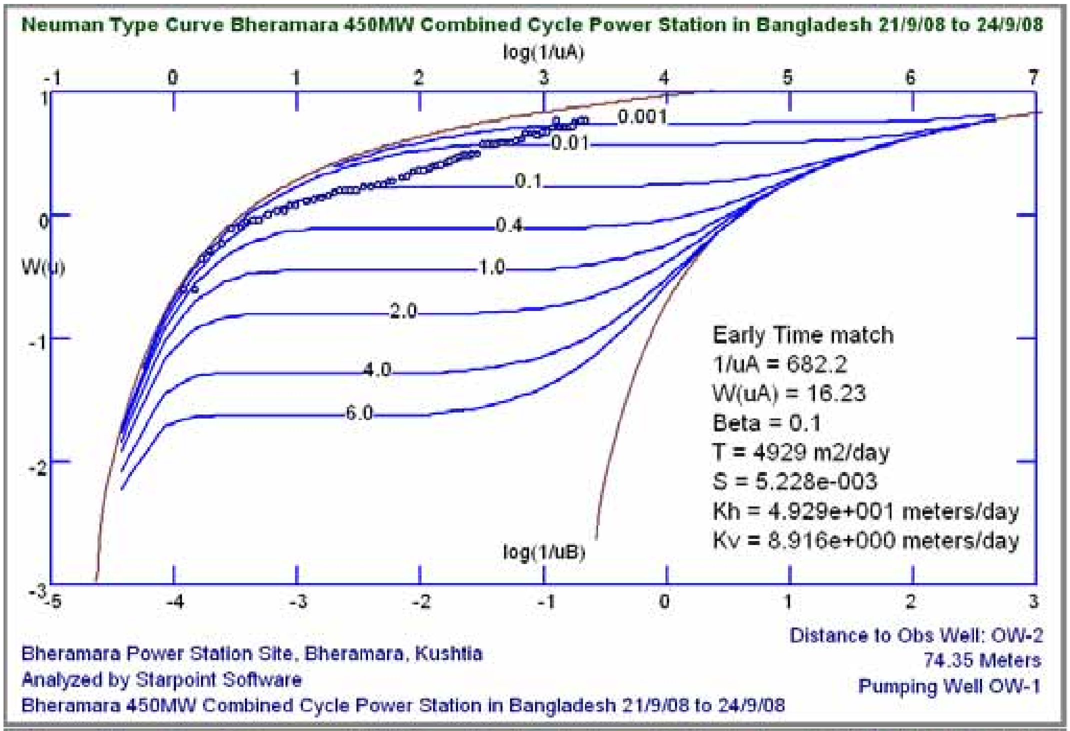

Theis Type Curve Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
Distance to Obs Well OW-11
404.1 Meters
Type Curve
u = 3.875e-002
1/u = 25.81
W(u) = 19.13
Transmissivity
5810 m2/day
Hydraulic Conductivity
5.810e+001 meters/day
Storativity
5.514e-003
W(u)
log(1/u)
Bheramara Power Station Site, Bheramara, Kushtia
Analyzed by Starpoint Software
Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08

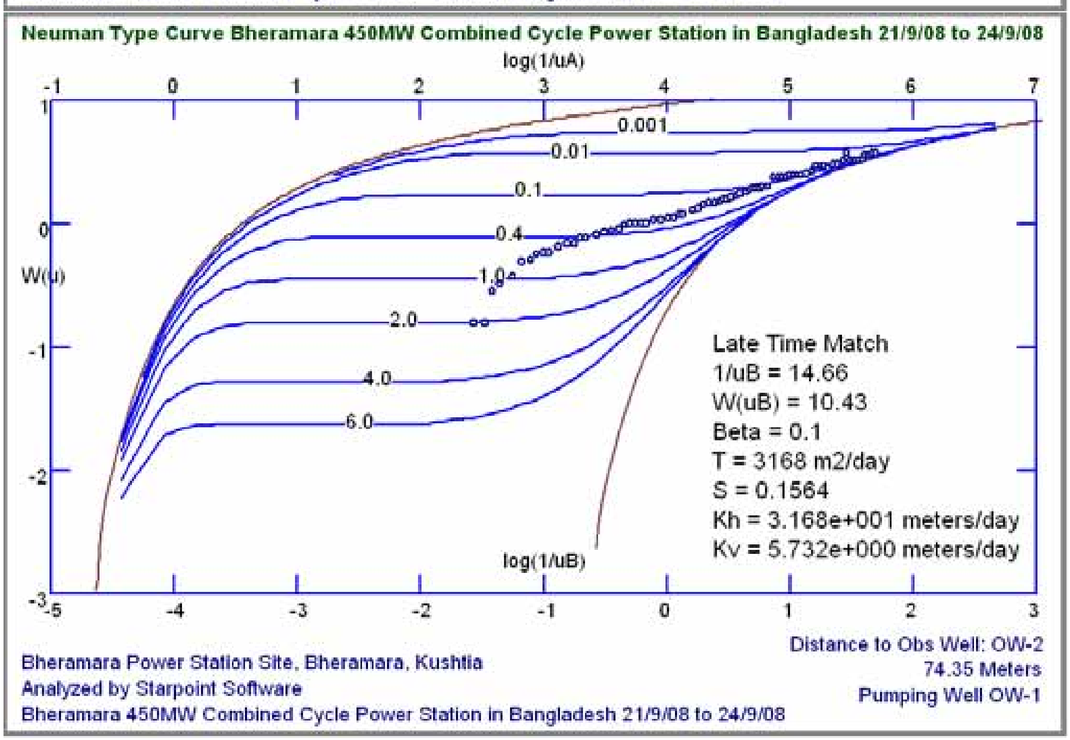

Theis Type Curve Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
Distance to Obs Well OW-12
374.3 Meters
Type Curve
u = 3.875e-002
1/u = 25.81
W(u) = 19.97
Transmissivity
6063 m2/day
Hydraulic Conductivity
6.063e+001 meters/day
Storativity
6.708e-003
W(u)
log(1/u)
Bheramara Power Station Site, Bheramara, Kushtia
Analyzed by Starpoint Software
Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08

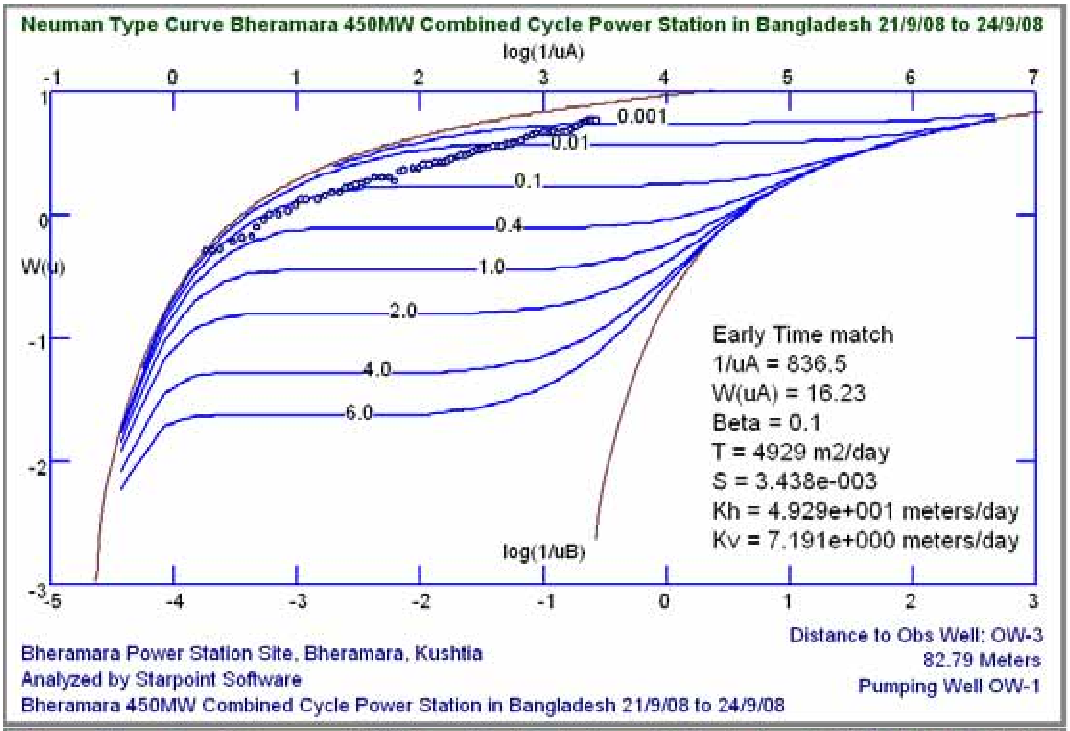
b. Neumann Curve Matching

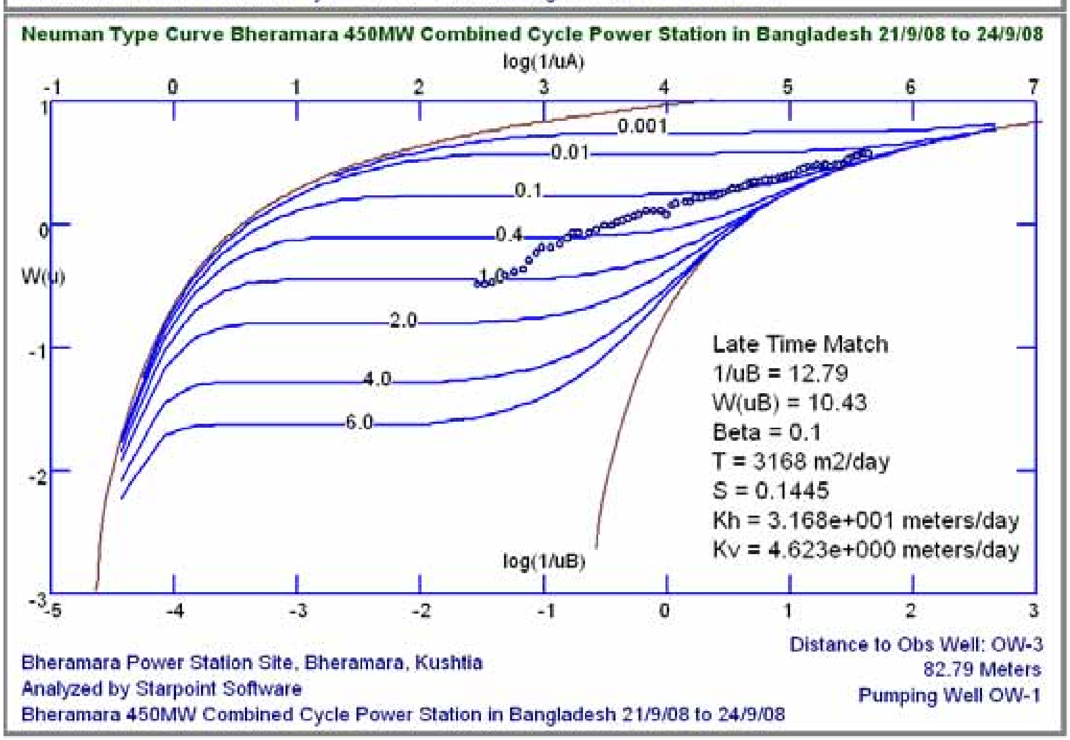


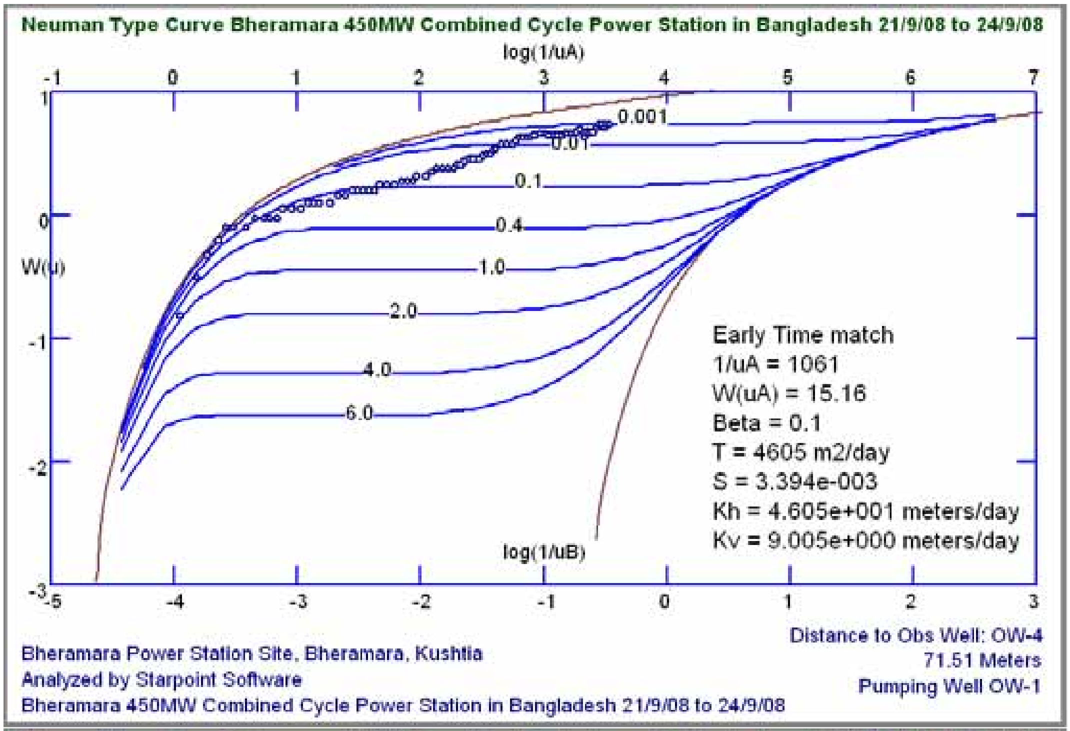


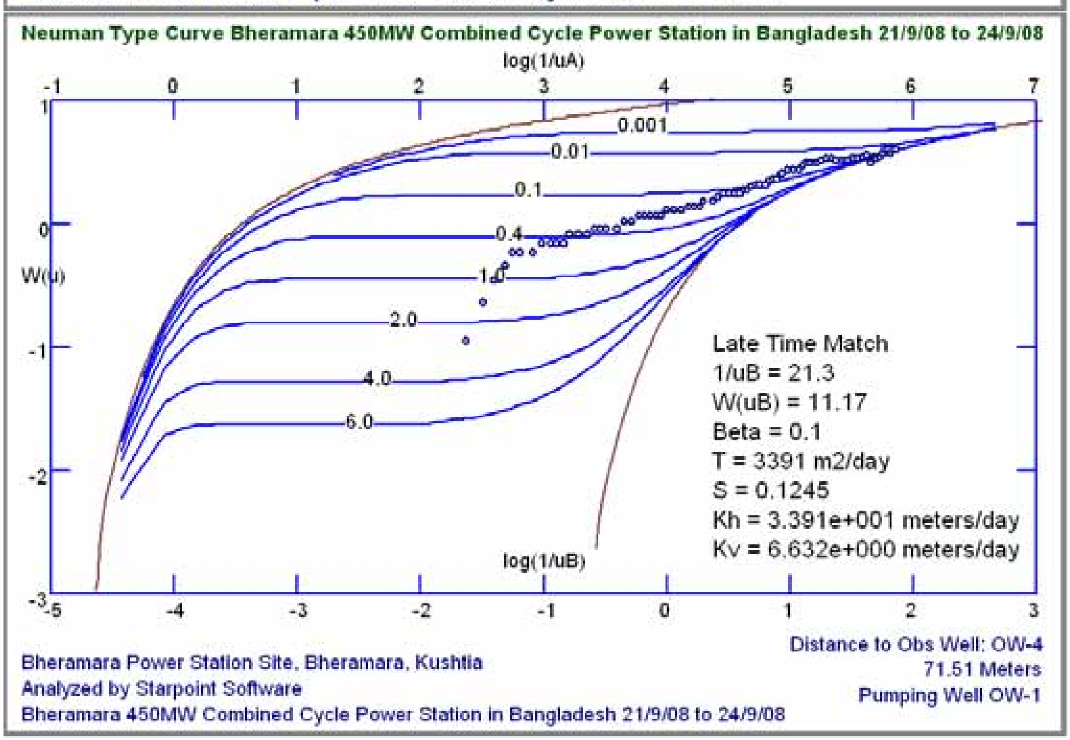

Neuman Type Curve Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
log(1/uA)
W(u)
log(1/uB)
0.001
0.01
0.1
0.4
1.0
2.0
4.0
6.0
Early Time match
1/uA = 682.2
W(uA) = 16.23
Beta = 0.1
T = 4929 m2/day
S = 5.228e-003
Kh = 4.929e+001 meters/day
Kv = 8.916e+000 meters/day
Distance to Obs Well: OW-2
74.35 Meters
Pumping Well OW-1
Bheramara Power Station Site, Bheramara, Kushtia
Analyzed by Starpoint Software
Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08

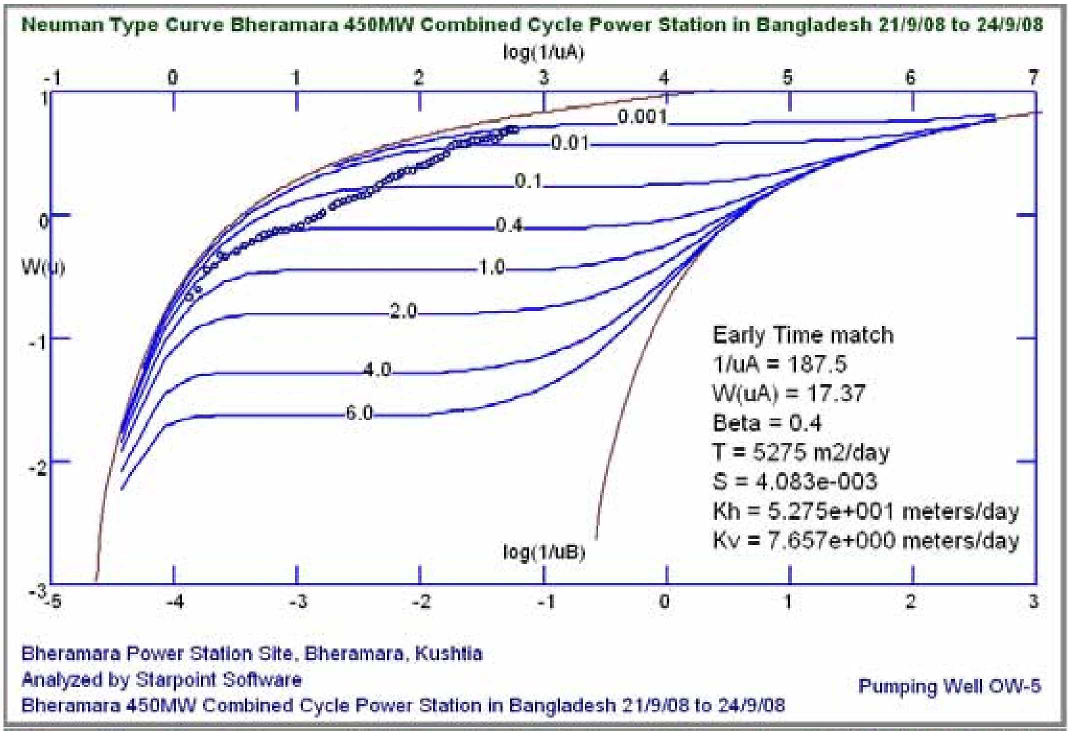

Neuman Type Curve Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
log(1/uA)
W(u)
log(1/uB)
0.001
0.01
0.1
0.4
1.0
2.0
4.0
6.0
Late Time Match
1/uB = 14.66
W(uB) = 10.43
Beta = 0.1
T = 3168 m2/day
S = 0.1564
Kh = 3.168e+001 meters/day
Kv = 5.732e+000 meters/day
Distance to Obs Well: OW-2
74.35 Meters
Pumping Well OW-1
Bheramara Power Station Site, Bheramara, Kushtia
Analyzed by Starpoint Software
Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08

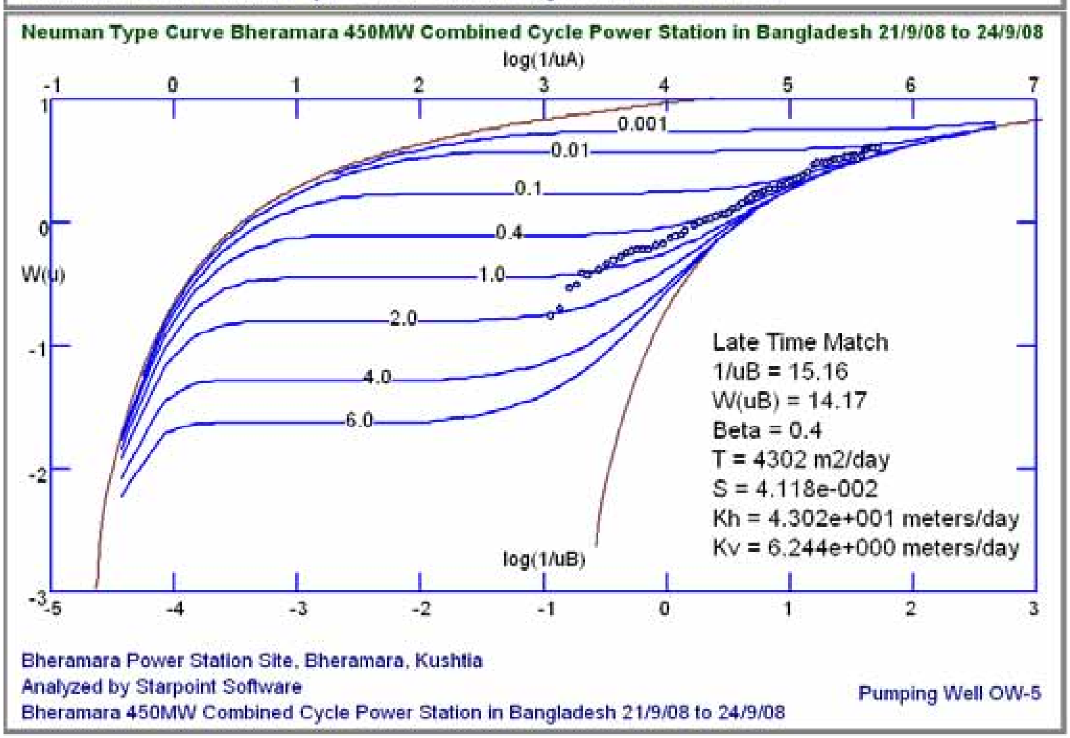

Neuman Type Curve Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
log(1/uA)
W(u)
0.001
0.01
0.1
0.4
1.0
2.0
4.0
6.0
Early Time match
1/uA = 836.5
W(uA) = 16.23
Beta = 0.1
T = 4929 m2/day
S = 3.438e-003
Kh = 4.929e+001 meters/day
Kv = 7.191e+000 meters/day
log(1/uB)
Distance to Obs Well: OW-3
82.79 Meters
Pumping Well OW-1
Bheramara Power Station Site, Bheramara, Kushtia
Analyzed by Starpoint Software
Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08

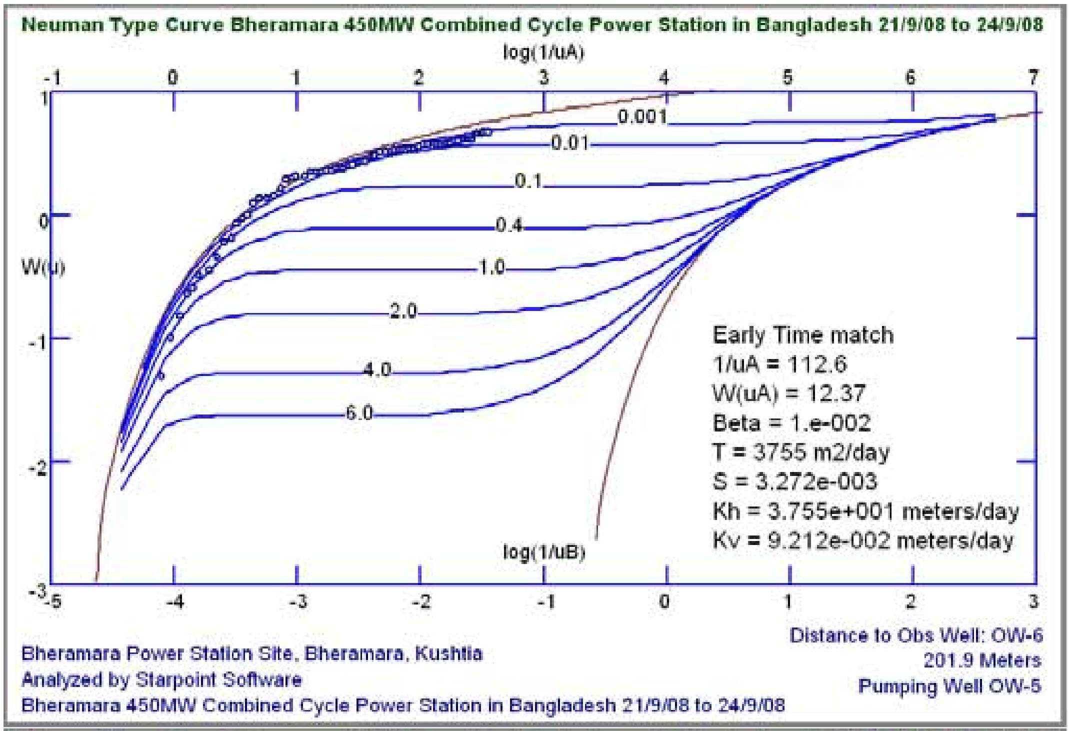

Neuman Type Curve Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
log(1/uA)
W(u)
0.001
0.01
0.1
0.4
1.0
2.0
4.0
6.0
Late Time Match
1/uB = 12.79
W(uB) = 10.43
Beta = 0.1
T = 3168 m2/day
S = 0.1445
Kh = 3.168e+001 meters/day
Kv = 4.623e+000 meters/day
log(1/uB)
Distance to Obs Well: OW-3
82.79 Meters
Pumping Well OW-1
Bheramara Power Station Site, Bheramara, Kushtia
Analyzed by Starpoint Software
Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08

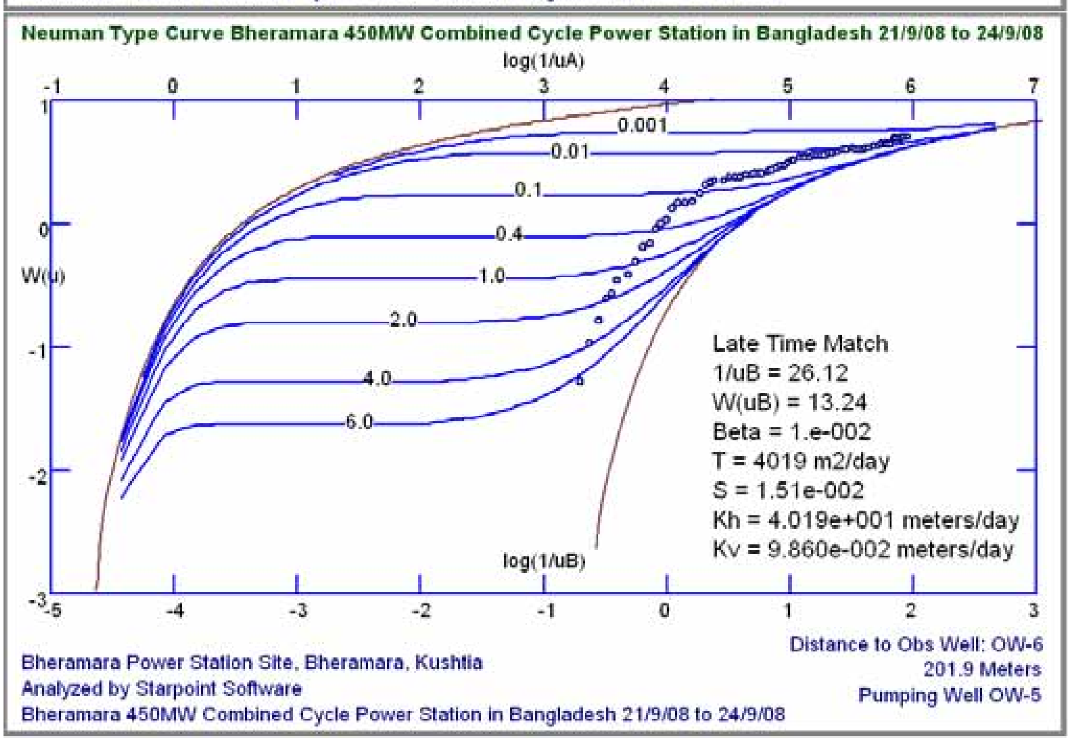

Neuman Type Curve Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
log(1/uA)
W(u)
0.001
0.01
0.1
0.4
1.0
2.0
4.0
6.0
Early Time match
1/uA = 1061
W(uA) = 15.16
Beta = 0.1
T = 4605 m2/day
S = 3.394e-003
Kh = 4.605e+001 meters/day
Kv = 9.005e+000 meters/day
log(1/uB)
Distance to Obs Well: OW-4
71.51 Meters
Pumping Well OW-1
Bheramara Power Station Site, Bheramara, Kushtia
Analyzed by Starpoint Software
Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08

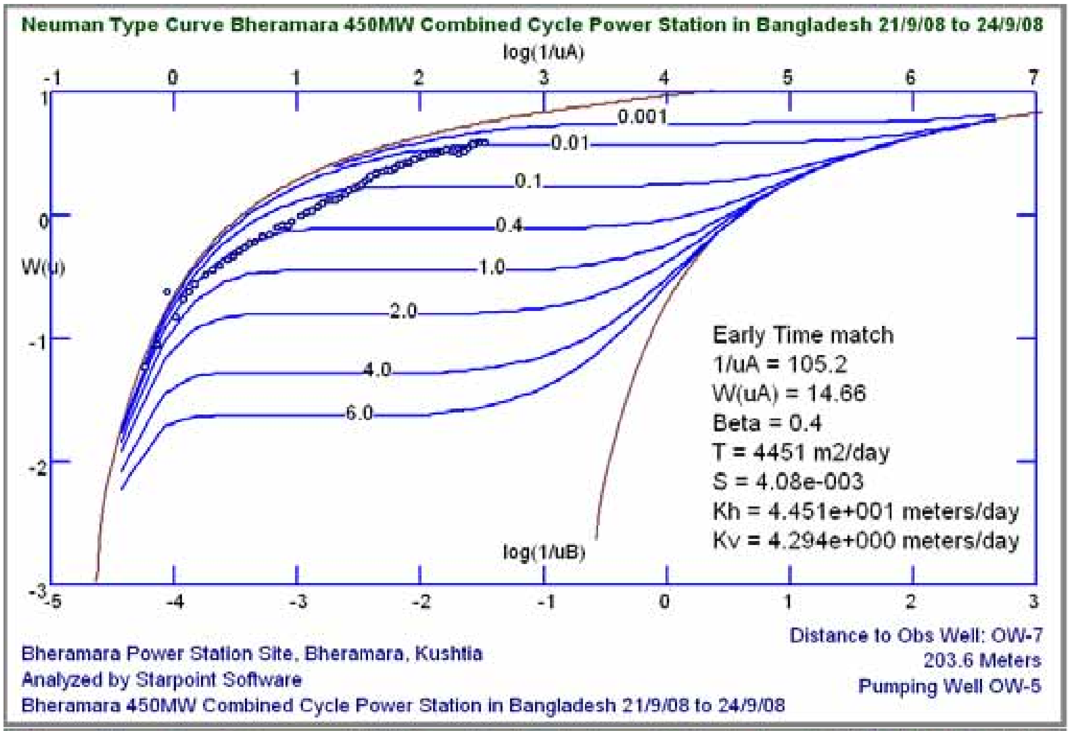

Neuman Type Curve Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
log(1/uA)
W(u)
0.001
0.01
0.1
0.4
1.0
2.0
4.0
6.0
Late Time Match
1/uB = 21.3
W(uB) = 11.17
Beta = 0.1
T = 3391 m2/day
S = 0.1245
Kh = 3.391e+001 meters/day
Kv = 6.632e+000 meters/day
log(1/uB)
Distance to Obs Well: OW-4
71.51 Meters
Pumping Well OW-1
Bheramara Power Station Site, Bheramara, Kushtia
Analyzed by Starpoint Software
Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08

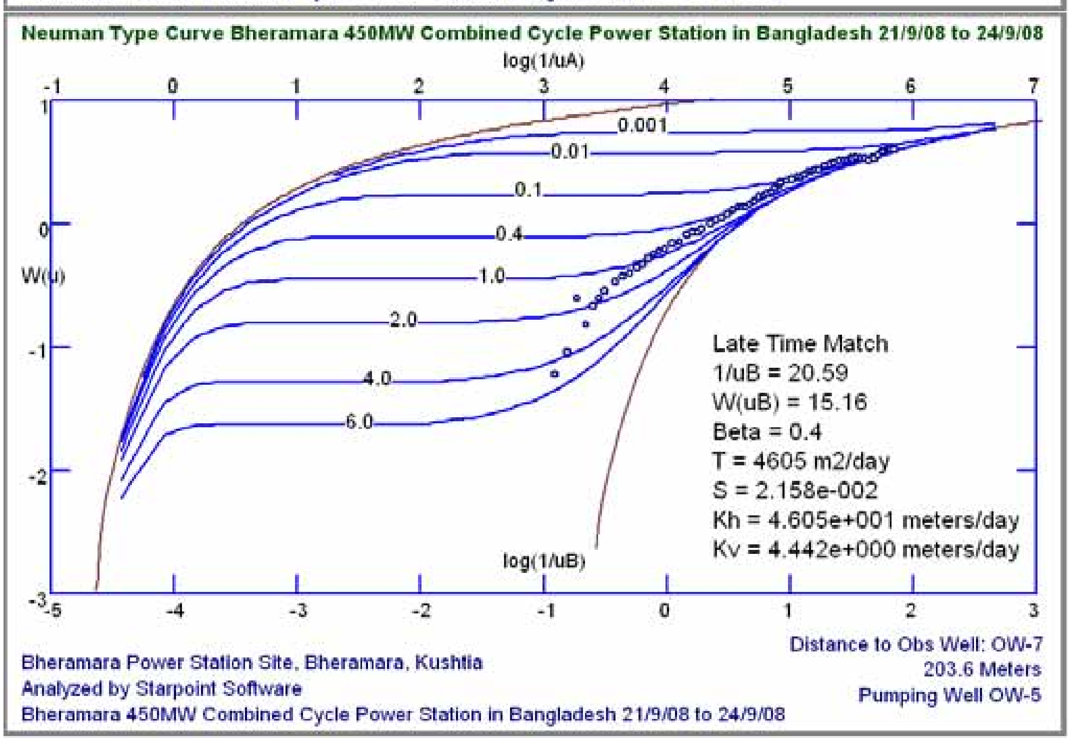

Neuman Type Curve Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
log(1/uA)
W(u)
log(1/uB)
0.001
0.01
0.1
0.4
1.0
2.0
4.0
6.0
Early Time match
1/uA = 187.5
W(uA) = 17.37
Beta = 0.4
T = 5275 m2/day
S = 4.083e-003
Kh = 5.275e+001 meters/day
Kv = 7.657e+000 meters/day
Bheramara Power Station Site, Bheramara, Kushtia
Analyzed by Starpoint Software
Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
Pumping Well OW-5

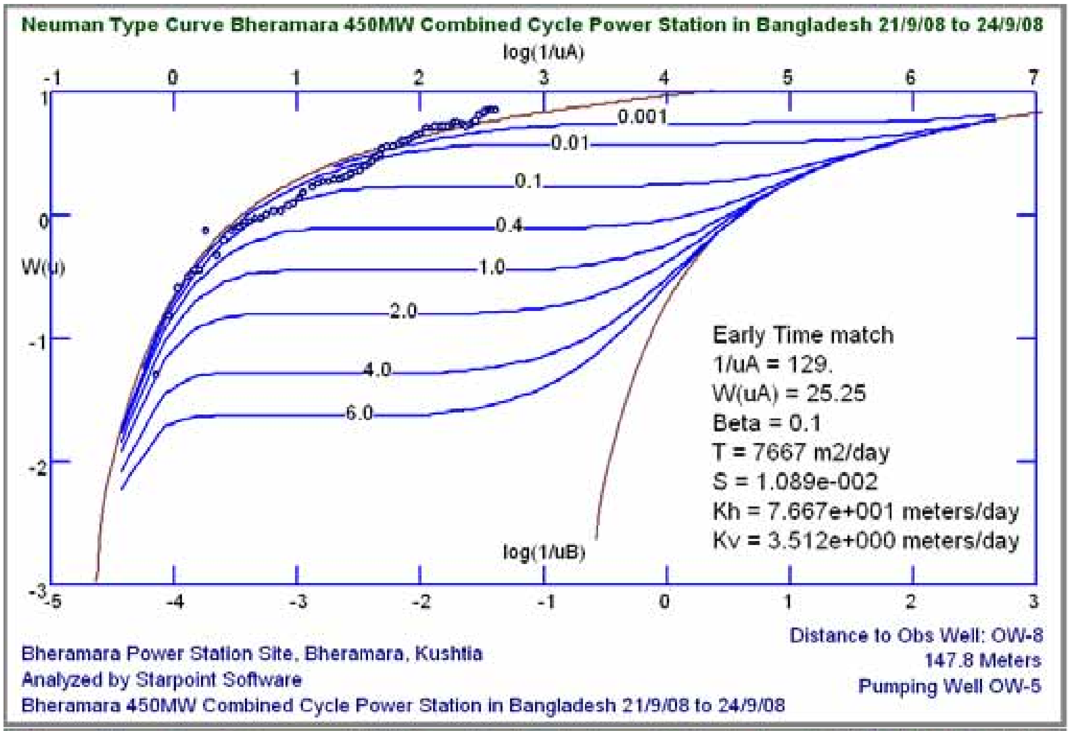

Neuman Type Curve Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
log(1/uA)
W(u)
log(1/uB)
0.001
0.01
0.1
0.4
1.0
2.0
4.0
6.0
Late Time Match
1/uB = 15.16
W(uB) = 14.17
Beta = 0.4
T = 4302 m2/day
S = 4.118e-002
Kh = 4.302e+001 meters/day
Kv = 6.244e+000 meters/day
Bheramara Power Station Site, Bheramara, Kushtia
Analyzed by Starpoint Software
Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
Pumping Well OW-5

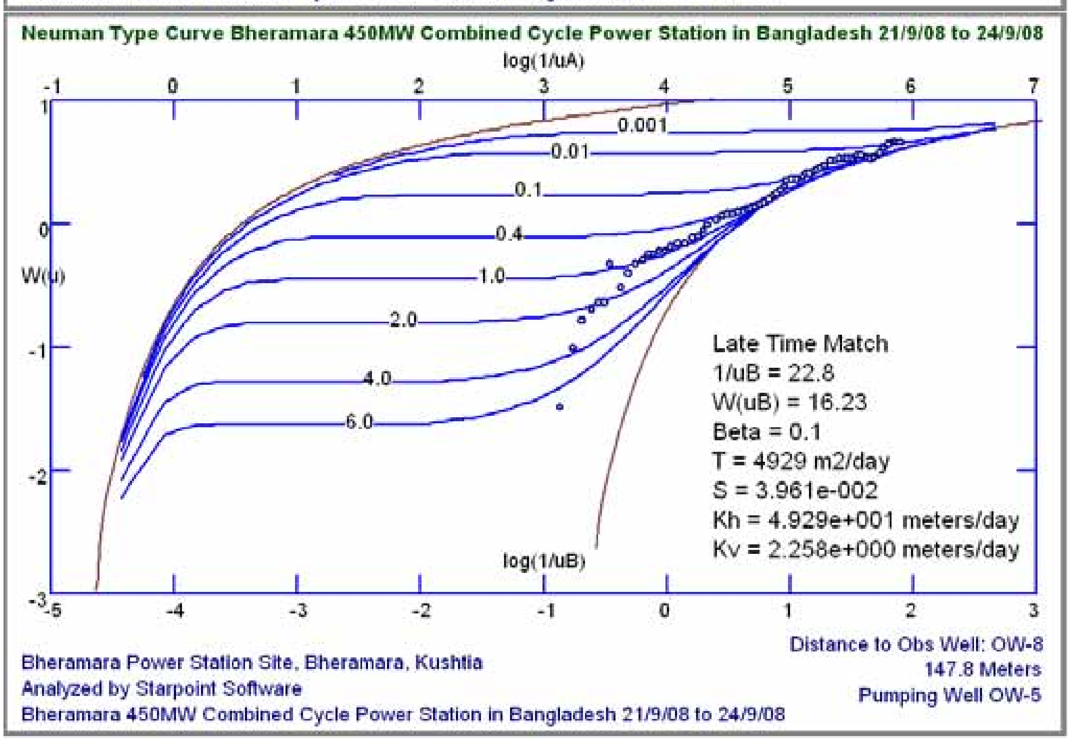

Neuman Type Curve Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
log(1/uA)
W(u)
log(1/uB)
0.001
0.01
0.1
0.4
1.0
2.0
4.0
6.0
Early Time match
1/uA = 112.6
W(uA) = 12.37
Beta = 1.e-002
T = 3755 m2/day
S = 3.272e-003
Kh = 3.755e+001 meters/day
Kv = 9.212e-002 meters/day
Bheramara Power Station Site, Bheramara, Kushtia
Analyzed by Starpoint Software
Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
Distance to Obs Well: OW-6
201.9 Meters
Pumping Well OW-5

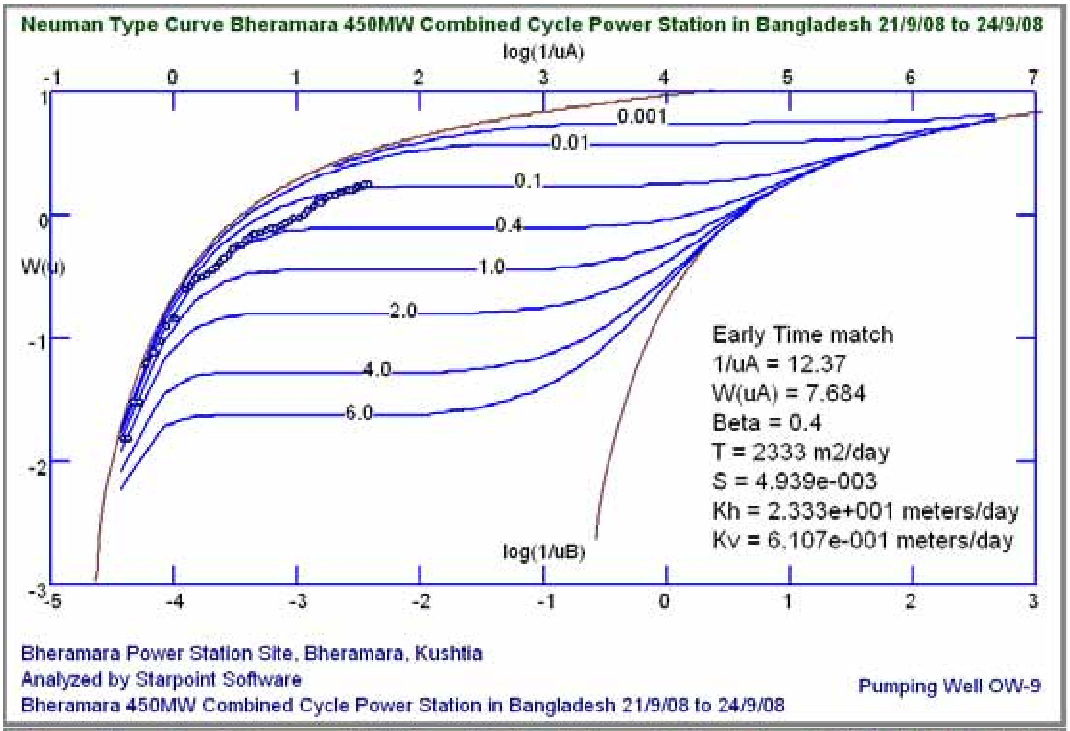

Neuman Type Curve Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
log(1/uA)
W(u)
log(1/uB)
0.001
0.01
0.1
0.4
1.0
2.0
4.0
6.0
Late Time Match
1/uB = 26.12
W(uB) = 13.24
Beta = 1.e-002
T = 4019 m2/day
S = 1.51e-002
Kh = 4.019e+001 meters/day
Kv = 9.860e-002 meters/day
Bheramara Power Station Site, Bheramara, Kushtia
Analyzed by Starpoint Software
Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
Distance to Obs Well: OW-6
201.9 Meters
Pumping Well OW-5

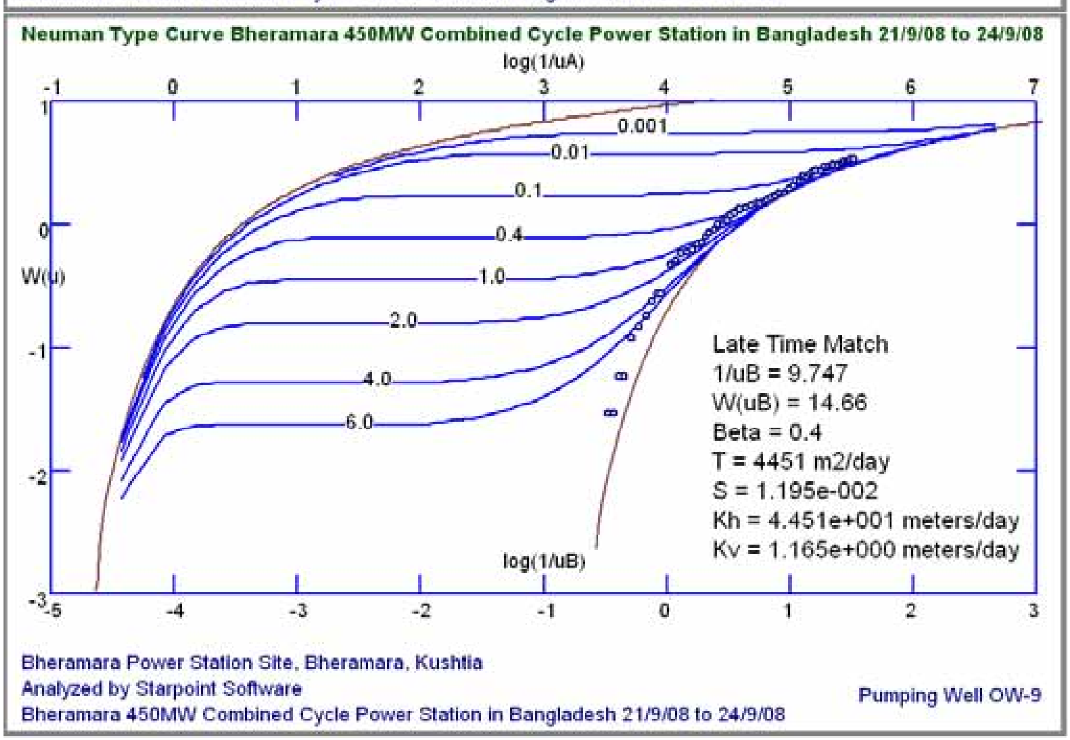

Neuman Type Curve Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
log(1/uA)
-1
0
1
2
3
4
5
6
7
1
0
-1
-2
-3
W(u)
0.001
0.01
0.1
0.4
1.0
2.0
4.0
6.0
Early Time match
1/uA = 105.2
W(uA) = 14.66
Beta = 0.4
T = 4451 m2/day
S = 4.08e-003
Kh = 4.451e+001 meters/day
Kv = 4.294e+000 meters/day
log(1/uB)
-5
-4
-3
-2
-1
0
1
2
3
Distance to Obs Well: OW-7
203.6 Meters
Pumping Well OW-5
Bheramara Power Station Site, Bheramara, Kushtia
Analyzed by Starpoint Software
Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08

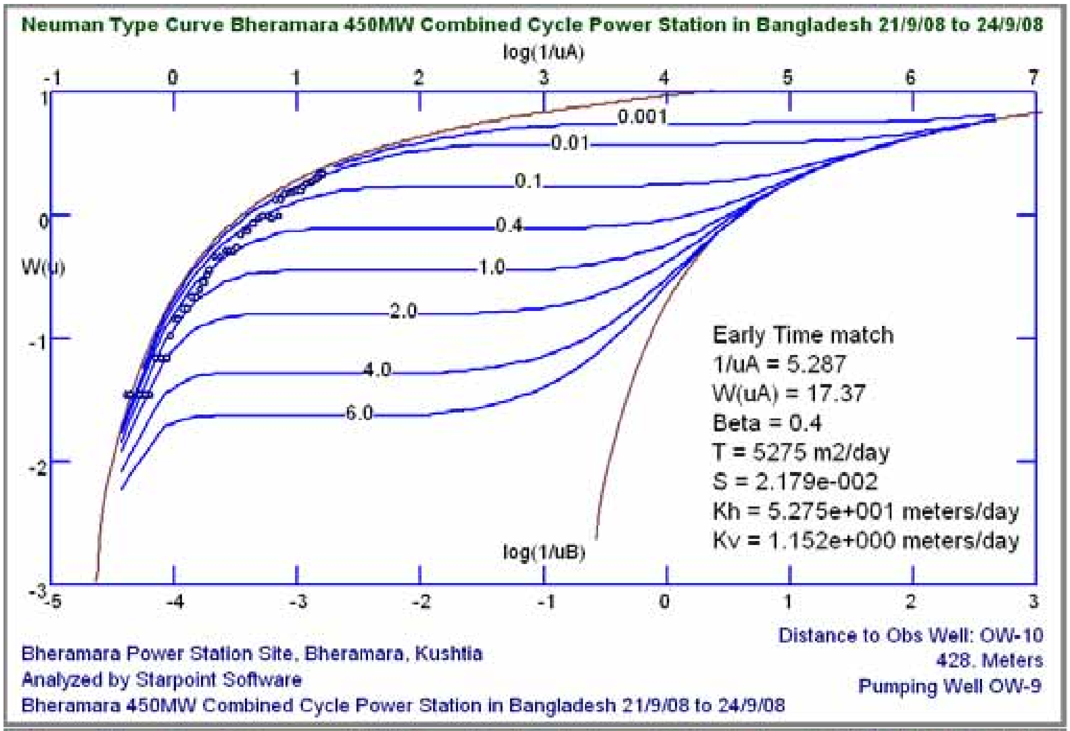

Neuman Type Curve Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
log(1/uA)
-1
0
1
2
3
4
5
6
7
1
0
-1
-2
-3
W(u)
0.001
0.01
0.1
0.4
1.0
2.0
4.0
6.0
Late Time Match
1/uB = 20.59
W(uB) = 15.16
Beta = 0.4
T = 4605 m2/day
S = 2.158e-002
Kh = 4.605e+001 meters/day
Kv = 4.442e+000 meters/day
log(1/uB)
-5
-4
-3
-2
-1
0
1
2
3
Distance to Obs Well: OW-7
203.6 Meters
Pumping Well OW-5
Bheramara Power Station Site, Bheramara, Kushtia
Analyzed by Starpoint Software
Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08

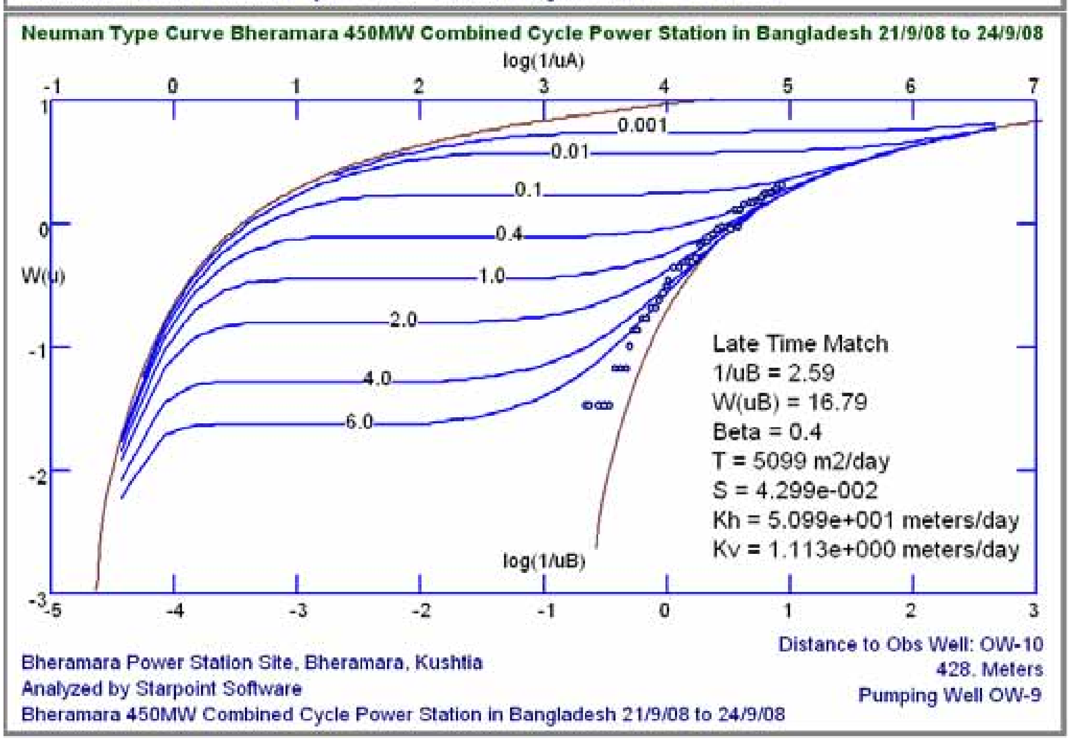

Neuman Type Curve Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
log(1/uA)
W(u)
0.001
0.01
0.1
0.4
1.0
2.0
4.0
6.0
Early Time match
1/uA = 129.
W(uA) = 25.25
Beta = 0.1
T = 7667 m2/day
S = 1.089e-002
Kh = 7.667e+001 meters/day
Kv = 3.512e+000 meters/day
log(1/uB)
Distance to Obs Well: OW-8
147.8 Meters
Pumping Well OW-5
Bheramara Power Station Site, Bheramara, Kushtia
Analyzed by Starpoint Software
Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08

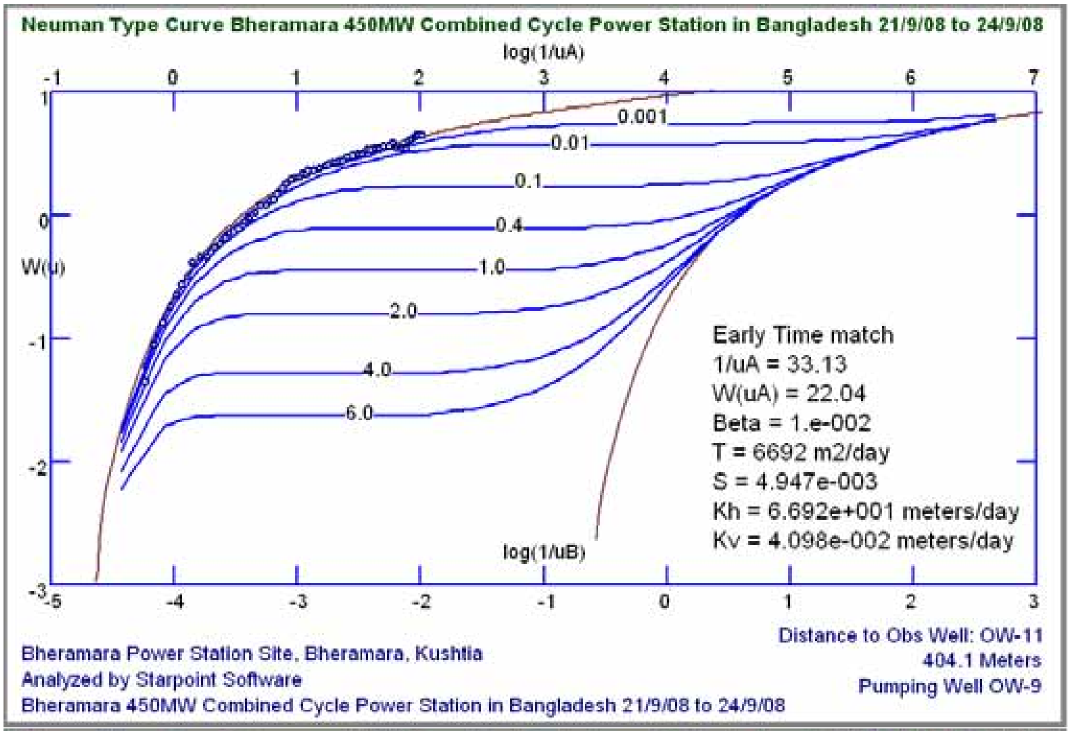

Neuman Type Curve Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
log(1/uA)
W(u)
0.001
0.01
0.1
0.4
1.0
2.0
4.0
6.0
Late Time Match
1/uB = 22.8
W(uB) = 16.23
Beta = 0.1
T = 4929 m2/day
S = 3.961e-002
Kh = 4.929e+001 meters/day
Kv = 2.258e+000 meters/day
log(1/uB)
Distance to Obs Well: OW-8
147.8 Meters
Pumping Well OW-5
Bheramara Power Station Site, Bheramara, Kushtia
Analyzed by Starpoint Software
Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08

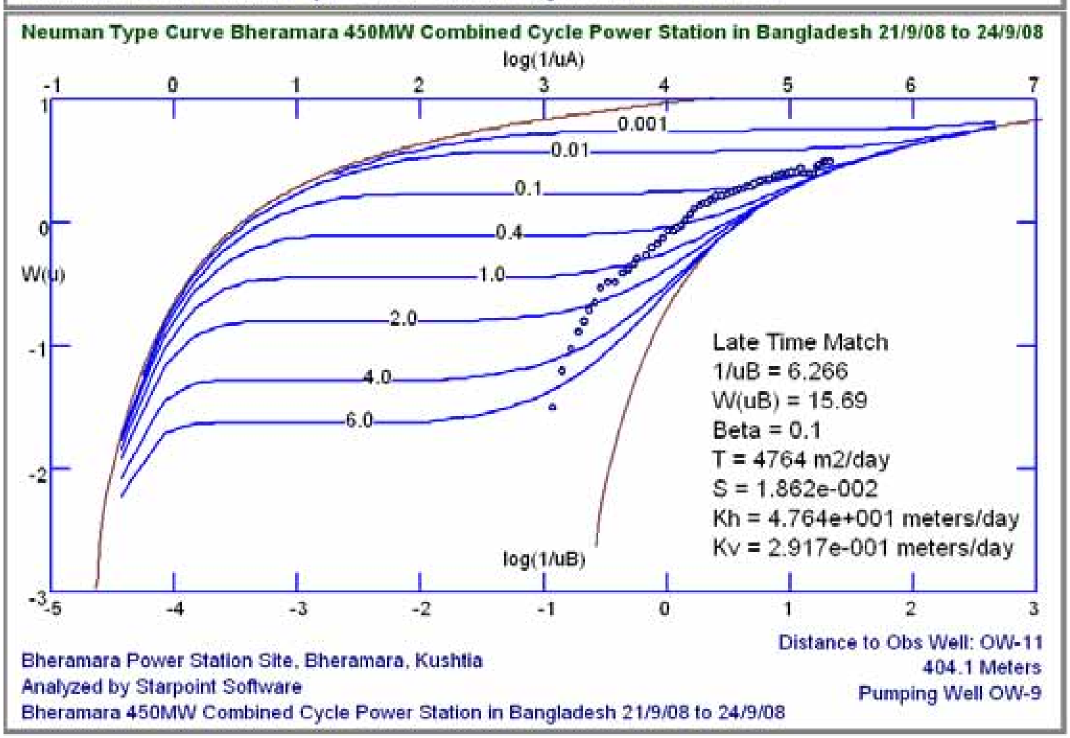

Neuman Type Curve Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
log(1/uA)
W(u)
log(1/uB)
0.001
0.01
0.1
0.4
1.0
2.0
4.0
6.0
Early Time match
1/uA = 12.37
W(uA) = 7.684
Beta = 0.4
T = 2333 m2/day
S = 4.939e-003
Kh = 2.333e+001 meters/day
Kv = 6.107e-001 meters/day
Bheramara Power Station Site, Bheramara, Kushtia
Analyzed by Starpoint Software
Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
Pumping Well OW-9

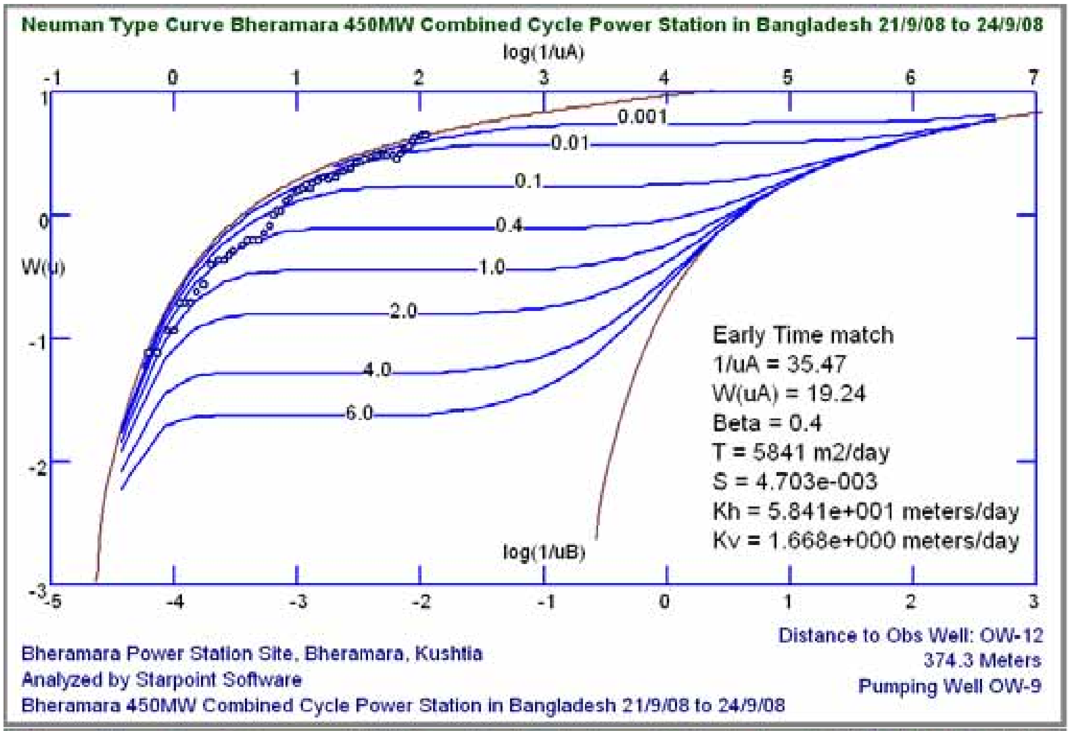

Neuman Type Curve Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
log(1/uA)
W(u)
log(1/uB)
0.001
0.01
0.1
0.4
1.0
2.0
4.0
6.0
Late Time Match
1/uB = 9.747
W(uB) = 14.66
Beta = 0.4
T = 4451 m2/day
S = 1.195e-002
Kh = 4.451e+001 meters/day
Kv = 1.165e+000 meters/day
Bheramara Power Station Site, Bheramara, Kushtia
Analyzed by Starpoint Software
Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
Pumping Well OW-9

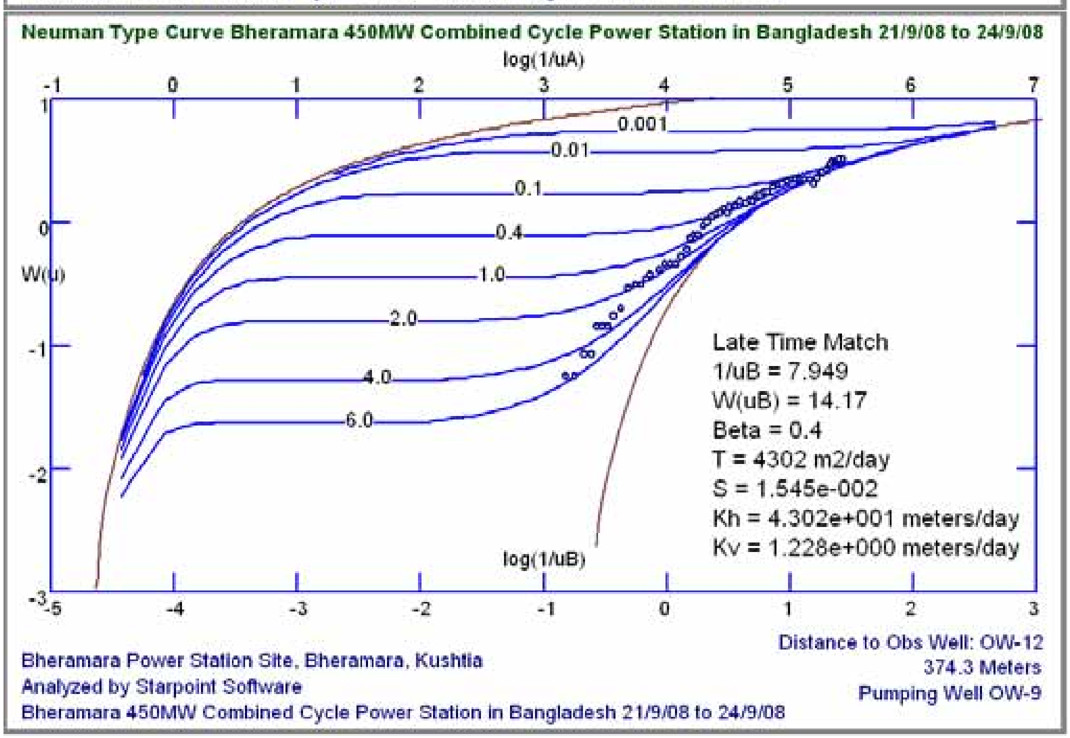

Neuman Type Curve Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
log(1/uA)
W(u)
0.001
0.01
0.1
0.4
1.0
2.0
4.0
6.0
Early Time match
1/uA = 5.287
W(uA) = 17.37
Beta = 0.4
T = 5275 m2/day
S = 2.179e-002
Kh = 5.275e+001 meters/day
Kv = 1.152e+000 meters/day
log(1/uB)
Distance to Obs Well: OW-10
428. Meters
Pumping Well OW-9
Bheramara Power Station Site, Bheramara, Kushtia
Analyzed by Starpoint Software
Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08


Neuman Type Curve Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
log(1/uA)
W(u)
0.001
0.01
0.1
0.4
1.0
2.0
4.0
6.0
Late Time Match
1/uB = 2.59
W(uB) = 16.79
Beta = 0.4
T = 5099 m2/day
S = 4.299e-002
Kh = 5.099e+001 meters/day
Kv = 1.113e+000 meters/day
log(1/uB)
Distance to Obs Well: OW-10
428. Meters
Pumping Well OW-9
Bheramara Power Station Site, Bheramara, Kushtia
Analyzed by Starpoint Software
Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08


Neuman Type Curve Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
log(1/uA)
W(u)
log(1/uB)
0.001
0.01
0.1
0.4
1.0
2.0
4.0
6.0
Early Time match
1/uA = 33.13
W(uA) = 22.04
Beta = 1.e-002
T = 6692 m2/day
S = 4.947e-003
Kh = 6.692e+001 meters/day
Kv = 4.098e-002 meters/day
Distance to Obs Well: OW-11
404.1 Meters
Pumping Well OW-9
Bheramara Power Station Site, Bheramara, Kushtia
Analyzed by Starpoint Software
Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08


Neuman Type Curve Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
log(1/uA)
W(u)
log(1/uB)
0.001
0.01
0.1
0.4
1.0
2.0
4.0
6.0
Late Time Match
1/uB = 6.266
W(uB) = 15.69
Beta = 0.1
T = 4764 m2/day
S = 1.862e-002
Kh = 4.764e+001 meters/day
Kv = 2.917e-001 meters/day
Distance to Obs Well: OW-11
404.1 Meters
Pumping Well OW-9
Bheramara Power Station Site, Bheramara, Kushtia
Analyzed by Starpoint Software
Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08


Neuman Type Curve Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
log(1/uA)
W(u)
log(1/uB)
0.001
0.01
0.1
0.4
1.0
2.0
4.0
6.0
Early Time match
1/uA = 35.47
W(uA) = 19.24
Beta = 0.4
T = 5841 m2/day
S = 4.703e-003
Kh = 5.841e+001 meters/day
Kv = 1.668e+000 meters/day
Bheramara Power Station Site, Bheramara, Kushtia
Analyzed by Starpoint Software
Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
Distance to Obs Well: OW-12
374.3 Meters
Pumping Well OW-9


Neuman Type Curve Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
log(1/uA)
W(u)
log(1/uB)
0.001
0.01
0.1
0.4
1.0
2.0
4.0
6.0
Late Time Match
1/uB = 7.949
W(uB) = 14.17
Beta = 0.4
T = 4302 m2/day
S = 1.545e-002
Kh = 4.302e+001 meters/day
Kv = 1.228e+000 meters/day
Bheramara Power Station Site, Bheramara, Kushtia
Analyzed by Starpoint Software
Bheramara 450MW Combined Cycle Power Station in Bangladesh 21/9/08 to 24/9/08
Distance to Obs Well: OW-12
374.3 Meters
Pumping Well OW-9

APPENDIX II Model Input Files

1. Pumping Wells at the Project Site

Stop Time (Day)	Start Time (Day)	Well Discharge (m^3/d)
0	31	-3120
31	59	-3120
59	90	-3120
90	120	-3120
120	151	-3120
151	181	-3120
181	212	-3120
212	243	-3120
243	274	-3120
274	304	-3120
304	335	-3120
335	365	-3120

2. Irrigation DTWs

Stop Time (Day)	Start Time (Day)	Well Discharge (m^3/d)
0	31	-1386
31	59	-1386
59	90	-1386
90	120	-1386
120	151	0
151	181	0
181	212	0
212	243	0
243	274	0
274	304	0
304	335	0
335	365	-1386

3. Municipal Wells

Stop Time (Day)	Start Time (Day)	Well Discharge (m^3/d)
0	31	-1500
31	59	-1500
59	90	-1500
90	120	-1500
120	151	-1500
151	181	-1500
181	212	-1500
212	243	-1500
243	274	-1500
274	304	-1500
304	335	-1500
335	365	-1500

3. Recharge Boundary

Stop Time (Day)	Start Time (Day)	Recharge Rate (mm/yr)
0	31	122
31	59	146
59	90	280
90	120	718
120	151	1119
151	181	1241
181	212	1241
212	243	998
243	274	596
274	304	377
304	335	146
335	365	122

4. EVT Boundary

Stop Time (Day)	Start Time (Day)	EVT (mm/yr)	Extinction Depth (m)
0	31	1119.6	3
31	59	1393.2	3
59	90	2089.2	3
90	120	2538	3
120	151	2788.8	3
151	181	2156.4	3
181	212	2047.2	3
212	243	2065.2	3
243	274	1825.2	3
274	304	1725.6	3
304	335	1316.4	3
335	365	1117.2	3

5. River Boundary

Stop Time (Day)	Start Time (Day)	River Stage (m)
0	31	6.47
31	59	5.98
59	90	5.23
90	120	5.48
120	151	5.98
151	181	6.97
181	212	10.46
212	243	13.47
243	274	12.95
274	304	11.46
304	335	8.97
335	365	7.47

APPENDIX III Model Sensitivity Analysis

Model sensitivity analysis has been conducted for calibrated values of hydraulic conductivity and storage parameters. Table A gives the results of model sensitivity analysis.

Table A. Results of model sensitivity analysis.

Hydrologic Characteristics	Composite Aquifer	Main Aquifer	% Change	Resulting Change Correlation coefficient
Horizontal hydraulic conductivity Kx & Ky (m/d)	15	67.5	50	95%
	10	45	0	96%
	5	22.5	-50	93%
Vertical hydraulic conductivity Kz (m/d)	1.5	6.75	50	95%
	1	4.5	0	96%
	0.5	2.25	-50	93%
Ss (1/m)	0.00015	0.0105	50	29%
	0.0001	0.007	0	96%
	0.00005	0.0035	-50	66%
Sy (%)	0.27	0.375	50	94%
	0.18	0.25	0	96%
	0.09	0.125	-50	95%
Effective porosity (%)	0.27	0.405	50	96%
	0.18	0.27	0	96%
	0.09	0.135	-50	96%
Total porosity (%)	0.3	0.45	50	96%
	0.2	0.3	0	96%
	0.1	0.15	-50	96%

Observed head data of KTA-7, KT-39, KT-40 and PA-7 have been used for model calibration. Figure A gives the matching of observed head data and model calculated data for calibrated model. The model calculates the correlation co-efficient of matching of observed and calculated data.

Figure B to Figure M give the correlation co-efficient of matching of observed and calculated data for different hydraulic characteristics of the aquifer.

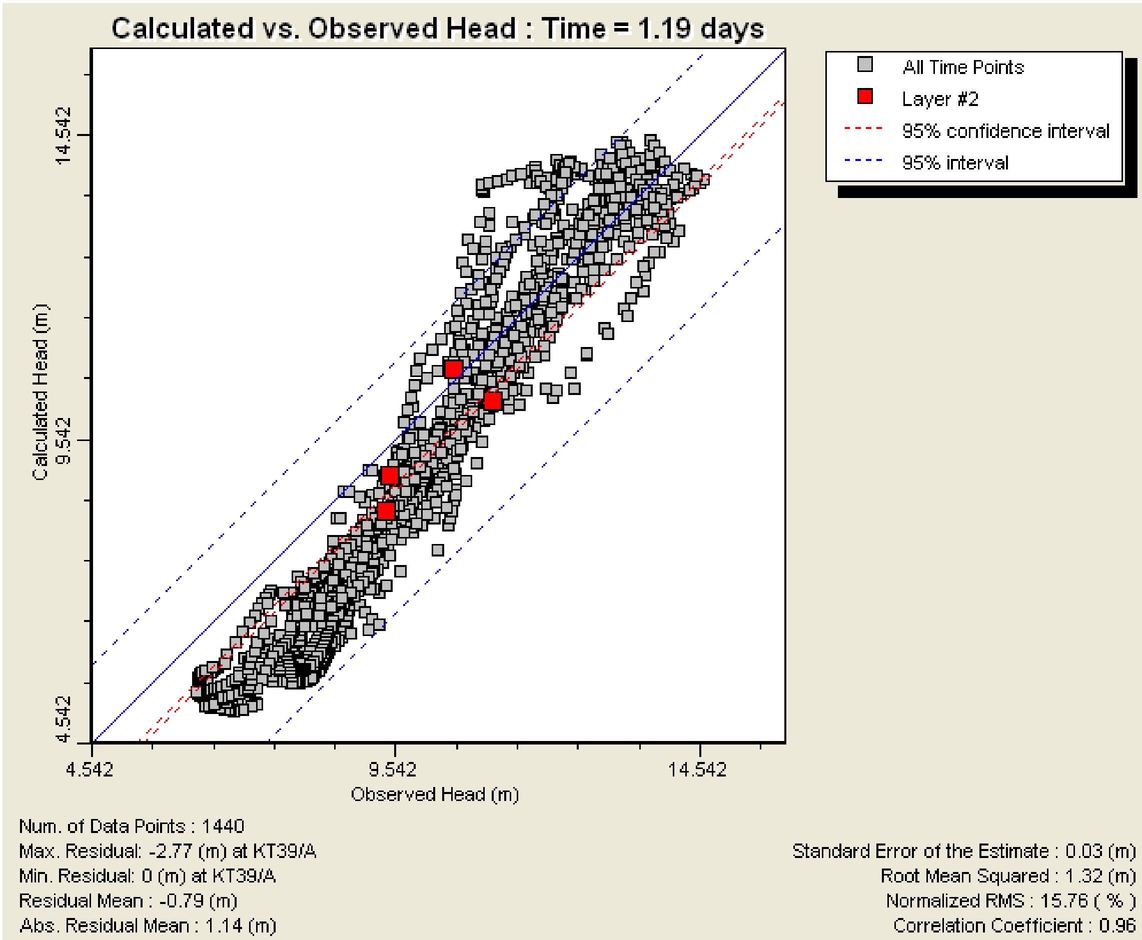


Figure A. Matching head data of observation wells KTA-7, KT-39, KT-40 and PA-7 with model calculated head data for calibrated model.

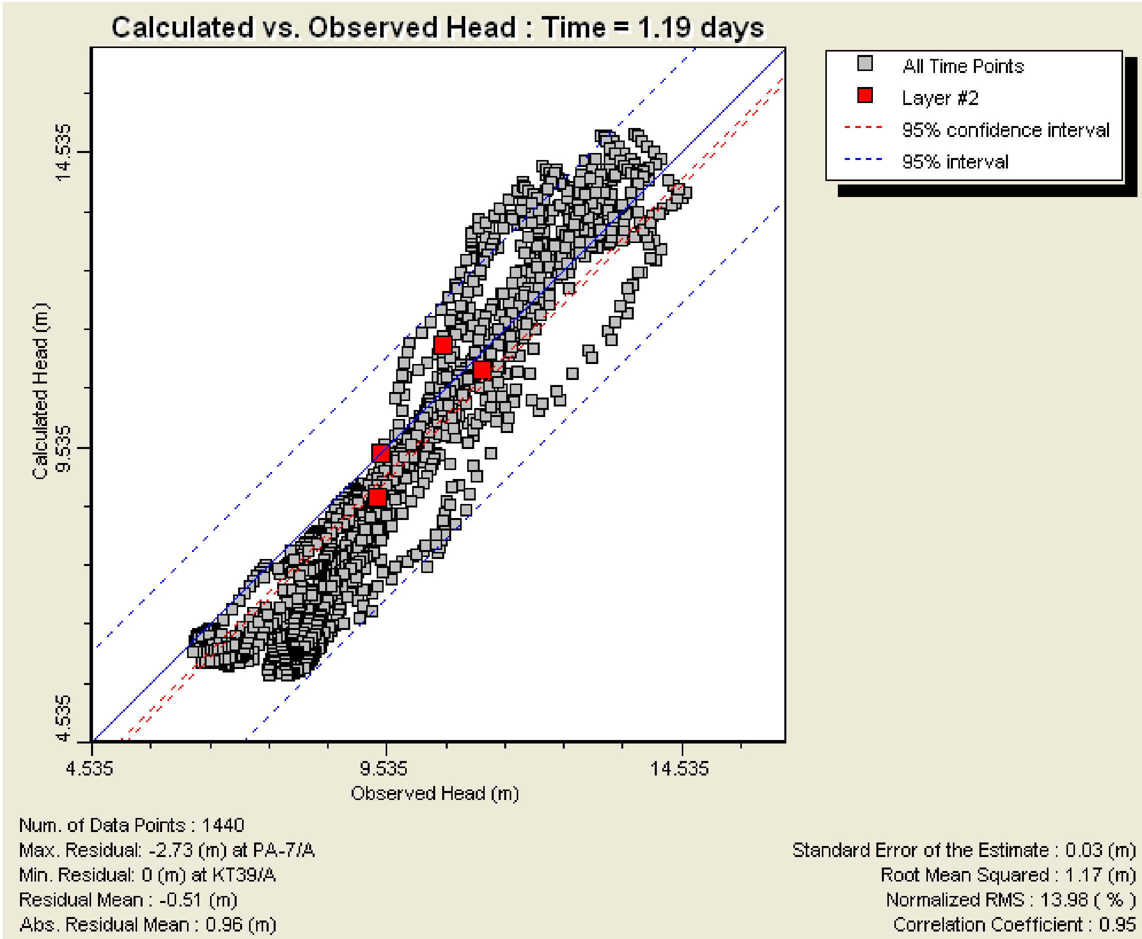


Figure B. Matching head data of observation wells KTA-7, KT-39, KT-40 and PA-7 with model calculated head data. Horizontal hydraulic conductivity Kx (m/d) and Ky (m/d) 50% increased.

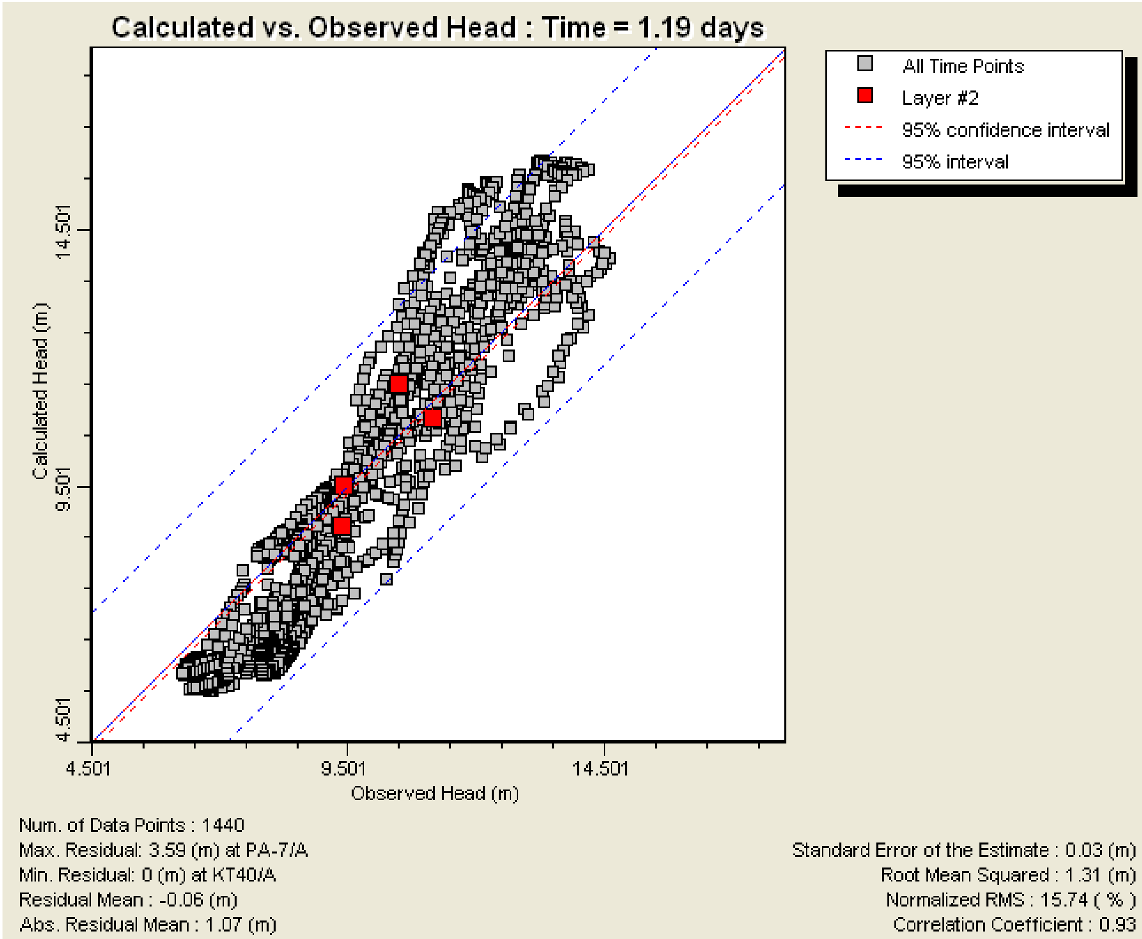


Figure C. Matching head data of observation wells KTA-7, KT-39, KT-40 and PA-7 with model calculated head data. Horizontal hydraulic conductivity Kx (m/d) and Ky (m/d) 50% decreased.

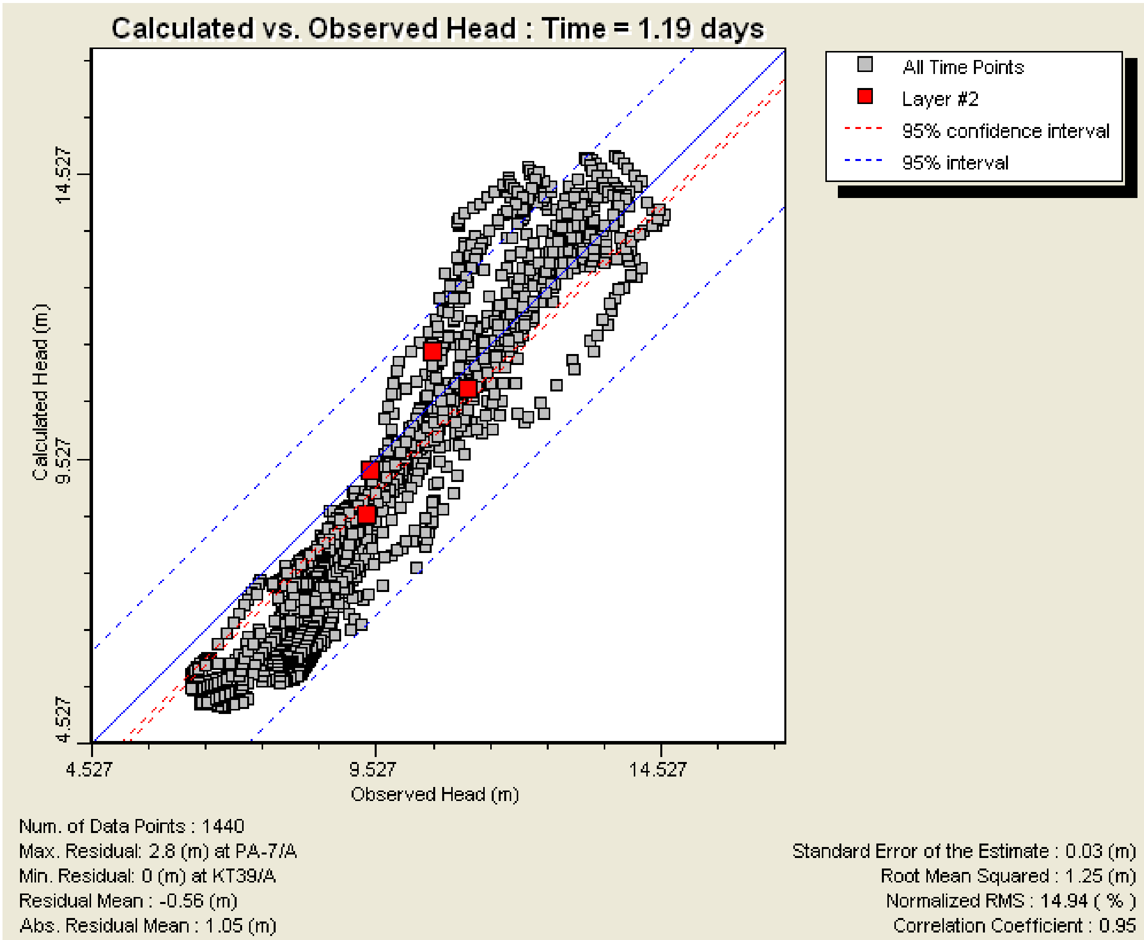


Figure D. Matching head data of observation wells KTA-7, KT-39, KT-40 and PA-7 with model calculated head data. Vertical hydraulic conductivity Kz (m/d) 50% increased.

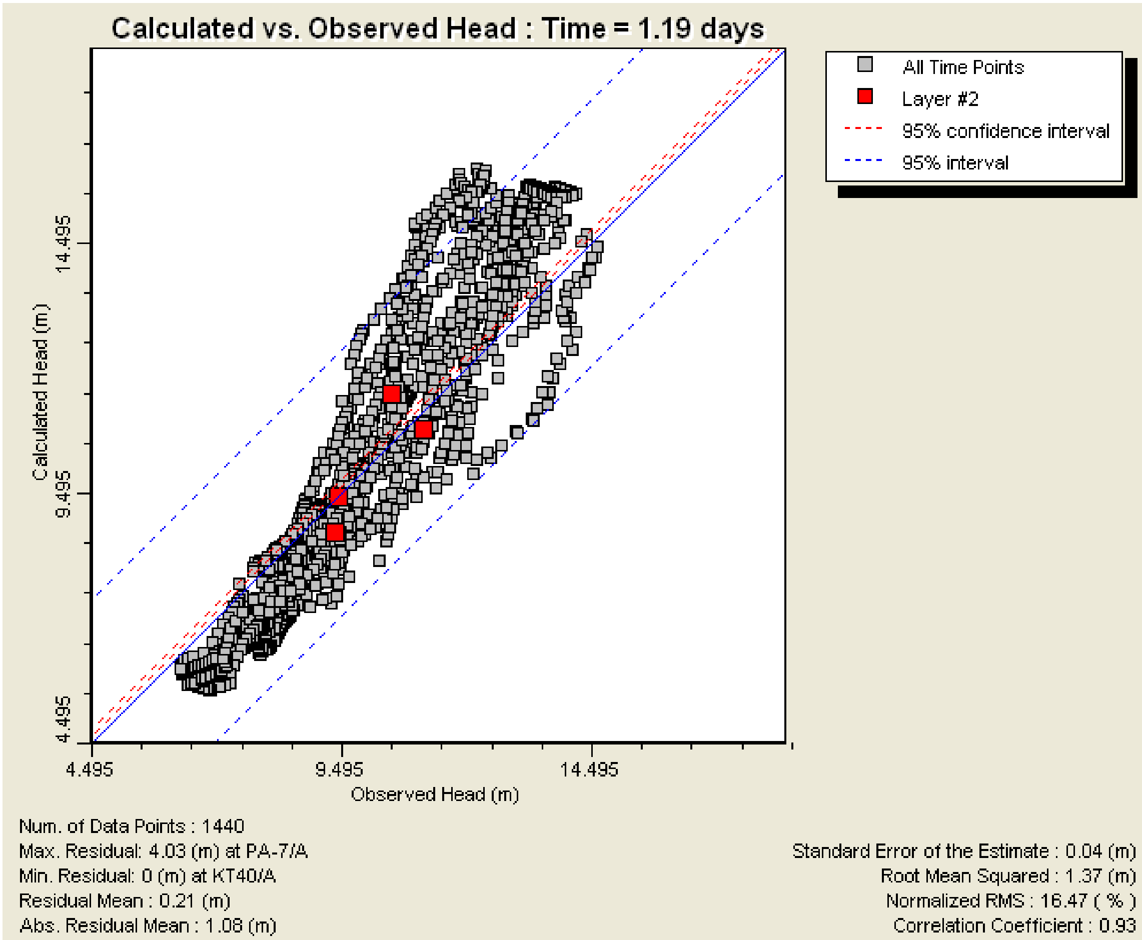


Figure E. Matching head data of observation wells KTA-7, KT-39, KT-40 and PA-7 with model calculated head data. Vertical hydraulic conductivity Kz (m/d) 50% decreased.

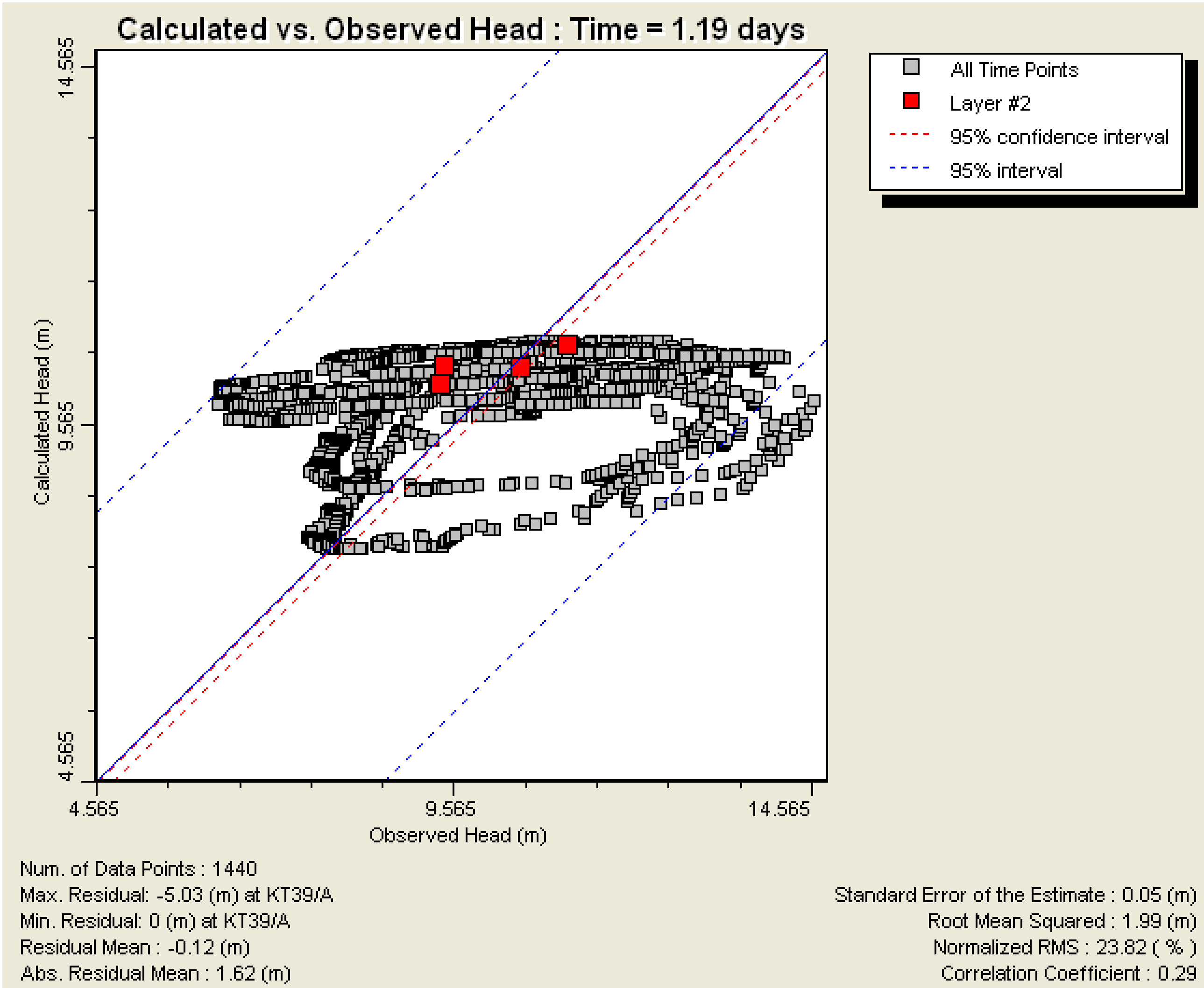


Figure F. Matching head data of observation wells KTA-7, KT-39, KT-40 and PA-7 with model calculated head data. Specific storage Ss (1/m) 50% increased.

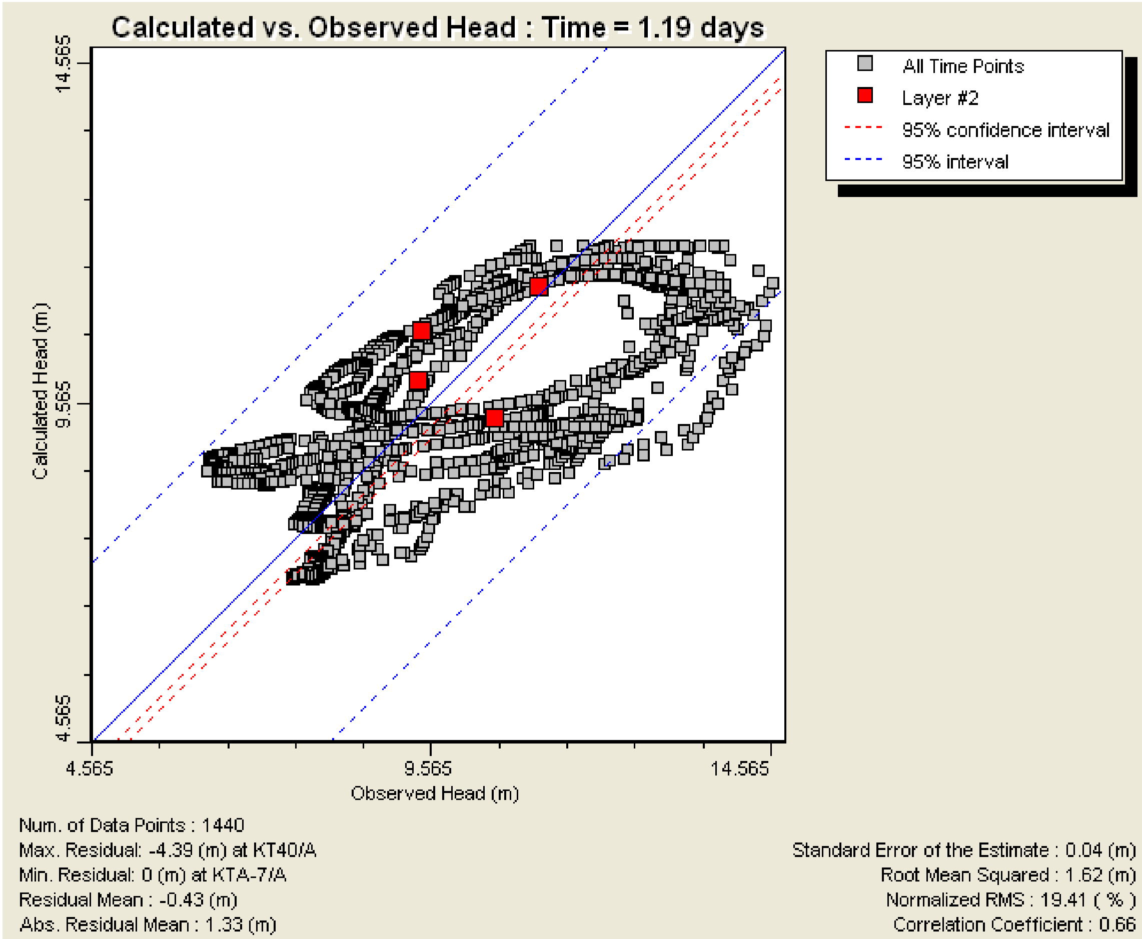


Figure G. Matching head data of observation wells KTA-7, KT-39, KT-40 and PA-7 with model calculated head data. Specific storage Ss (1/m) 50% decreased.

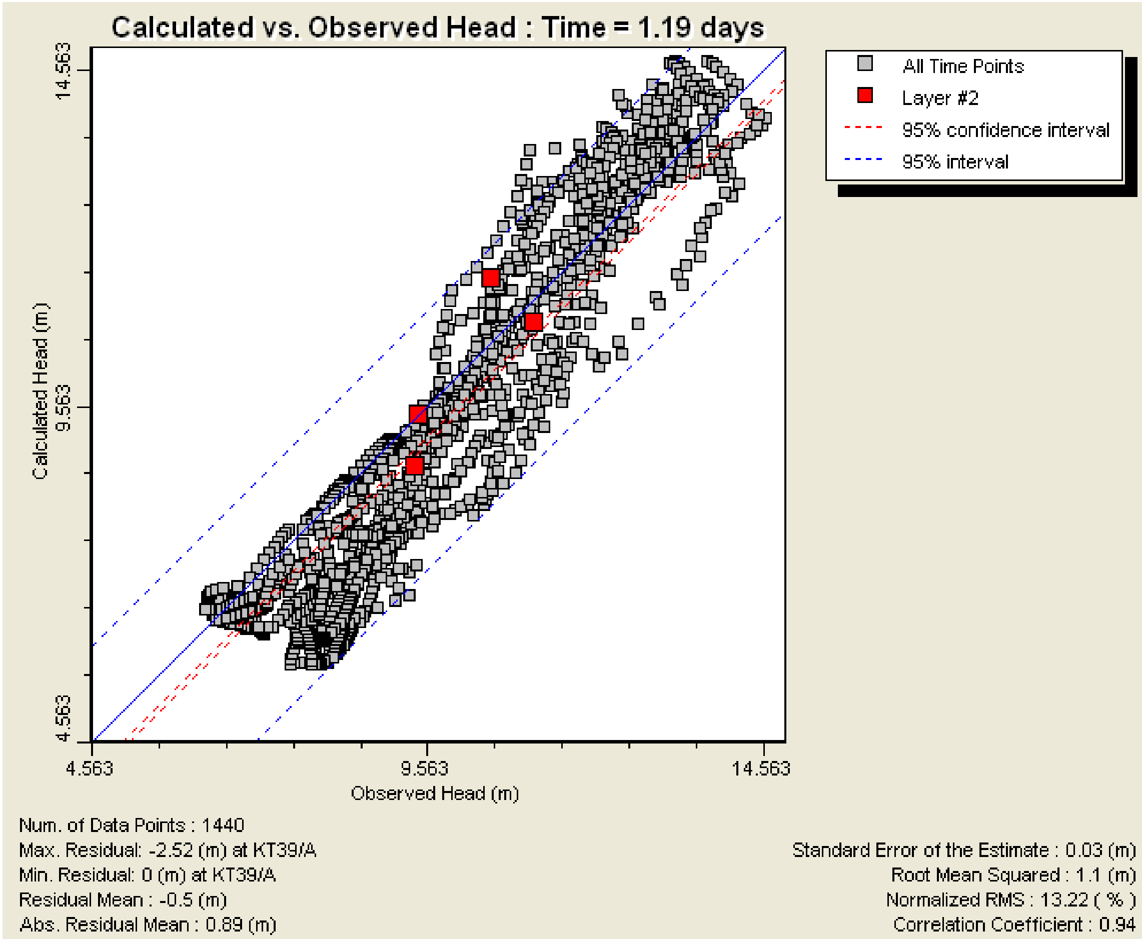


Figure H. Matching head data of observation wells KTA-7, KT-39, KT-40 and PA-7 with model calculated head data. Specific yield Sy 50% increased.

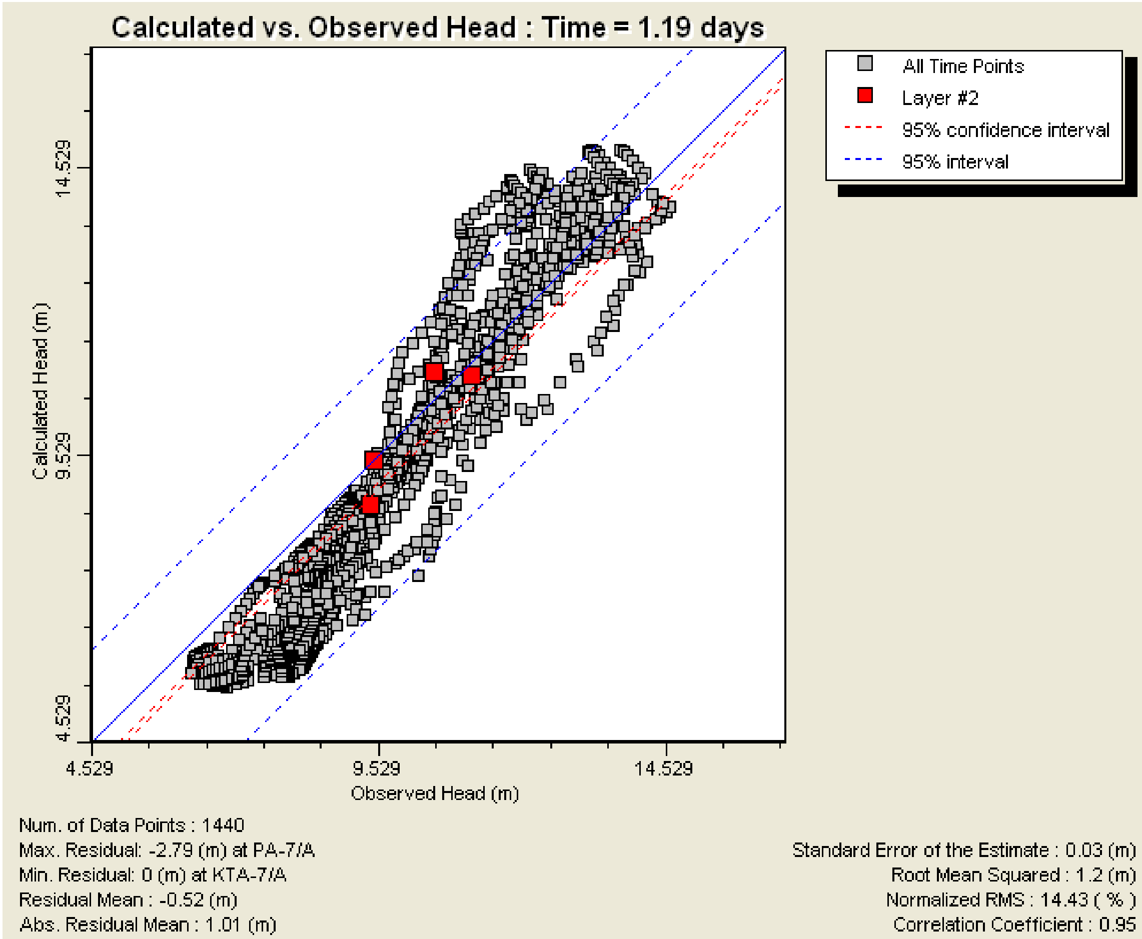


Figure I. Matching head data of observation wells KTA-7, KT-39, KT-40 and PA-7 with model calculated head data. Specific yield Sy 50% decreased.

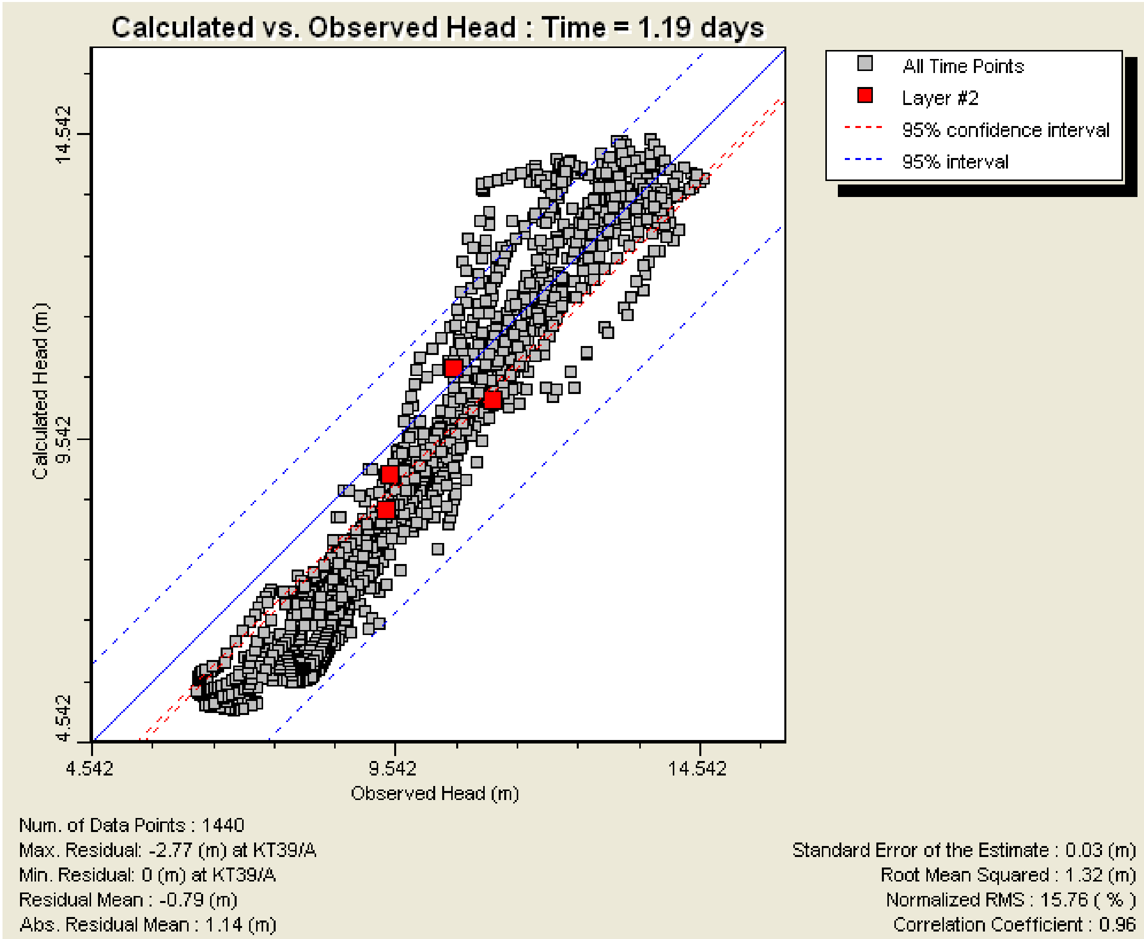


Figure J. Matching head data of observation wells KTA-7, KT-39, KT-40 and PA-7 with model calculated head data. Effective porosity 50% increased.

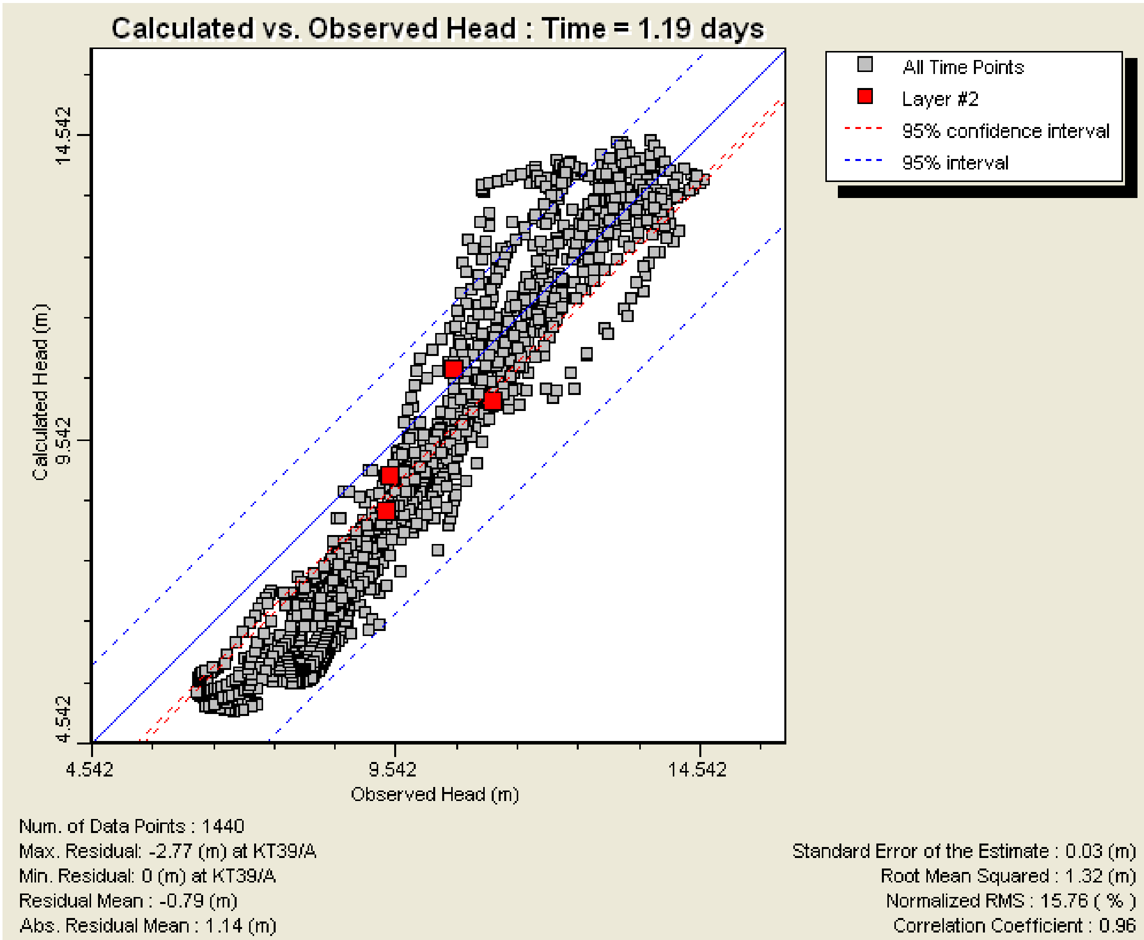


Figure K. Matching head data of observation wells KTA-7, KT-39, KT-40 and PA-7 with model calculated head data. Effective porosity 50% decreased.

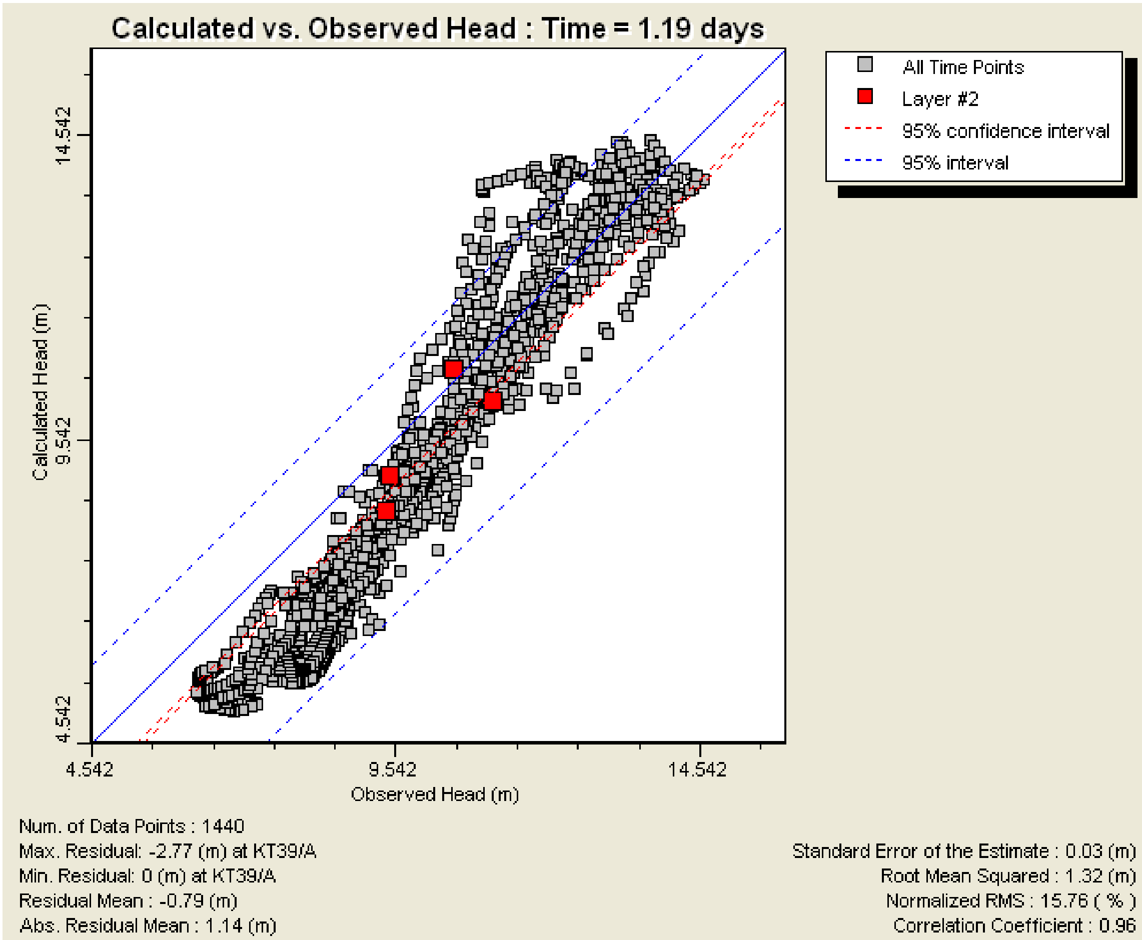


Figure L. Matching head data of observation wells KTA-7, KT-39, KT-40 and PA-7 with model calculated head data. Total porosity 50% increased.

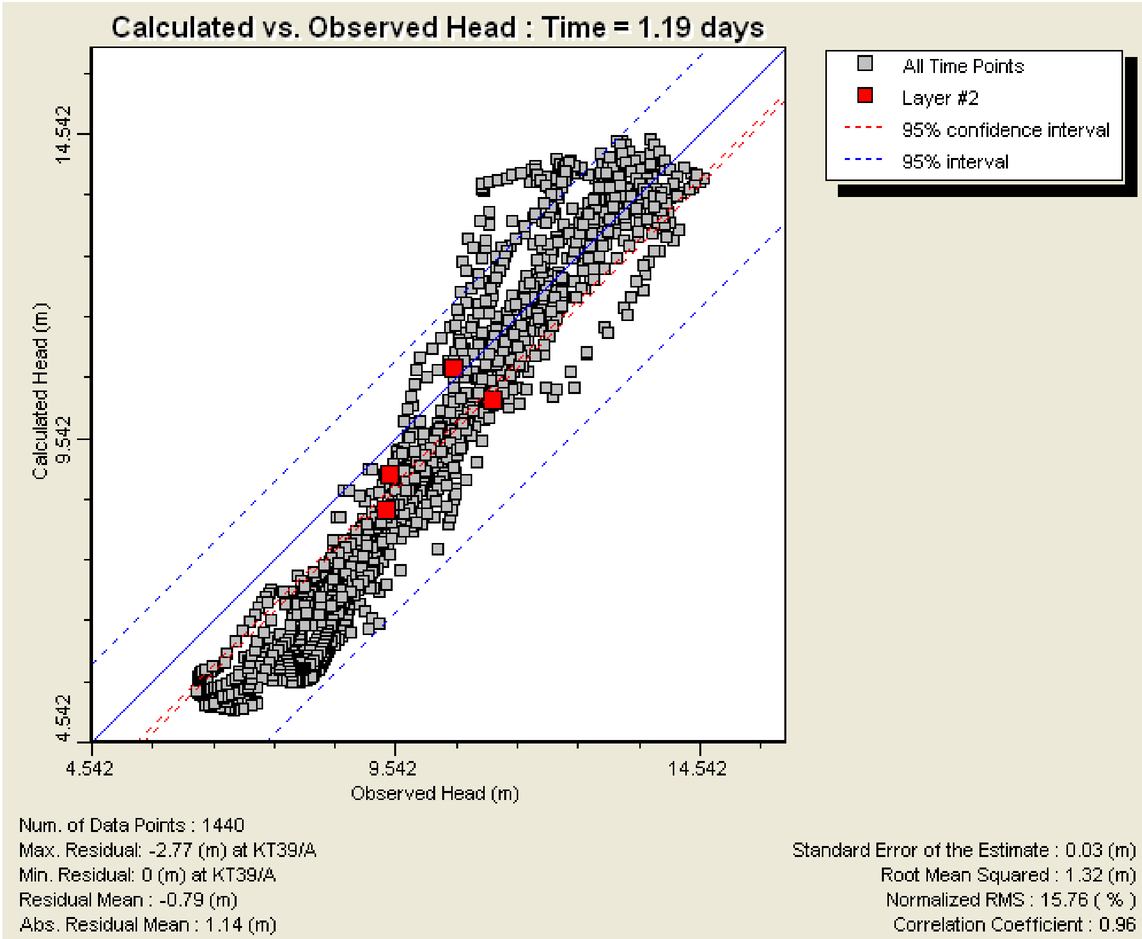


Figure M. Matching head data of observation wells KTA-7, KT-39, KT-40 and PA-7 with model calculated head data. Total porosity 50% decreased.