

A STUDY ON GROUNDWATER DEPLETION AND LAND SUBSIDENCE IN DHAKA CITY

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A STUDY ON GROUNDWATER DEPLETION AND LAND SUBSIDENCE IN DHAKA CITY

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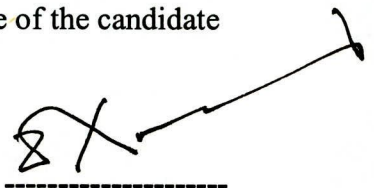
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ABSTRACT

Groundwater is the primary source of safe water to meet the essential demands of people in Bangladesh. Dhaka the capital city, with its enormous population takes a huge toll on its groundwater resources. In order to meet this growing demand various organizations mainly DWASA and private users have already installed nearly 2000 high capacity DTWs. Continuous pumping with so many wells from an area less than 450 km² has rendered the groundwater resources in stressed condition. This is likely to cause some adverse environmental impact like land subsidence. Many countries of the world have already experienced land subsidence of severe magnitude due to excessive groundwater pumping. Formation beneath the city of Dhaka is also susceptible to such phenomenon. This gives an early indication for an urgent need to alleviate pressure on the upper aquifers being exploited and explore for more suitable and sustainable sources to supplement the present water supply.

DWASA is entrusted with supply of piped water to Dhaka Metropolitan City and its adjacent area. At present 75% city area is under DWASA water supply coverage, out of which 82% is from groundwater sources. In an attempt to find alternate sources DWASA has started exploiting the deep aquifer at a depth of around 300 m. But the source and recharge mechanism of this aquifer is yet unknown and can not support the development of a long term strategy for water supply of Dhaka City.

From the previous studies, the development of Ground Water and Land Subsidence Model by EPC and MMP (1991) and its updating by BUET (2000) have been the most important and relevant to the present study. In the wake of recent development the previous model has become an inadequate tool to simulate the deep aquifer. So the current study was undertaken to setup a groundwater and land subsidence model that is flexible enough to simulate deep aquifer system and any other new changes. A versatile groundwater modeling tool called 'MODFLOW-2000 with Argus ONE' has been used for the current study.

MODFLOW-2000 uses the coupling of law of conservation of mass and Darcy's equation to simulate groundwater flow. The subsidence module is integrated into MODFLOW-2000 to compute the land subsidence using the groundwater model. The subsidence is computed basing on the Terzaghi's theory of one dimensional consolidation.

The groundwater model under the current study covers an area of 8,778 km² and includes the districts of Dhaka, Manikganj, Gazipur, Narshindi, Narayanganj and Munshiganj. The model area is discretized to 500 m grid inside Dhaka City. In the vertical direction the model is defined by 6 geologic layers. The model was calibrated by matching the hydrographs within and outside the Dhaka Region. The calibrated model was then used to estimate the land subsidence in and around Dhaka City.

The simulated hydrographs at important places of Dhaka City confirms the declining trend of groundwater level. The piezometric levels at Motijheel and Gulshan are found to be -52 and -43 m PWD respectively in December 2004. The corresponding subsidence as estimated by the model is maximum 4.9 cm. Results of model scenario runs indicate that the groundwater in the upper Dupi Tila aquifer would stabilize by April 2006 if no increase of abstraction is allowed after December 2004. Subsidence results for the same scenario shows that subsidence almost ceases with the stabilization of groundwater. Results of another scenario shows abstraction from deep aquifer with 94 wells in operation would deplete the groundwater by 20 m in 2020. But the situation in deep aquifer can only be confirmed after collecting observed data for a complete hydrological cycle.

If the current situation prevails the condition in the upper aquifers will worsen and many existing wells will go inoperative. Recharge from rainfall has become negligible due to lowering of water level and increased urbanization. The reduced storage capacity of the aquifers may cause land subsidence of such magnitude that may affect life and property. All these facts suggest that a comprehensive policy must be undertaken to counter/prevent the possible adverse effects on groundwater resource of Dhaka City.

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LIST OF SYMBOLS

C_c	Compression Index
C_s	Swelling Index
Δb	Change in Layer Thickness
Δh	Change in Hydraulic Head
e	Void Ratio
h	Hydraulic Head
K_h	Horizontal Hydraulic Conductivity
K_v	Vertical Hydraulic Conductivity
K_x	Hydraulic Conductivity Along X
K_y	Hydraulic Conductivity Along Y
K_z	Hydraulic Conductivity Along Z
n	Porosity
P_e	Preconsolidation Stress
q	Flow per unit area of porous media
R	Volumetric flux per unit volume of source and/or sink of water
S_k	Skeletal Storage Coefficient
S_s	Specific Storage
S_{sk}	Skeletal Specific Storage
S_{ske}	Elastic Skeletal Specific Storage
S_{skv}	Inelastic Skeletal Specific Storage
S_{sw}	Specific Storage due to Compressibility of Water
S_y	Specific Yield
γ	Specific Weight of Water
ρ_b	Bulk Density of Porous Medium
ρ_w	Density of Water
α	Compressibility of Porous Medium
β_w	Compressibility of Water
σ_z	Total Vertical Stress
σ_z'	Effective Vertical Stress

LIST OF ABBREVIATIONS

Argus ONE	Argus Open Numerical Environment
BMD	Bangladesh Meteorological Department
BTM	Bangladesh Transverse Mercator
BUET	Bangladesh Institute of Engineering and Technology
BWBD	Bangladesh Water Development Board
DBF	Data Base Files
DDMW	Dhaka Deep Monitoring Well
DEM	Digital Elevation Model
DHI	Danish Hydraulic Institute
DOS	Disk Operating System
DTW	Deep Tube Well
DWASA	Dhaka Water Supply and Sewerage Authority
EPC	Engineering Planning Consultants
ET	Evapotranspiration
FD	Finite Difference
GIS	Geographical Information System
GLM	Groundwater and Land Subsidence Model
GPS	Global Positioning System
GUI	Graphical User Interface
GW Chart	Groundwater Chart
GWL	Groundwater Level
HUF	Hydrologic Unit Flow
IBS1	Interbed Storage 1
ID	Identification
IDS	Interactive Database System
InSAR	Interferometry Synthetic Aperture Radar
IWM	Institute of Water Modeling
LPF	Layer Property Flow
MIS	Management Information System
MLD	Million Liter per Day
MMP	Sir Macdonald and Partners
MODFLOW	Modular Finite Difference Groundwater Flow
MODs	Maintenance operation and distributions
MPO	Master Plan Organization
MS	Microsoft
MW	Monitoring Well
NMSL	New Mean Sea Level
OMSL	Old Mean Sea Level

PIE	Plug In Extensions
PWD	Public Works Department
RFL	Rainfall
RFLEVP	Rainfall and Evapotranspiration
SCU	Subsidence Computation Unit
SDMW	Singair Deep Monitoring Well
SOB	Survey of Bangladesh
STW	Shallow Tube Well
SUB Package	Subsidence and Aquifer System Compaction Package
SWL	Static Water Level
SWMC	Surface Water Modeling Centre
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
WL	Water Level
WLQ	Water Level and Discharge



Chapter 1

INTRODUCTION

1.1 General

Groundwater is the primary source of freshwater to meet the various demands in Bangladesh. In earlier days extraction of groundwater was limited to using hand tube wells mainly for the purpose of drinking. Over the years the use of groundwater has steadily increased and diversified in agricultural, domestic, industrial and commercial sectors. Due to excessive and indiscriminate withdrawal of groundwater in Dhaka City the water table is continuously depleting during the last several decades. This is likely to cause a disorder of environment in near future. One such negative environmental impact is the subsidence of land surface in areas of excessive groundwater withdrawal. Land subsidence is known as sudden sinking or gradual settling of the earth's surface owing to movement of earth materials. Though no strict accounting has been made, it is likely that most of the water related subsidence is caused by the compaction of compressible sediments in and around areas of extensive groundwater pumping. Land subsidence attributable to the compaction of aquifer system is often an overlooked hazard and an environmental consequence of groundwater withdrawal (Galloway et al., 1999) in many countries of the world. This can also result in a permanent reduction in the total storage capacity of the aquifer system. The reduced storage capacity can degrade the groundwater resource both in terms of quantity and quality.

The capital city of Dhaka is located approximately at the centre of the country. Currently it accommodates over 10 million people out of total 140 million. The growth trend indicates that by 2025 the population would reach more than 20 million and situation is likely to worsen if no drastic measure is taken to control the influx. The city is already overburdened with huge population making the environment increasingly polluted. Requirement of water of this population is about 2200 million liter per day (MLD). At present 75% of the city area is under DWASA supply coverage. Out of the total supply of 1495 MLD, 82% is from groundwater sources tapping through 426 Deep Tube Wells

(DTW); the remaining 18% is supplied from the two major water treatment plants at Saidabad and Chandighat and two smaller units in Narayanganj. Due to excessive pumping the water levels in the upper and intermediate aquifers have substantially depleted rendering some wells inoperative and reducing the water production of others. As a consequence a severe concern has been raised about the adverse impacts of long-term excessive groundwater pumpage. The pressing concern is like gradual or sudden sinking of the land surface as a result of dewatering of the interceded clay formations within the aquifers. The geology of the subsurface under Dhaka City is found susceptible to such incident due to long-term excessive groundwater withdrawal.

1.2 Background and rationale of the study

In many modern cities in the world land subsidence due to groundwater pumping has been quite devastating. It can cause damage to bridges, roads, railroads, storm drains, sanitary sewers, pipelines, canals, levees and also to private and public buildings. After large-scale development of groundwater began in the Southwest America after World War II, land subsidence has occurred in many areas in the range from less than 0.3 m to a level of 9 m as estimated in the year 1997 (Streitz and Hansen, 2001). Poland and Davis provided descriptive summaries (Poland and Davis, 1969) of all the well-documented cases of major land subsidence caused by the withdrawal of fluids. They presented several case histories where subsidence has been associated with oil and gas production, together with a large number of cases that involve large-scale groundwater abstraction. There are well known cases of land subsidence due to groundwater overdrafts in Mexico City, Mexico and in the San Joaquin valley, California (Loannis et al., 2004).

These evidences being a grave concern for the policy makers of the country, efforts have been made to study the impact of excessive and long-term groundwater extraction on the environment and thereafter to estimate the safe yield of groundwater resource to meet the future demands. To make an assessment of the state of groundwater resource and its impact on the environment, EPC and MMP developed a groundwater and land subsidence model for DWASA in 1991 (EPC and MMP, 1991). It was a DOS version model, not user friendly. Subsequently BUET undertook a study to modify and update the model in order to make it

user friendly so that DWASA engineers can use it without much difficulties. The modified model called 'GLM 2000' (Windows based) was used to simulate the groundwater flow and land subsidence (BUET, 2000) with observed data up to 1999 and was in use to show some prediction up to 2010 and 2020.

Over the past few years the number of DWASA and privately owned DTWs has increased beyond proportion and the depletion of the groundwater level in the upper and intermediate aquifer has been alarming. To redress the situation DWASA has recently started exploring groundwater from the deep aquifer penetrating depths close or beyond 300 m. The hydraulic head in the deep aquifer is quite encouraging and already 28 DTWs are in operation till March 2006. But the source and recharge mechanism of groundwater in this deep aquifer is yet to be known. With this recent development of groundwater by DWASA, the 'GLM 2000' has become an inadequate tool because it only permits modeling for a maximum of four geologic layers. In the light of above development, now there is a need to use a model (e.g., MODFLOW) that will allow the simulation of deep aquifer system. In the current study two more geological layers have been incorporated (e.g., deep aquitard and deep aquifer) to simulate the extraction of water from deep aquifer. The study area as shown in Figure 1.1 includes districts of Dhaka, Gazipur, Manikganj, Munshiganj, Narshingdi and Narayanganj for the simulation of the groundwater flows.

Recently groundwater modeling has been an effective way to investigate subsurface water in many countries of the world. U.S. Geological Survey (USGS) originated software MODFLOW is being extensively used worldwide to carry out research in the field of groundwater resource management. It is a diverse tool that can incorporate several other physical processes associated with the groundwater flow. Groundwater contamination and land subsidence due to groundwater pumping are the two important phenomena that can be simulated using the current versions of MODFLOW.

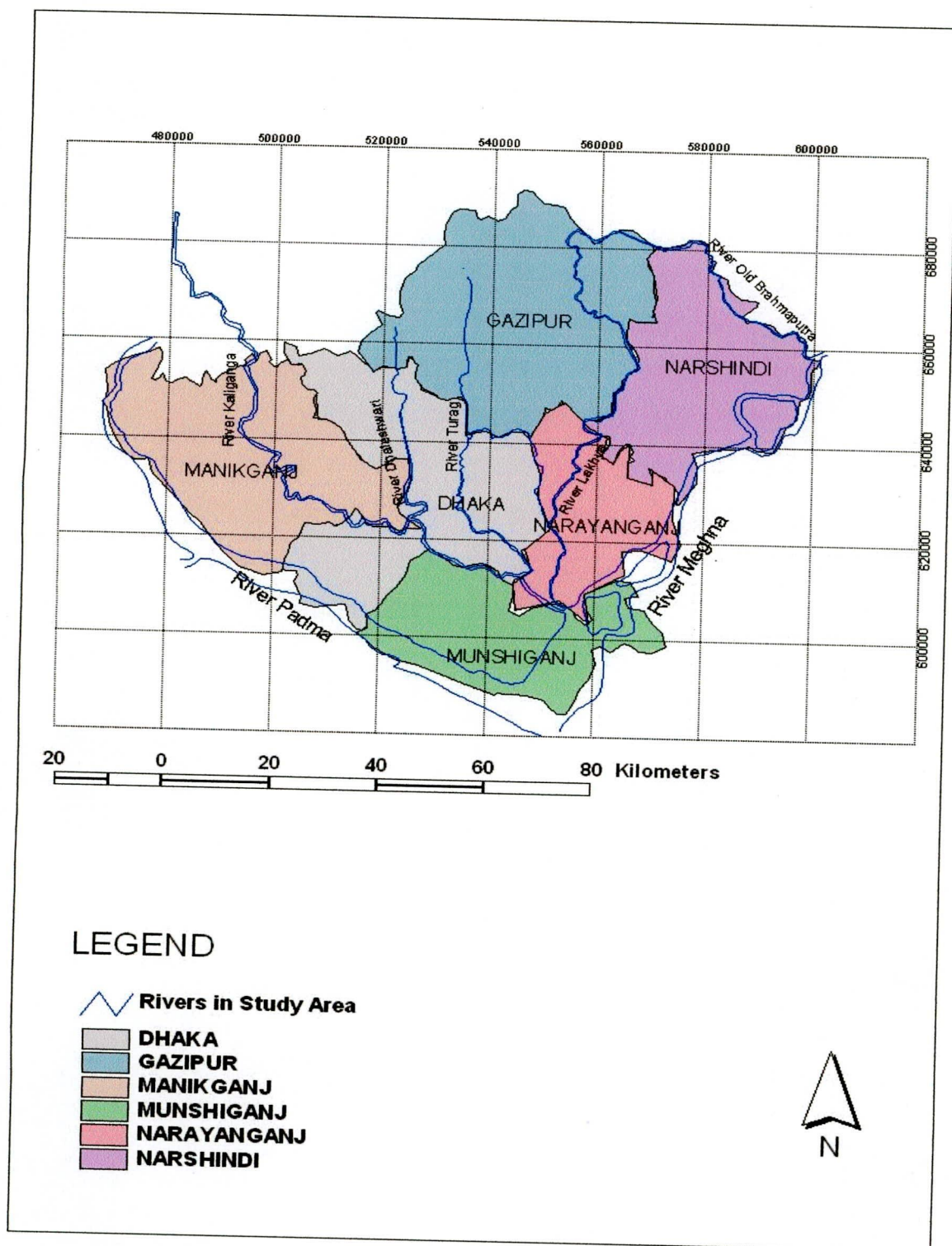


Figure 1.1 Map showing the districts and major rivers in the study area

1.3 Objectives of the study

- I. To simulate the state of groundwater depletion in Dhaka region by groundwater modeling considering all major geological, hydro-geological properties and land features.
- II. To make an estimate of land subsidence using the groundwater model in selected areas of the Dhaka City.
- III. To obtain results on subsidence from the model for various future groundwater development scenarios in Dhaka City.

1.4 Organization of the thesis

Chapter 1 gives a general introduction, focuses on the rationale and background of the study, and lists the study objectives.

Chapter 2 discusses the pervious studies on groundwater modeling and land subsidence in the study area and presents instances of land subsidence that has occurred worldwide.

Chapter 3 presents the theoretical basis of groundwater modeling and estimating the land subsidence.

Chapter 4 gives an elaborate description of the study area that includes geology, hydro-geology, land features, climate and all other relevant characteristics of the study area.

Chapter 5 deals with data requirement, data collection from both primary and secondary sources, data analysis and processing for model input. Also presents the details of the model setup and the ways of getting the desired output to achieve the study objectives.

Chapter 6 discusses the details of model calibration and results of analyses of various future scenario runs. Also presents the results on sensitivity and water budget analyses.

Chapter 7 presents the conclusions and recommendations that came out of the present study reflecting the results and analyses of the modeling works, sensitivity analysis and water budget.

Chapter 2

REVIEW OF LITERATURE

2.1 General

Water is essential to people and the largest available source of fresh water lies underground. Increased demands for water have stimulated the development of groundwater resources. History of groundwater development dates back to ancient times. The Old Testament contains numerous references to groundwater, springs and dug wells. Over the years techniques of investigating the occurrence and movement of groundwater have been improved and better equipment for extracting groundwater has been developed. New concepts of resource management have been established and research has contributed to a better understanding of the subject. Thus the knowledge of groundwater hydrology once veiled in mystery has grown rapidly in recent decades. The literature is now composed of interdisciplinary contributions from geologists, hydrologists, engineers, chemists, mathematicians, petroleum and agricultural scientists.

Groundwater is also the primary source of water for rural, industrial and irrigation demands. It provides 70% of world's drinking water. State of Florida in USA relies on groundwater for 95% of its total water supply (Jackson et al., 1989). The dependence on groundwater has been increasing worldwide due to increase of population, urbanization and irrigated lands. The process of urbanization often caused depletion in groundwater levels as a result of decreased recharge and increased withdrawal. Large scale groundwater development has been initiated by the developed countries ever since their industrial revolution approximately over a century ago. Some of those countries have already experienced the adverse effects of mining water and other fluids from underground. One of the most prominent and inevitable environmental influences of long term groundwater withdrawal is the subsidence of land surface.

2.2 Groundwater modeling studies in Dhaka City

History of groundwater modeling study is very recent in Bangladesh. Few groundwater models have been used in the past to assess the condition of groundwater resource and its probable impact in Dhaka City. The studies that can be listed in time sequence are as under:

- a. R.M. Parson (Parsons, 1980) and Montgomery developed a groundwater model for DWASA in 1980.
- b. Solomon and Chidley reviewed the Parson's model in 1986 (Solomon and Chidley, 1986).
- c. Dhaka Region Groundwater and Subsidence Model developed by EPC and MMP (EPC and MMP, 1991) for DWASA in 1991.
- d. A three-dimensional mathematical model has been developed (Bhuiyan and Bhuiyan, 1997) using Galerkin finite element method
- e. Fourth Dhaka Water Supply Project (WSP, 1998) undertaken by erstwhile Surface Water Modeling Center (SWMC) in association with Danish Hydraulic Institute (DHI). The project investigated the possibility of using surface water as sources to supplement the existing groundwater in 1998. An integrated hydrological modeling system named MIKE SHE was used for that study.
- f. Recently in 2000, a team comprising experts from BUET made a modification (BUET, 2000) of regional groundwater and subsidence model that was developed by EPC and MMP (1991).

R.M.Parsons/Montgomery developed a groundwater model for DWASA in 1980 (Parsons, 1980). The model was used to assess the impact of additional groundwater abstraction on the aquifer system. It was based on finite difference method. The aquifer system was simulated as a single aquifer unit overlain by a semi-confining layer. The study area being surrounded by major rivers, it was expected to maintain a good interaction between rivers and aquifer system. But when the model was run in

predictive mode to assess the impact of increased abstraction from 1980 to 2010, the results of the model showed poor relation between the rivers and the aquifers. It did not consider the effect of river contribution to the aquifer with the increase of abstraction from aquifer.

In 1986, Solomon and Chidley (Solomon and Chidley, 1986) reviewed the Parsons Model (1980) and used a USGS model to assess the groundwater resource considering the effect of rivers and the potential recharge values from MPO and the hydro-geological parameters from BWDB. But the results were not satisfactory and similar to those of previous model of R.M. Parsons and Tames M. Montgomery. They did not calibrate their USGS model against historical data before the predictive run. However, they came to a conclusion that a detailed modeling of Dhaka area is necessary with special emphasis on extending the model boundaries to the major rivers with improved simulation of recharge mechanism.

The Dhaka Region Groundwater and Subsidence Model study was started by DWASA in 1989 and the main objectives were the assessment of the impact of increased groundwater abstraction on groundwater balance in greater Dhaka area due to proposed installation of 50 new and 10 replacement tube wells, quantification of future groundwater abstraction and evaluation of the effect of increased groundwater abstraction on the compaction of clay and silt layers overlying the main aquifer. The model was based on integrated finite difference method. A basic feature of the model was the resolution of three-dimensional groundwater flow into its horizontal and vertical components. The areal extent of the model is bounded by three major rivers of Jamuna, Ganges and Meghna in three sides and the remaining northern part is bounded partly by Old Brahmaputra and partly by northern edge of Gazipur and Manikganj districts. The groundwater resources model consists of two integrated units. The regional model evaluated the consequences of groundwater development on a regional basis. The Dhaka sub-model considered the Dhaka metropolitan area and immediate surroundings. This model is sufficiently refined to take into account the spatial variability of various parameters such as local relief, geology, physiography and

distribution of abstraction. The model developed is a four layer model: lower aquifer, lower aquitard, upper aquifer and upper aquitards (Figure 2.1). The two fundamental principles used are continuity of mass and Darcy's law. The flows are horizontal in aquifers and vertical in aquitards. Both steady and transient states of flow are encountered in the model. The geometry of aquifer system is defined by the elevations of top and bases of different layers. Two prediction runs, one for the continuation of present conditions from 1991 to 2010 and another for the Crash Program with no further urbanization of Dhaka from 1990 to 2010 had been performed. The hydrograph of the prediction run one indicated that steady state condition was achieved by 1992/1993, with only a minor increase in drawdown in Dhaka City. Prediction run two with the new cash program wells added, showed an additional drawdown of between 3 m and 8 m in Dhaka City.

A three-dimensional mathematical model has been developed (Bhuiyan and Bhuiyan, 1997) using Galerkin finite element method for simulation of transient saturated-unsaturated groundwater flow in the multi-aquifer system. The model has tested a number of published schematized problems from the available literature. To verify the model further in simulating a complex hydro-geological situation, a strip land of Dhaka City along the bank of the river Buriganga was studied. The boundary conditions of the domain were derived from river water level and piezometric level data. The model calibration and sensitivity analysis of the parameters had been performed in that study. Simulated piezometric head profiles show the rise and fall with river water levels at the nodes near the river but this phenomenon diminish rapidly away from the river at remote nodes where continuous declining trend of piezometric levels were observed.

In 1998 under the Fourth Dhaka Water Supply Project by SWMC in association with DHI investigated the possibility of using surface water as sources to supplement the existing groundwater supply and hence alleviate the excessive pressure on the groundwater resource (WSP, 1998). The main objective of the groundwater modeling was to establish a sound scientific basis for formulating a sustainable Water

Management Plan for Dhaka City. The specific objectives were to develop an integrated hydrological model for Dhaka City and to apply the model to predict the effects on groundwater changes and recharge for different water allocation scenarios. An integrated hydrological modeling system MIKE SHE was adapted for that study. Three options run (i) understanding groundwater condition of Dhaka City in 2006 (ii) understanding groundwater condition of Dhaka City in 2016 and (iii) understanding the impact of conjunctive use of groundwater for the period 1990-1997 have been performed. The result shows that the recharge from the rivers may increase as the head gradient between the lower aquifer and the rivers increases, but there are considerable deficits of water in most DWASA zones. The deficit indicates a non-sustainable situation with increasing drawdown. The calibrated model is thus useful in estimating not only the present available resource but also to predict the effects on groundwater changes under alternative water allocation scenarios which act as a decision making tool for Water Management Plan of Dhaka City.

Recently, in 2000, to meet the present day requirement, BUET updated the Dhaka region groundwater and subsidence study developed by DWASA in 1991. The objectives of the study were to make the model user's friendly and menu driven so that the model can be easily operated and used by DWASA engineers. The time invariant data had been used from 1991 study and the time variant data had been collected, updated and processed for model input for the period from 1991 to 1999. The setup of the model had been the same as previous model of EPC and MMP. Each model polygon had associated nodes for which piezometric levels were computed during model simulation. Three prediction runs for the evaluation of groundwater table had been performed. Prediction run one simulated the continuation of present conditions during the period from 2000 to 2010. It has been concluded that present abstraction within the Dhaka can be sustained given that mean recharge and river level conditions remain same as it was. Prediction run two simulated the increased DWASA withdrawal with present trend from 2000 to 2020 assuming that only DWASA abstraction will be increased all other options remain same as it was. Prediction run-3 was performed to simulate the conditions to meet the total demand of that time by increasing number of

wells from 330 to 450. The result of the prediction run one shows steady state condition achieved by 2004 where prediction runs two and three show remarkable declination of groundwater table in Dhaka City.

2.3 Land subsidence studies in Dhaka City

Two subsidence studies have so far been conducted as part of groundwater modeling study in the area. The subsidence studies by EPC and MMP (1991) and BUET (2000) are based on a one dimensional model for vertical settlement in a clay layer. The theoretical basis and the methods of estimating subsidence are described in brief in following paragraphs:

Mathematical formulation

For one-dimensional (vertical) consolidation and swelling of soils, the basic differential equation that describes the settlement and swelling process can be derived from the equations of motion of pore-water and continuity of mass. The motion of water in the vertical direction in a saturated porous media can be expressed through Darcy's equation as:

$$q = K_v \frac{\partial \phi}{\partial z} \quad (2.1)$$

$$\frac{\partial q}{\partial z} = K_v \frac{\partial^2 \phi}{\partial z^2} \quad (2.2)$$

where, q = vertical flow of water through a unit area, K_v = vertical hydraulic conductivity, z = position relative to a selected datum and ϕ = piezometric head at level z . The continuity equation for a complete compressible soil which contains non-compressible pore water can be expressed as:

$$\frac{\partial q}{\partial z} = -\frac{\partial n}{\partial t} + S_y \frac{\partial \phi}{\partial t} \quad (2.3)$$

where n = porosity, S_y = specific yield, and t = time. The first term in the right hand side of Eq (2.3) relates to the change in pore-water storage due to deformation of the

skeleton of the soil. The second term relates to a loss or gain in storage due to a change in water table elevation and thus a change from full to partial saturated conditions and vice versa. The change in porosity can be expressed in terms of void ratio by:

$$\frac{\partial n}{\partial t} = \frac{1}{(1 + e_0)} \frac{\partial e}{\partial t} \quad (2.4)$$

where, e_0 = initial void ratio, e = void ratio at time t . The void ratio can be related to effective stress as follows:

$$e = a + b \ln \sigma \quad (2.5)$$

where, σ = effective stress, a and b = coefficients which define the relationship between e and σ . Effective stress can be related to piezometric head by:

$$\sigma = P - \gamma(\phi - z) \quad (2.6)$$

where, P = total stress at level z , γ = specific weight of pore water. Combining Eqs (2.4), (2.5) and (2.6) gives:

$$\frac{\partial n}{\partial t} = - \frac{-b\gamma}{[(1 + e_0)\{P - \gamma(\phi - z)\}]} \frac{\partial \phi}{\partial t} \quad (2.7)$$

The continuity Eq (2.3) may now be re-written as:

$$\frac{\partial q}{\partial z} = \left[\frac{b\gamma}{(1 + e_0)\{P - \gamma(\phi - z)\}} + S_y \right] \frac{\partial \phi}{\partial t} \quad (2.8)$$

Combination of Eqs (2.2) and (2.8) results in a differential equation which is equivalent to the well known Terzaghi and Peck's equation can be written as below:

$$K_v \frac{\partial^2 q}{\partial z^2} = \left[\frac{b\gamma}{(1 + e_0)\{P - \gamma(\phi - z)\}} + S_y \right] \frac{\partial \phi}{\partial t} \quad (2.9)$$

Model assumptions

Following assumptions have been introduced in the model formulation:

- Non-homogeneous conditions are approximated by sub-dividing the soil layer into a number of sub-layers within which homogeneous conditions were assumed.

- The permeability is assumed to be independent of void ratio. In reality a reduction in void ratio due to compaction of the soil results in a reduction in soil permeability thus a slowing down of the consolidation process. The assumption of a constant permeability results in an over-estimation of the short term rate of consolidation, which, considering the scale of the model and scope of the study, is of minor significance.
- Consolidation and swelling occurs in a vertical direction only, an assumption which is valid considering the regional scale of subsidence risk assessment.
- The modeled layers are simulated as fully saturated and thus the second term in the right hand side of Eq (2.3) is not used.
- Total stress is independent of time and thus constant at a given depth.

The subsidence model solves the differential Eq (2.9), developed by Terzaghi and Peck (1967). The model is operated by using output from the groundwater resource model to define the boundary conditions at the top and bottom of aquitards as illustrated in Figure 2.1. The clay layer is subdivided into a number of sub-layers for which parameters that control flow and settlement are prescribed. The model simulates pressure changes and settlements in the clay sub-layers. Then the settlement for a clay layer is obtained by adding computed settlements for all sub-layers.

Data requirement and analysis

For the purpose of estimating land subsidence due to drawdown, the following information and soil properties of the clay layers (aquitards) were required:

- Thickness of the layers, b
- Vertical permeability, K_v
- Bulk density, ρ_b
- Void ratio, e
- Compression index, C_c
- Swelling index, C_s
- Over-consolidation stress, P_e

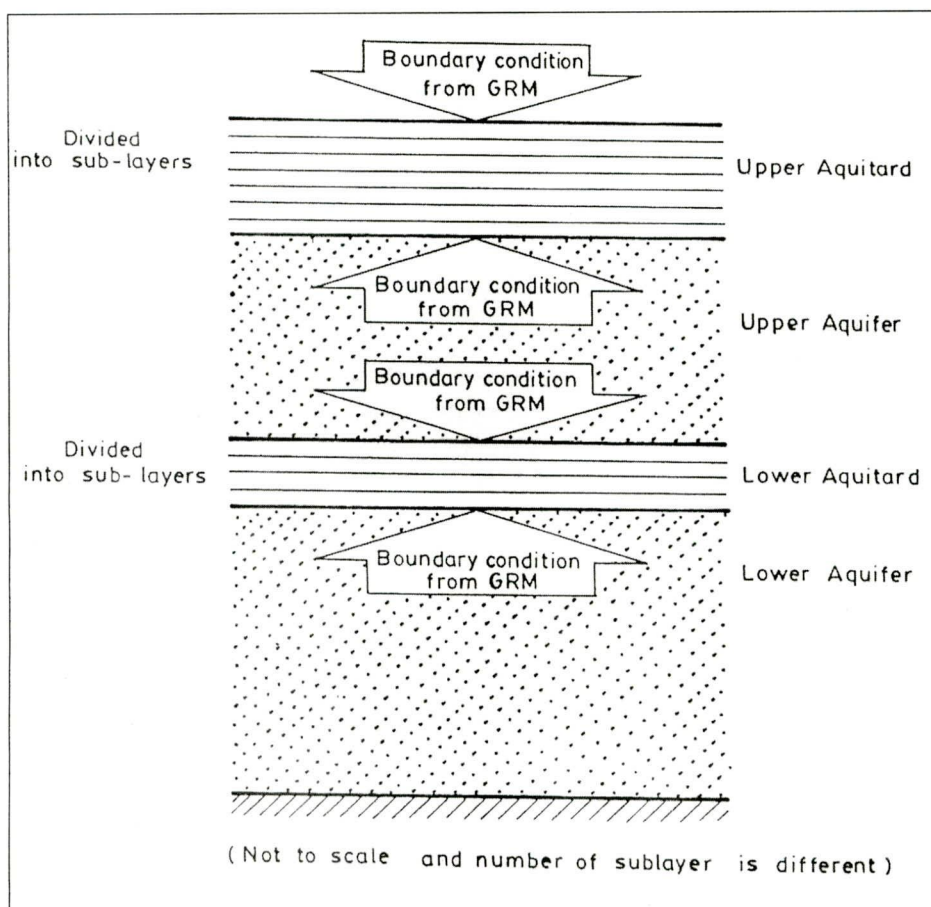


Figure 2.1 Schematic representation of clay layers (aquitards) of a geologic unit in the subsidence model (EPC and MMP, 1991)

There were few published accounts of geotechnical properties of soils in the Dhaka area. However, there are a great volume of unpublished site investigation reports. Borehole and laboratory test data for several hundred sites within the subsidence study area were obtained which that was used in all the previous studies. Virtually all cohesive soil properties for the study area have been obtained from laboratory tests on so called undisturbed samples obtained during routine investigations.

Table 2.1 shows range of index and compressibility parameters for various geological units within Dhaka region as given in the previous study by EPC and MMP (1991). It can be seen from Table 2.1 that except for highland alluvium, all the other formations are likely to undergo less consolidation settlement due to lowering of water

level. Also, it is to be noted that the natural water content of these soils are close to plastic limit indicating the soils to be over-consolidated. Therefore, settlement estimates made on the basis of assumption that soils are normally consolidated will overestimate the ground subsidence level. Over-consolidation is necessarily a function of depth, and declines very rapidly in the top ten meters. Approximate values for range of excess pre-consolidation pressure are given in the previous studies.

Table 2.1 Range of index and compressibility parameters for various geological formations within Dhaka region (EPC and MMP, 1991)

Soil Type	LL	PL	% of silt	% of clay	Cc
Highland Alluvium	49	25	81	13	0.5
Madhupur clay 1	52	26	74	18	0.2
Madhupur clay 2	47	25	78	5	0.2
Dupi Tila 1	47	25	76	12	0.3
Dupi Tila 2	37	27	77	3	0.1

Note: LL – Liquid Limit, PL – Plastic Limit, Cc – Compression Index

The one-dimensional compressibility characteristics of a soil profile are fundamental in determining the vertical strains associated with settlement. Ground surface displacement represents the cumulative sum of vertical strains within various strata influenced by changes in effective stress. Subsidence may therefore results from large strains occurring in a relatively thin compressible stratum, or from smaller strains within greater thickness of stiffer, less compressible materials.

Computation of the subsidence in BUET (2000) was based on the sub-divided regions of the geotechnical sub-areas called Subsidence Computation Units or SCUs (Figure 5.29). In the study, 14 SCUs were used which were represented by 14 grid points. The node numbers of these grid points were the same which were used for the groundwater resource model. The transient model run had been made from the year 1990 to 1999 for both the Worst Credible and Best Estimate cases (based on geotechnical properties in relation to their susceptibility to subsidence). Time step used for the model run was 10 days and results of settlements were available for each year.

Comparison of the model results with the observation for some selected locations are shown in Table 2.2.

Table 2.2 Comparison between the prediction and measured subsidence at some selected locations (BUET, 2000)

Route/location	Model predicted subsidence (mm)	Measured subsidence (mm)
Tongi	11 to 12	7 to 13
Airport-Banani route	25 to 44	17 to 27
Mohakhali-Kamalapur route	55 to 86	11 to 63

Based on soil properties and predicted depth of groundwater level for the year up to 2010, amount of ground settlement in various nodes (centre of model polygon) were calculated in BUET (2000). The calculations were based on two estimates - one using soil conditions close to average condition stated as best estimate and the other considering probable worst soil condition noted as worst credible estimate. The settlements calculated were due to consolidation of the clay layers affected by drawdown and therefore were dependent on amount of drawdown and thickness of the aquitards (clay layers). Table 2.3 shows estimated settlement of various nodes due to lowering of water level for the year 2010. It can be seen that most settlement would take place in the centre of the city where the drawdown is maximum.

Limitation of previous study

Main limitation of the previous studies (EPC and MMP, 1991 and BUET, 2000) is related to the geometry of the model as shown in Figure 2.1. The model had 4 geological layers and the bottom of the lower aquifer was considered impervious. But currently DWASA is extracting water from the deep aquifer underlying the lower aquifer defined in the pervious model. Also the source code for both groundwater and subsidence model need modification to change the model setup.

Table 2.3 Predicted subsidence corresponding to predicted depth of GWL below ground surface for the year 2010 (BUET, 2000)

Model node No.	SCU	Estimated Settlement mm						Depth of GWL from Ground Surface(m)
		Best Estimate			Worst Credible			
		Upper Aquitard	Lower Aquitard	Total	Upper Aquitard	Lower Aquitard	Total	
335	1A-1	19.98	16.13	36.11	41.18	82.66	123.84	33.398
	1A-2	39.69	16.09	55.78	120.01	83.28	203.29	33.398
257	1B-1	18.51	10.17	28.68	34.03	55.24	89.27	27.018
	1B-2	51.29	10.21	61.5	288.94	55.48	344.42	27.018
230	1C-1	19.98	145.11	165.09	26.34	241.18	267.52	44.475
240	10-1	33.71	24.04	57.75	50.21	128.99	179.2	43.551
	1D-2	38.93	24.44	63.37	88.99	132.23	221.22	43.551
272	1E-1	21.06	129.21	150.27	37.66	152.91	190.57	63.279
	1E-2	78.62	117.45	196.07	765.09	154.44	919.53	63.279
372	1F-1	43.93	16.51	60.44	55.51	79.89	135.4	30.566
444	1G-1	25.58	4.23	29.81	30.78	5.16	35.94	9.03
	1G-2	29.05	4.05	33.1	30.04	4.94	34.98	9.03
231	1H-1	32.34	17.21	49.55	36.05	51.08	87.13	26,323
	1H-2	21.36	17.18	38.54	54.15	51.05	105.2	26.323
254	02-1	0	0	0	0	0	0	0
	02-2	0	0	0	0	0	0	0
493	03-1	12.87	1.1	13.97	21.35	1.7	23.05	2.457
	03-2	12.13	1.14	13.27	19.93	1.77	21.7	2.457
475	04-1	1.23	0.3	1.53	0.44	0.29	0.73	0.147
299	5A-1	0.76	0.03	0.79	2.47	0.03	2.5	0.759
	5A-2	3,19	0.03	3.22	4.81	0.03	4.84	0.759
155	5B-1	0	0	0	0	0	0	0
197	06-1	7.82	0.94	8.76	87.13	1.22	88.35	1.087

2.4 Previous modeling studies on land subsidence worldwide

Numerical models to simulate and predict aquifer-system compaction were developed during the last three decades of the 1900s with the advent of digital

computers capable of solving large systems of finite-difference and finite-element equations. New methods to simulate compaction in aquifer systems were developed by Gambolati (Gambolati, 1970; Gambolati, 1972a and 1972b), Gambolati and Freeze (Gambolati and Freeze, 1973), Helm (Helm, 1975 and 1976), Narasimhan and Witherspoon (Narasimhan and Witherspoon, 1977), and Neuman and others (Neuman et al., 1982). The one-dimensional (vertical) model presented by Helm computes compaction caused by specified water-level changes. This approach is used to analyze compaction at borehole extensometer sites for which there are detailed records of compaction and water-level changes (Epstein, 1987; Hanson, 1989). More recent efforts have focused on incorporating subsidence calculations in widely used two or three-dimensional models of groundwater flow. Meyer and Carr (Meyer and Carr, 1979), Williamson and others (Williamson et al., 1989), and Morgan and Dettinger (Morgan and Dettinger, 1996) modified and used finite-difference models to simulate groundwater flow and subsidence in the area of Houston, Texas; the Central Valley, California; and Las Vegas Valley, Nevada, respectively.

Leake and Prudic (Leake and Prudic, 1991) developed the Interbed Storage Package, version 1 (IBS1), to simulate regional-scale compaction of interbeds within aquifers using the groundwater model program, MODFLOW (McDonald and Harbaugh, 1988). IBS1 also can be used to simulate compaction of confining units if these units can be discretized into one or more model layers (Larson et al., 2001; Nishikawa et al., 2001). MODFLOW and the IBS1 Package also have been used to simulate regional groundwater flow and land subsidence (Hanson et al., 1990; Hanson and Benedict, 1994; Nishikawa et al., 2001; Hanson et al., 2002; Kasmarek and Stromm, 2002), and one-dimensional groundwater flow and compaction measured at a borehole extensometer site (Sneed and Galloway, 2000). The IBS1 Package assumes that during one model time step, head changes in aquifer material are propagated throughout the entire thickness of compressible interbeds. Thus, the release of water from or uptake of water into interbed storage during this time step represents the full volume specified by the interbed storage coefficients and the change in aquifer hydraulic head.

2.5 Prominent cases of land subsidence worldwide

In recent years it has become apparent that the extensive exploitation of groundwater resources has brought with it an undesired environmental side effect. At many localities in the world, groundwater extraction from unconsolidated aquifer-aquitard systems has been accompanied by significant land subsidence. Poland and Davis (1969) and Poland (1984) provide descriptive summaries of all the well-documented cases of major land subsidence caused by the withdrawal of fluids. They present several case histories where subsidence has been associated with oil and gas production, together with a large number of cases that involve long term groundwater pumping. Table 2.4 lists some of the strongest evidences of land subsidence those have occurred worldwide.

Table 2.4 Land subsidence worldwide due to groundwater withdrawal (Poland, 1984)

Sl	Country	Location	Depth range of compacting beds	Maximum subsidence (m)	Area of subsidence (km ²)	Time of principal occurrence	Remedial measures taken or not
1	Australia	Latrobe Valley	10 - 300	1.6	100	1961 - 1978	Taken
2	China	Shanghai	3 - 300	2.63	121	1921 - 1965	Taken
3	Great Britain	London	50 - 100	0.35	450	1865 - 1932	Not taken
4	Hungary	Debrecen	50 - 250	0.42	390	1920 - 1975	Not taken
5	Italy	Po Delta	100 - 600	3.2	2600	1951 - 1966	Taken
6	Japan	Tokyo	0 - 400	4.59	3420	1918 - 1978	Taken
7	Mexico	Mexico City	0 - 50	9	225	1891 - 1978	Taken
8	New Zealand	Wairakel	250 - 800	6.5	30	1952 - 1978	Not taken
9	South Africa	Far West Rand	30 - 200	9	NA	1959 - 1975	Taken
10	Thailand	Bangkok	0 - 200	0.13	NA	1955 - 1978	Not taken
11	USA	Arizona	50 - 350	3.6	700	1950 - 1978	Taken
12	USA	California	50 - 330	4.1	650	1918 - 1970	Taken
13	USA	San Joaquin Valley	60 - 900	9	6200	1930 - 1975	Taken
14	USA	New Orleans	150 - 260	0.8	150	1940 - 1975	Not taken
15	USA	Las Vegas, Nevada	60 - 300	1.7	300	1935 - 1975	Taken
16	USA	Houston, Texas	60 - 900	2.75	12000	1943 - 1978	Taken

A brief account of some of the important cases of land subsidence is given in the following paragraphs:

Shanghai, China

Shanghai is the largest industrial city in China, standing on the coast of East China Sea and situated at the front edge of the Yangtze Delta. The elevation of the flat lying city area is 3 to 4 meters above sea level. The summer-winter temperature variation is very large. The Whangpoo River and Soochow Creek, both being the outlets of Taihu Lake, are the chief tidal water ways of the city.

Land subsidence was first reported in 1921. After liberation, with the rapid development of industrial production, the exploitation of groundwater increased, and subsidence continued. The greatest subsidence occurred from 1956 to 1959, at an annual rate of 98 mm. Up to 1965, the maximum cumulative subsidence, as indicated by one of the bench marks in the city area, was as high as 2.63 m. The area of cumulative subsidence exceeding 500 mm was 121 km², forming two plate shape depressions in the urban district and affecting the suburban districts, too.

Mexico city, Mexico

The subsidence of Mexico City is one of the most remarkable cases in the world. The city is directly underlain by unconsolidated and saturated lacustrine (fresh water lake) clays. Beneath the clays are thick saturated deposits of unconsolidated sand and gravel beds interbedded with clayey silts. The primary water for the city is derived from the sands and gravels, and when water is pumped from them, the overlying clays are slowly dewatered (Figueroa, 1977). The porosity in the unconsolidated clays is high and when water is removed they can compress significantly. Extensive groundwater pumping from 1940 to 1960 caused dewatering and compression of the

overlying clays that has led to as much as 27 feet of ground surface subsidence (Poland, 1984).

In Mexico City, rapid land subsidence caused by groundwater withdrawal and associated aquifer-system compaction has damaged colonial-era buildings, buckled highways, and disrupted water supply and waste-water drainage. Figure 2.2 shows the main Cathedral in Mexico City that leans to the left after centuries of subsidence. Maximum rates of subsidence approach 2 feet per year and total subsidence during the 20th century is as great as 30 feet (New York Times International, January 29, 1998).

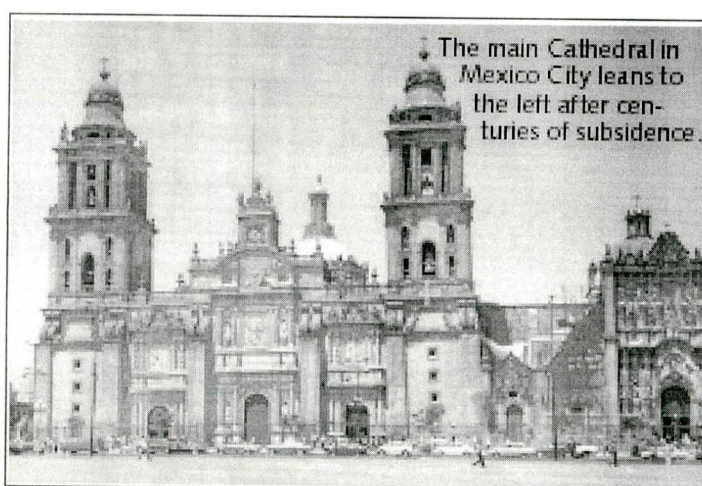


Figure 2.2 Main cathedral in Mexico City leans to the left due to land subsidence

Ravenna, Italy

Land subsidence in this area has been observed for a long time but only recently did the related consequences become critical. Progressively affecting the entire territory of about 700 km², the subsidence increasingly threatens not only the industrial and urban areas but also the surrounding vast marshland reclamations which could be submerged once again. The existing of several buildings and historical monuments is jeopardized as well, since their foundations have to be kept dry by pumping out water continuously.

Field measurements such as leveling and hydraulic head records were carried out almost annually, using networks of suitably placed bench marks and piezometers. It was revealed that the area was experiencing subsidence in excess of 3 cm per year. The maximum rate of about 11 cm subsidence was recorded in the industrial zone between 1972 and 1973 and in Ravenna's historical centre about 8 cm per year was observed. The shape of the subsiding areas is found to be in close correspondence with the cone of depression of the aquifers in both periods.

Santa Clara Valley, California, USA

Land subsidence in the central part of Santa Clara Valley-beneath the southern part of San Francisco Bay and extending to the southern edge of San Jose was first recognized in 1932-1933. The subsidence was noted when a benchmark at San Jose, established in 1912, was resurveyed and found to have subsided. Re-leveling of a line of first order levels established by the national geodetic survey in 1912 showed about 1.2 m of subsidence in down town San Jose in 1933. The subsiding area extends southwards about 750 km². The central part of the area experienced 0.3 to 2.4 m of subsidence from 1934 to 1967.

The comparison of artesian head change and subsidence from 1916 to 1967 demonstrates beyond a reasonable doubt that the increase of effective stress resulting from the declining artesian head caused the subsidence.

San Joaquin Valley, California, USA

The principal areas of land subsidence due to groundwater withdrawal in California, USA are in the San Joaquin Valley and the Santa Clara Valley. In San Joaquin Valley, subsidence due to groundwater withdrawal occurs in three areas – the Los Banos Kettleman City area on the central west side, the Tulare – Wesco area on the south-east border, and the Arvin-Maricopa area at the south end (Figure 2.3).

Subsidence due to the compaction of aquifer systems in response to excessive decline of water levels had affected about 13,500 km² of the San Joaquin Valley by

1970. Figure 2.3 also depicts the distribution and magnitude of subsidence exceeding 0.3 m that had occurred by 1970, affecting an area of 11,100 km². Figure 2.4 shows the maximum subsidence (9 m) in this area in 1977 at a location 16 km west of Mendota.

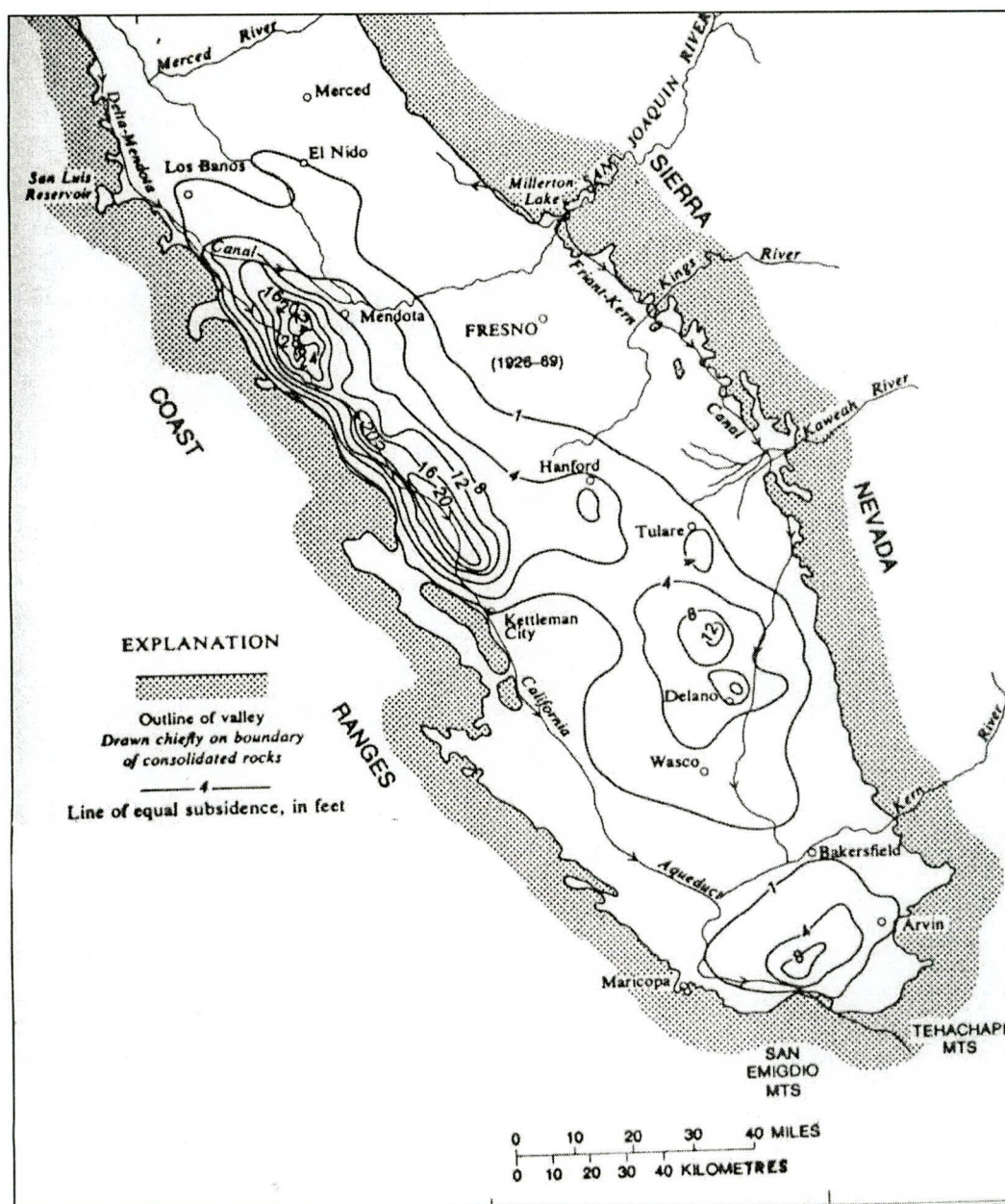


Figure 2.3 Land Subsidence in San Joaquin Valley, California, 1926 – 1970

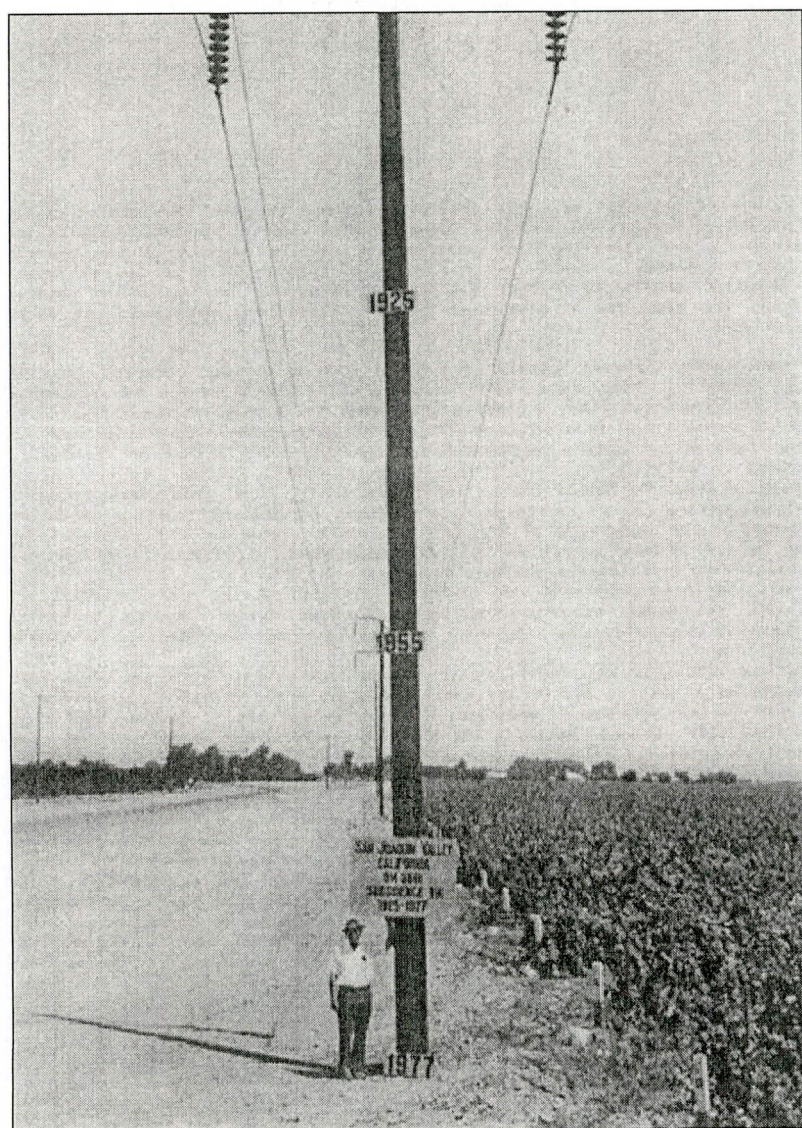


Figure 2.4 Joseph F. Poland of U.S. Geological Survey stands near the bench mark S661 southwest of Mendota in the San Joaquin Valley, California. The bench mark subsided 9 m from 1927 to 1977, because of intensive withdrawal of groundwater. Sings on the power pole indicate the respective positions of land surface in 1925, 1955 and 1977.

Houston-Galveston Region of Texas, USA

Development of groundwater in the Houston-Galveston region for municipal supply and irrigation began in the 1890's. Groundwater withdrawal increased gradually to about $4.4 \text{ m}^3/\text{s}$ with population growth, increased irrigation and industrial use until the late 1930's. construction of large industrial complex in the region began in 1937,

and by 1954 the groundwater pumping had increased to about $18 \text{ m}^3/\text{s}$. By 1972 the pumping rate further increased to about $23 \text{ m}^3/\text{s}$.

The pumping of larger amounts of groundwater has resulted in water level decline during 1943-1973 of as much as 61-99 m in affected areas. The annual average rate of water level decline for 1943-1973 was 2 m and 3.3 m in the two aquifers of the area. As much as 2.3 m of subsidence occurred in this area during 1943-1973. The area of the greatest amount of subsidence coincides with the greatest amount of artesian-pressure decline.

Wairakei geothermal field, New Zealand

The Wairakei geothermal area is located 8 km north of the Lake Taupo in the centre of the North Island of New Zealand. Geothermal investigations began in 1950 and culminated with the commissioning of the first stage of power station in 1958 and the second stage in 1964. Steam is supplied to the power station by 64 wells, most of which produce a steam-water mixture at the well head. The 64 production wells cover an area of 2 km^2 which is known as the production field area.

The first indication of ground movement came in 1956 when discrepancies were found in the levels of several bench marks since the previous survey in 1950 (Hatton, 1970). One bench mark had subsided 7.6 cm. A leveling network was established and gradually expanded. In a comprehensive survey in 1971 the area of subsiding ground was found to exceed 30 km^2 .

Nobi plain, Japan

The Nobi Plain underlain by compressible sediments is situated in the central part of Japan and is about 1800 km^2 in area. The increasing withdrawal of groundwater in Nobi plain is shown in Table 2.5. The withdrawal of groundwater was 32 percent of

the average annual rainfall on this plain. This volume was much larger than the natural recharge of groundwater.

Table 2.5 Withdrawal of groundwater in the Nobi Plain

Year	Groundwater Withdrawal Mm ³ /day
1925	0.001638
1945	0.129088
1950	0.15404
1955	0.360301
1960	0.849338
1965	1.552764
1970	3.002128
1973	3.514195

In the 1920's piezometric levels of confined aquifers were above the ground surface in most of this plain. In the 1940's flowing wells were still observed in this area. But since then, the piezometric levels have declined due to the increase in number of artesian wells. During the period from 1950 to 1973 the subsidence increased exponentially and some areas subsided more than 20 cm in 1973. Due to the land subsidence the area below mean sea level enlarged from 186 km² to 248 km² in 1973.

Chapter 3

THEORY OF GROUNDWATER FLOW AND LAND SUBSIDENCE

3.1 General

U.S. Geological Survey's Modular Finite-Difference Groundwater Flow Model commonly known as MODFLOW is a computer program that numerically solves the three-dimensional groundwater flow equation for a porous medium. As the name implies the program is broken up into a series of modules each of which is used to model a specific process affecting groundwater flow. One module, for example, deals with wells, and another deals with recharge. A separate module is embedded in MODFLOW which can simulate land subsidence associated with groundwater flow. MODFLOW can simulate groundwater flow only in the saturated zone. MODFLOW itself does not have a graphical user interface. Instead, the user must prepare a series of text files that specify the problem to be modeled. These files can be voluminous and preparing them manually is a time-consuming and error-prone process. Argus ONE together with the MODFLOW GUI provides a graphical user interface for MODFLOW which vastly simplifies the process of creating MODFLOW input files. For the present study a recent version of MODFLOW named MODFLOW-2000 is used. Following sections briefly describe the programs and the theoretical basis of the modules that simulate groundwater flow and land subsidence.

3.2 MODFLOW graphical user interface and Argus ONE

MODFLOW Graphical User Interface (MODFLOW GUI) with Argus ONE is the media and preprocessor for all input data for the MODFLOW-2000 and other packages related to groundwater flow. A utility program, named GW Chart, was developed in conjunction with the MODFLOW GUI and is used for post-processing the output from MODFLOW. A series of example models are created and can be used to learn about the features of MODFLOW, Argus ONE and the MODFLOW GUI. These are available at <http://water.usgs.gov/nrp/gwsoftware/modflow-gui/modflow-gui.html>.

Basic function of MODFLOW GUI is to create a series of Argus ONE layers that are required to set up a MODFLOW model. For example, it creates a grid layer named 'MODFLOW FD Grid' to discretize the model area and an information layer named 'Elevation Top Unit1' that specifies elevation of top surface of the uppermost geologic unit. During the model run Argus ONE exports the input data to MODFLOW-2000. The results (hydraulic head/drawdown/subsidence) can be obtained at the center of each cell in the model cell using the postprocessor in MODFLOW GUI and GW Chart. Each geologic unit (an aquifer or aquitard) in the model can have a series of Argus ONE layers related to it. In addition, there will be Argus ONE layers that are not related to a specific geologic unit. The Argus ONE layers are of various types. Grid layers, for example can be used to store a grid. Data layers store a series of data points used for fast interpolation. Information layers store contours (points, lines or polygons). Map layers can be used for contour maps, scanned images and other text and symbols to specify spatial information in the model area. Domain layer specify the model boundary and store information used to generate a grid.

Most of the Argus ONE layers can have parameters. Argus ONE parameters are used to store data of a specific type on an Argus ONE layer. For example, on the Hydraulic Conductivity Unit1 Argus ONE layer, there are two Argus ONE parameters: K_x and K_z . K_x is the horizontal hydraulic conductivity in the grid's X direction (in the order of increasing column numbers). K_z is the vertical hydraulic conductivity. Thus K_x and K_z store two different types of information. The user can draw contours on an Argus ONE information layer if it is the active layer. Details of how to use Argus ONE and MODFLOW GUI are available at <http://water.usgs.gov/nrp/gwsoftware/modflow-gui/modflow-gui.html> and in the document titled Open-File Report-00-315 (Winston, 2000).

3.3 Groundwater flow equations and solution technique

The widely accepted theory governing the movement of groundwater through porous earth material is based on the coupling of principle of conservation of mass and

Darcy's law. For three-dimensional groundwater flow, the governing partial differential equation under transient condition may be written as:

$$\frac{\partial}{\partial x} \left[K_x \frac{\partial h}{\partial x} \right] + \frac{\partial}{\partial y} \left[K_y \frac{\partial h}{\partial y} \right] + \frac{\partial}{\partial z} \left[K_z \frac{\partial h}{\partial z} \right] \pm R = S_s \frac{\partial h}{\partial t} \quad (3.1)$$

where, K_x , K_y and K_z = hydraulic conductivities along x , y and z coordinates (L/T), respectively; h = potentiometric head (L); R = volumetric flux per unit volume representing source and/or sink of water ($L^3/L^3/T$); S_s = specific storage (1/L); t = time (T).

The above governing equation is based on the following assumptions: (i) groundwater is of constant density, (ii) the aquifer has constant storage characteristics, and (iii) absence of preferential flow. Along with the specification of boundary and initial conditions, Eq (3.1) constitutes a mathematical representation of the groundwater flow system.

The general form of the finite-difference representation for Eq (3.1) can be written according to Anderson and Woessner (1992) as:

$$Bh_{i-1,j,k} + Ch_{i,j+1,k} + Dh_{i+1,j,k} + Eh_{i,j-1,k} + Fh_{i,j,k+1} + Gh_{i,j,k-1} + Hh_{i,j,k} = \text{RHS}_{i,j,k} \quad (3.2)$$

where, $h_{i-1,j,k}$ = head at node $i-1, j, k$; $h_{i,j+1,k}$ = head at node $i, j+1, k$; and so on. B, C, D, E, F and G = functions of hydraulic conductivity between the nodes; H = function of both hydraulic conductivity and storage characteristics; RHS = storage and source and/or sink terms.

McDonald and Harbaugh (1988) developed the finite-difference solution of Eq (3.1) for the groundwater flow model MODFLOW using a block-centered formulation (i.e., nodes are taken to be at the center of the cells). The set of equations formed essentially follows the general form given by Eq (3.2). Figure 3.1 shows three-dimensional blocks of the aquifer system.

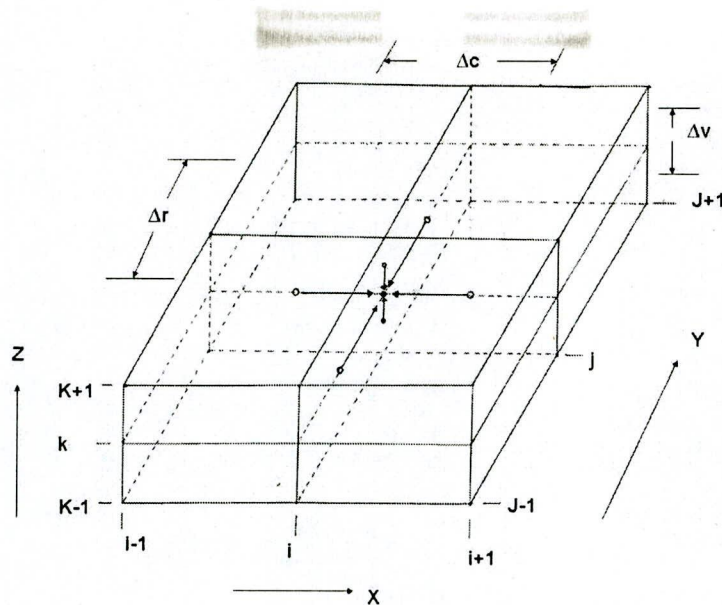


Figure 3.1 Discretization of three dimensional aquifer blocks

The finite-difference scheme emanates from the application of mass conservation and Darcy's law to cell i, j, k . The influx to this cell contributed by the six adjacent cells ($i - 1, j, k$; $i + 1, j, k$; $i, j - 1, k$; $i, j + 1, k$; $i, j, k - 1$ and $i, j, k + 1$) may be represented by the following equations.

For flow into the cell along the row direction:

$$q_{i,j+1/2,k} = KR_{i,j+1/2,k} \Delta c_i \Delta v_k \frac{(h_{i,j+1,k} - h_{i,j,k})}{\Delta r_{j+1}} \quad (3.3)$$

$$q_{i,j-1/2,k} = KR_{i,j-1/2,k} \Delta c_i \Delta v_k \frac{(h_{i,j-1,k} - h_{i,j,k})}{\Delta r_{j-1}} \quad (3.4)$$

For flow along the column direction:

$$q_{i+1/2,j,k} = KC_{i+1/2,j,k} \Delta r_j \Delta v_k \frac{(h_{i+1,j,k} - h_{i,j,k})}{\Delta c_{i+1}} \quad (3.5)$$

$$q_{i-1/2,j,k} = KC_{i-1/2,j,k} \Delta r_j \Delta v_k \frac{(h_{i-1,j,k} - h_{i,j,k})}{\Delta c_{i-1}} \quad (3.6)$$

For flow in the vertical direction:

$$q_{i,j,k+1/2} = KV_{i,j,k+1/2} \Delta r_j \Delta c_i \frac{(h_{i,j,k+1} - h_{i,j,k})}{\Delta v_{k+1}} \quad (3.7)$$

$$q_{i,j,k-1/2} = KV_{i,j,k-1/2} \Delta r_j \Delta c_i \frac{(h_{i,j,k-1} - h_{i,j,k})}{\Delta v_{k-1}} \quad (3.8)$$

where, q = volumetric fluid flow; h = head at the node; KR = hydraulic conductivity along the row; KC = hydraulic conductivity along the column; KV = hydraulic conductivity along the vertical direction; Δc = column width; Δr = row width; Δv = vertical thickness of the cell. The subscripts of each of these terms indicate the location or direction being considered.

Eqs (3.3) to (3.8) may be further simplified by combining the grid dimensions and hydraulic conductivity into a single constant termed as conductance. The resulting equations represent flows into cell (i, j, k) from internal sources. To account for flows into cell (i, j, k) from features or processes external to the aquifer such as areal recharge, evapotranspiration, drains, streams, or wells, additional terms may be incorporated into these equations. These flows may be dependent on the head in the receiving cell but independent of all other heads in the aquifer, or they may be entirely independent of head in the receiving cell. In general, for N external sources or stresses affecting a single cell, the combined flow may be expressed as:

$$QS_{i,j,k} = \sum_{n=1}^N p_{i,j,k,n} h_{i,j,k} + \sum_{n=1}^N q_{i,j,k,n} \quad (3.9)$$

where, $QS_{i,j,k}$ = external flow rate into cell (i, j, k) ; $h_{i,j,k}$ = head at the cell; $p_{i,j,k}$ = constant representing head-dependent flow; $q_{i,j,k}$ = constant representing head-independent flow.

The overall equation representing mass balance considering both internal and external sources and the aquifer storage characteristics may then be written as:

$$q_{i,j-1/2,k} + q_{i,j+1/2,k} + q_{i-1/2,j,k} + q_{i+1/2,j,k} + q_{i,j,k-1/2} + q_{i,j,k+1/2} + QS_{i,j,k} = SS_{i,j,k} \frac{\Delta h_{i,j,k}}{\Delta t} \Delta r_j \Delta c_i \Delta v_k \quad (3.10)$$

where, $\frac{\Delta h_{i,j,k}}{\Delta t}$ = finite-difference approximation for the derivative of head with respect to time; $SS_{i,j,k}$ = specific storage of cell (i, j, k) ; $\Delta r_j \Delta c_i \Delta v_k$ = volume of cell (i, j, k) .

Substituting the flow equations Eqs (3.3) to (3.8) expressed in terms of conductance, into Eq (3.10) gives the following finite-difference approximation for cell (i, j, k) :

$$CR_{i,j-1/2,k}(h_{i,j-1,k} - h_{i,j,k}) + CR_{i,j+1/2,k}(h_{i,j+1,k} - h_{i,j,k}) + CC_{i-1/2,j,k}(h_{i-1,j,k} - h_{i,j,k}) + CC_{i+1/2,j,k}(h_{i+1,j,k} - h_{i,j,k}) + CV_{i,j,k-1/2}(h_{i,j,k-1} - h_{i,j,k}) + CV_{i,j,k+1/2}(h_{i,j,k+1} - h_{i,j,k}) + P_{i,j,k}h_{i,j,k} + Q_{i,j,k} = \frac{SS_{i,j,k}(\Delta r_j \Delta c_i \Delta v_k)\Delta h_{i,j,k}}{\Delta t} \quad (3.11)$$

where, CR , CC and CV = conductance in row, column, and vertical directions, respectively; $P_{i,j,k}$ and $Q_{i,j,k}$ = summation of flows that are head-dependent and head-independent, respectively.

The time derivative of head ($\Delta \eta_{i,j,k} / \Delta \tau$) is approximated using a backward difference approach (i.e., approximation of this derivative extends backward in time from t_m , the time at which the flow terms are calculated). This scheme is used in MODFLOW over other techniques because it is always numerically stable (i.e., errors introduced at any time diminish progressively at succeeding times) (McDonald and Harbaugh, 1988).

Using the backward difference approach and rearranging and combining terms lead to the following final form of the finite-difference equation for cell (i, j, k) :

$$\begin{aligned}
& CV_{i,j,k-1/2} h_{i,j,k-1}^m + CC_{i-1/2,j,k} h_{i-1,j,k}^m + CR_{i,j-1/2,k} h_{i,j-1,k}^m + (-CV_{i,j,k-1/2} - CC_{i-1/2,j,k} \\
& - CR_{i,j-1/2,k} - CR_{i,j+1/2,k} - CC_{i+1/2,j,k} - CV_{i,j,k+1/2} + HCOF_{i,j,k}) h_{i,j,k}^m \\
& + CR_{i,j+1/2,k} h_{i,j+1,k}^m + CC_{i+1/2,j,k} h_{i+1,j,k}^m + CV_{i,j,k+1/2} h_{i,j,k+1}^m = RHS_{i,j,k}
\end{aligned} \tag{3.12}$$

$$\text{where, } HCOF_{i,j,k} = P_{i,j,k} - \frac{SC1_{i,j,k}}{(t_m - t_{m-1})} \tag{3.13}$$

$$RHS_{i,j,k} = -Q_{i,j,k} - \frac{SC1_{i,j,k} h_{i,j,k}^{m-1}}{(t_m - t_{m-1})} \tag{3.14}$$

$$SC1_{i,j,k} = SS_{i,j,k} \Delta r_j \Delta c_i \Delta v_k \tag{3.15}$$

h^m = head at time t_m ; h^{m-1} = head at time t_{m-1} .

For each of the variable-head cells in the flow domain, a system of equations based on Eq (3.12) can be written in matrix form as:

$$[A]\{h\} = \{q\} \tag{3.16}$$

where, $[A]$ = matrix of the coefficients of head, from the left side of Eq (3.12), for all active nodes in the mesh; $\{h\}$ = vector of head values at the end of time step m for all nodes in the mesh; $\{q\}$ = vector of the constant terms, RHS , for all nodes of the mesh.

For transient simulation, the head distributions at successive times are calculated by solving the system of equations simultaneously, given the initial head distribution. The resulting heads become the initial heads for the next iteration, and the process is repeated to obtain the new head distribution. The whole scheme is performed repeatedly for as many time steps as necessary to cover the entire simulation period.

3.4 Land subsidence

Land subsidence may be caused by aquifer-system compaction, drainage of organic soils, underground mining, hydro-compaction of near-surface deposits, natural

compaction, sinkholes, petroleum reservoir compaction, tectonism, thawing permafrost, and other processes (National Research Council, 1991). More than 80 percent of the identified subsidence worldwide is a consequence of human impact on subsurface water, and the increasing development of land and water resources probably will exacerbate existing land subsidence problems and initiate new ones. Likely hazards and environmental consequences of land subsidence include damage to engineering structures, earth fissures, enhanced coastal and riverine flooding, loss of saltwater and freshwater marsh ecosystems and reactivation of surface faults creating new potential pathways for surface runoff to contaminate aquifers.

For the purposes of this study, compaction of aquifer system refers to the change in vertical thickness that accompanies changing stresses on the aquifer system. A decrease in thickness of an interbed or confining unit (as shown in Figure 3.2) is referred to as a positive value of compaction, and an increase as a negative value. All aquifer system under go some degree of deformation in response to changes in stress. The seasonal cycle of recharge and discharge from unconsolidated heterogeneous aquifer system typically causes measurable elastic (recoverable) compaction (Riley, 1969; Poland and Ireland, 1988; Heywood, 1997) and commensurate uplift and subsidence (millimeters to centimeters) of the land surface (Amelung et al., 1999; Bawden et al., 2001; Hoffmann et al., 2001; Lu and Danskin, 2001). Removing water from storage in the fine-grained silts and clays interbedded in the aquifer system causes these highly compressible sediments to compact, resulting in land subsidence. Fine-grained interbeds and confining units within or adjacent to unconsolidated aquifers that undergo head changes related to the development of the groundwater resource are particularly susceptible to compaction. As groundwater is drained to the coarser-grained sediments that constitute the aquifers, compaction can occur elastically (recoverable) or inelastically (nonrecoverable) causing permanent subsidence, depending on the stress history of these interbeds and confining units. When an unconsolidated heterogeneous aquifer system is developed as a groundwater resource, most of the groundwater produced comes initially from storage in the aquifers, the more permeable interbeds, and the fringes of thicker interbeds and confining units. After some time, when lowered heads in the adjacent aquifers have established vertical head gradients

between the aquifers and the interior parts of the thicker or less permeable interbeds and confining units, groundwater flows from the interbeds and confining units to the aquifers. When the magnitude and areal extent of the head decline in the aquifers become large, a significant fraction of the water supplied to pumping wells can be derived from groundwater released from storage in the interbeds and confining units (Poland et al., 1975).

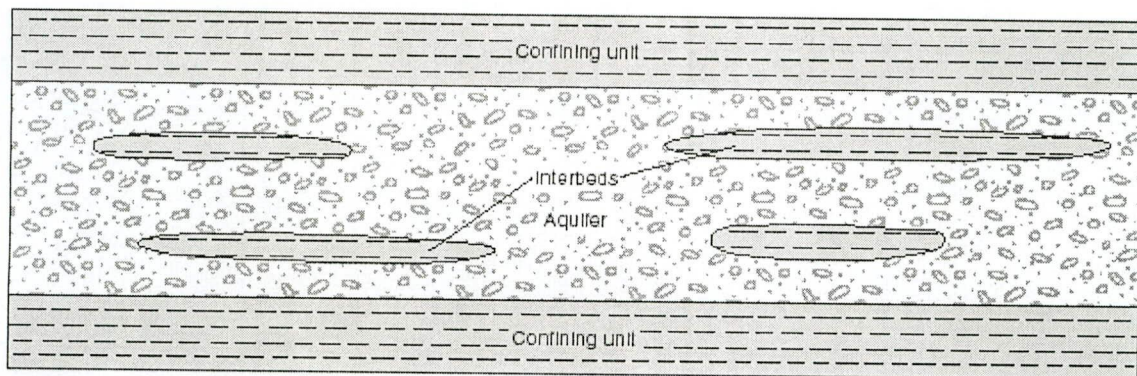


Figure 3.2. Poorly permeable interbeds within a relatively permeable confined aquifer, bounded at top and bottom by confining units.

In confined aquifer system, the water supplied to pumping wells is derived from the expansion of the water and the compression of the sediments that constitute the matrix or granular skeleton of the aquifer system (Jacob, 1940). Water compressibility and matrix compressibility, along with porosity, determine the storativity of the aquifers and of the interbeds and confining units in the aquifer system. Typically, skeletal (of aquifer matrix only) compressibilities (and therefore storativities) of interbeds and confining units are several orders of magnitude larger than compressibilities of coarser-grained aquifers, which are typically much larger than water compressibility. Therefore, virtually all of the water derived from interbed and confining-unit storage is due to the compressibility of the granular skeleton. The storativities of the interbed and confining units and the drainage of these units largely govern the compaction of these aquifer system and account for all but a negligible amount of the land subsidence that often accompanies groundwater development in this aquifer system.

3.4.1 Simulation of land subsidence with MODFLOW-2000

Simulation tools for characterizing, understanding, and predicting responses of aquifer system to stresses imposed by groundwater development are needed to help improve management of groundwater resources. The process of aquifer-system compaction has not been routinely incorporated in groundwater flow models. Because of the growing need to simulate aquifer-system compaction and land subsidence and to improve the capability to do so, a new simulation package was developed under MODFLOW-2000 (Harbaugh et al., 2000). The package is called the Subsidence and Aquifer-System Compaction Package and is referred to as the SUB Package or simply SUB in this report.

Only the vertical component of displacement is simulated using SUB. Though theoretically and practically some horizontal displacement occurs in aquifer systems in response to pumping and seasonal recharge/discharge stresses (Wolff, 1970; Carpenter, 1993; Helm, 1994; Hsieh, 1996; Bawden et al., 2001; Burbey, 2001), these displacements tend to be highly localized and occur near pumping wells, near local heterogeneities, and near the margins of groundwater basins. At regional scales and for regional groundwater flow and aquifer-system compaction models, the local horizontal displacements contribute little to the overall change in groundwater storage, and SUB ignores them.

3.4.2 Compressible layers

Compressible sediments in aquifer system may occur as discontinuous interbeds within aquifers or as extensive confining units adjacent to aquifers (Figure 3.3A). The term interbed is used to denote a poorly permeable bed within an aquifer (Figure 3.2). Such interbeds are assumed to (1) consist of highly compressible clay and silt deposits from which water flows vertically to adjacent coarse-grained beds, (2) be of insufficient lateral extent to be a confining unit that separates adjacent aquifers, (3) have relatively small thickness in comparison to lateral extent, and (4) have a significantly lower hydraulic conductivity than the surrounding sediments (considered to be aquifer material), yet porous

and permeable enough to uptake or release water in response to head changes in the adjacent aquifer material.

In basin-scale groundwater model like the one under present study, simulation of flow and storage changes in individual interbeds within aquifers is not practical because of difficulties in mapping the interbeds and also because high resolution of the finite-difference grid would be required to represent small geologic features. In contrast, flow and storage changes in individual confining units can be simulated in basin-scale flow models. To simulate flow and storage changes in confining units, one or more model layers must be used to represent each confining unit (Figure 3.3 B and C). Increasing the number of model layers increases the accuracy in simulating flow and storage changes but also increases computation time and computer storage requirements (Leake et al., 1994).

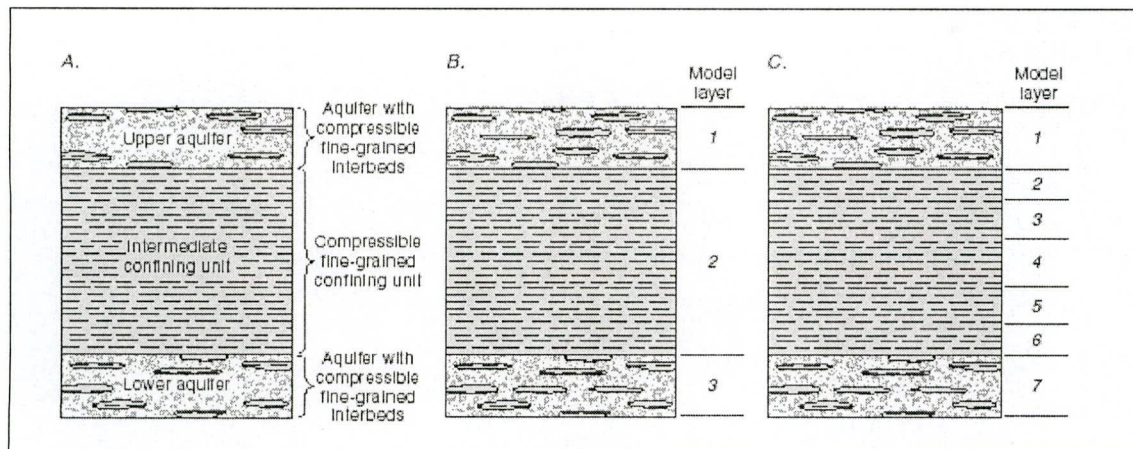


Figure 3.3 Compressible beds in an aquifer system and two approaches to represent the confining units in the MODFLOW simulation of aquifer-system compaction using the SUB Package. (A) Vertical section of an aquifer system with compressible sediments within and adjacent to aquifers; (B) Use of one model layer to simulate flow and storage changes in the confining unit; (C) Use of five model layers to simulate flow and storage changes in the confining unit.

3.4.3 Theory of land subsidence

The theoretical basis used in MODFLOW-2000 for the computation of subsidence is the Terzaghi's theory of one-dimensional consolidation that ignores horizontal strains and stress gradients.

Effective stress and stress changes

The equation of sediment compaction and changes in hydraulic head is based on the Terzaghi's (Terzaghi, 1925) principle of effective stress,

$$\sigma'_z = \sigma_z - p \quad (3.17)$$

where, σ'_z = vertical component of effective stress, σ_z = total vertical stress and p = fluid pore pressure. It is assumed that the total vertical stress remains constant with time, that is $\Delta\sigma_z = 0$. Thus, the method presented applies to sediment compaction subject to a constant geostatic load.

Analyses of saturated groundwater flow system commonly use hydraulic head rather than pore pressure. Total hydraulic head is the sum of the pressure head and the elevation head,

$$h = \frac{p}{\rho_w g} + z \quad (3.18)$$

where, h = total hydraulic head, ρ_w = density of water and g = gravitational acceleration and z = elevation head referenced to an arbitrary datum

A change in effective stress resulting from a given head change generally differs in confined and unconfined (water table) aquifers. In an unconfined aquifer, a change in head corresponds to a draining or re-wetting of pore space and results in a change in the geostatic load or the total stress on the underlying sediments as well as the pore pressure. The change in effective stress caused by a head change in the saturated portion of an unconfined aquifer can be described as (Poland and Davis, 1969)

$$\Delta\sigma'_z = -\rho_w g(1 - n + n_w)\Delta h \quad (3.19)$$

where, $\Delta\sigma'_z$ = change in vertical effective stress (positive for increase), n = aquifer porosity, n_w = moisture content in the unsaturated zone, as a fraction of total volume and Δh = change in head.

It may be noted that changes in head in an unconfined aquifer, which represent changes in the position of the water table, constitute a mass change in that aquifer. This represents a change in the total stress for all underlying confined aquifers.

In a confined aquifer, the total stress changes negligibly with changes in pore pressure as water is released from or is taken into storage by the saturated porous medium as a result of the compression or expansion of the medium and (or) the water. The change in water density associated with the expansion or compression of the water is negligible. Thus the change in effective stress for a given change in head can be expressed as (Poland and Davis, 1969)

$$\Delta\sigma'_z = -\rho_w g \Delta h \quad (3.20)$$

Compaction of compressible sediments

Changes in effective stress cause compaction and expansion of the sediments constituting many aquifer systems. In this report, the term compaction is used to describe a reduction in the thickness of a horizontal interbed/confining unit. A negative compaction signifies an expansion or increased thickness of the interbed/confining unit. The compressibility, α , of the sediment is defined as,

$$\alpha = \frac{\frac{dV}{V}}{d\sigma'} \quad (3.21)$$

where, dV = change in volume of a control volume with initial volume V , and $d\sigma'$ = change in effective stress.

Neglecting horizontal displacement, a one-dimensional vertical compressibility α_z can be defined as,

$$\alpha_z = \frac{-\frac{db}{b}}{d\sigma'_z} \quad (3.22)$$

Where, db = change in thickness of a control volume with initial thickness b and $d\sigma'_z$ = change in effective stress in vertical direction.

If the change in effective stress is only due to a change in pore pressure, Eq (3.20) can be used to express Eq (3.22) as

$$\rho_w g \alpha_z b = S_{sk} b = S_k = \frac{db}{dh} \quad (3.23)$$

Where, $S_{sk} = \rho_w g \alpha_z$, the skeletal specific storage, S_k = skeletal storage coefficient and dh = Change in hydraulic head

Now if S_s is the specific storage of an aquitard then its relation with skeletal specific storage (S_{sk}) can be defined as,

$$S_s = S_{sk} + S_{sw} \quad (3.24)$$

in which

$$S_{sw} = n\beta_w \rho_w g$$

where, S_{sw} = component of specific storage due to the compressibility of water, n = porosity and β_w = compressibility of water. For consolidating aquitards $S_{sk} \gg S_{sw}$ (Poland, 1984). So it can be concluded that the difference between skeletal specific storage and specific storage itself will be negligible.

Preconsolidation stress and inelastic compaction

Laboratory consolidation tests on sediment cores and measurements of aquifer-system compaction obtained from borehole investigations indicate that the compressibility, and thus the skeletal specific storage, can assume very different values depending on

whether the effective stress exceeds the previous maximum effective stress, termed the preconsolidation stress (Johnson et al., 1968; Riley, 1969; Jorgensen, 1980). If the effective stress remains less than the preconsolidation stress, a further increase in effective stress (or decrease in hydraulic head) causes a small elastic compaction in both coarse and fine-grained sediments. This compaction is recoverable if the effective stress returns to its initial value. In the elastic range, the compressibility, and thus ultimate compaction, is generally slightly greater for fine-grained sediments than for coarse-grained sediments. If the effective stress exceeds the preconsolidation stress, many fine-grained sediments compact inelastically. Inelastic compaction is explained by a physical rearrangement of the grains in the sediments (Meade, 1964) and is largely permanent. Inelastic compaction of coarse-grained sediments is generally negligible compared to that of fine-grained sediments. However, for many cases applicable to aquifer-system compaction where incremental changes in effective stress are typically small, Eq (3.23) can be linearised as

$$\Delta b = S_k \Delta h \quad (3.25)$$

where, Δb = change in thickness of the sediment layer and Δh = change in hydraulic head

Eq (3.25) is the final form of equation, which is used to calculate the layer compaction numerically and the ultimate subsidence of the model sediment layers.

To account for the marked change of the skeletal specific storage when the effective stress exceeds the preconsolidation stress, two separate values are used

$$\begin{aligned} S_{sk} &= S_{ske} \text{ for } \sigma'_z < \sigma'_{z(pc)} \\ &= S_{skv} \text{ for } \sigma'_z \geq \sigma'_{z(pc)} \end{aligned} \quad (3.26)$$

where, S_{ske} = elastic skeletal specific storage, S_{skv} = inelastic or virgin skeletal specific storage, and $\sigma'_{z(pc)}$ = preconsolidation stress. The skeletal component of inelastic specific storage is not a constant but rather is a function effective stress. Jorgenson (1980) relates the two quantities by

$$S_{skv} = \frac{0.434C_c\gamma_w}{\sigma'_z(1+e_0)} \quad (3.27)$$

where, C_c = compression index, e_0 = initial void ratio

For many fine-grained sediments, S_{skv} is much greater than S_{ske} . Using two constant values for the skeletal specific storage, one each for stresses greater than and less than the preconsolidation stress, linearizes the nonlinear stress/compaction relation with respect to the preconsolidation stress.

3.4.4 Numerical simulation of subsidence in compressible sediments

For the compressible sediments flow per unit volume q is as follows

$$q = \gamma S_{sk} \frac{\partial h}{\partial t} \quad (3.28)$$

with

$$\begin{aligned} S_{sk} &= S_{ske} \quad \text{for } h > h_{min} \\ &= S_{skv} \quad \text{for } h \leq h_{min} \end{aligned}$$

where, h_{min} is the lowest previous head or the equivalent preconsolidation stress expressed in terms of preconsolidation head.

The term q can be combined with the source term, R , or added to the right-hand side of Eq (3.1). S_{sk} is the skeletal specific storage, which assumes an elastic or inelastic (virgin) value depending on whether the head is above or below h_{min} . Here, h_{min} is used to define the preconsolidation stress in terms of a preconsolidation head. It can be noted that this is equivalent to Eq (3.26), with the assumption that the total stress (geostatic load) remains constant, and therefore assumes that the water levels in any overlying unconfined

aquifers remain approximately constant. Similarly, the compaction of these interbeds/confining units can be determined directly from Eq (3.25).

Depending on the flow package used, the MODFLOW-2000 program (Harbaugh et al., 2000) requires the specification of either the dimensionless storage coefficient for each model layer [Block-Centered Flow (BCF) Package)], or the specific storage for each model layer [Layer-Property Flow (LPF) Package]. During this study the LPF package was used to define the properties of various layers. Many interbeds/confining units in a model layer can be grouped into a system of interbeds/confining units. A system of interbeds/confining units is assigned total elastic and total inelastic skeletal storage coefficients in the SUB input file. A representative skeletal storage coefficient for all N interbeds/confining units of a system can be computed by:

$$S_k = \sum_{i=1}^N S_{k_i} = \sum_{i=1}^N S_{sk_i} b_i \quad (3.29)$$

Storage changes and the corresponding compaction in the interbeds/confining units are computed at every time step. These computations must account for any elastic storage changes from changes in head in a time step above the level of the preconsolidation head at the end of the previous time step, as well as any inelastic storage changes from decreases in head below the preconsolidation head. The expression that accounts for total flux (flow per unit area), q , into or out of elastic and (or) inelastic skeletal storage at cell i for time step m is

$$q_i^m = \frac{S_k^m}{\Delta t^m} (h^m - H^{m-1}) + \frac{S_{ke}}{\Delta t^m} (H^{m-1} - h^{m-1}) \quad (3.30)$$

where

$$\begin{aligned} S_k^m &= S_{ke} \quad \text{for } h^m > H^{m-1} \\ &= S_{kv} \quad \text{for } h^m \leq H^{m-1} \end{aligned}$$

In Eq (3.30) the superscripts denote the time step. The quantities h^m and H^{m-1} are the head at the end of time step m and the preconsolidation head at the end of time step $m-1$, respectively, and Δt^m is the length of the m th time step. The compaction at cell i during time step m is computed by multiplying q_i^m by the length of the time step Δt^m . The method implicitly selects the appropriate specific storage at the end of a time step and apportions storage changes to either elastic, inelastic, or both components within a time step.

Using this approach permits the use of larger time steps without incurring significant errors caused by the typically large difference between the inelastic and elastic skeletal storage coefficients (Leake, 1990; Leake and Prudic, 1991).

Equations (3.28) and (3.30) account only for water derived from skeletal storage in the interbeds/confining units. Though water released from or taken into storage related to the compressibility of water commonly is negligible compared with the larger storage changes accompanying inelastic compaction in the interbeds/confining units, such changes can be accounted for by adding an appropriate storage quantity in the flow package used. For the LPF Package, the specific storage owing to the expansion and compression of water, S_{sw} , should be included.

Chapter 4

STUDY AREA

4.1 Geographical location

The area under this study is the central region of the country. It is bounded on the west by river Padma on the east by river Meghna and old Brahmaputra. The study area includes the districts of Dhaka, Gazipur, Manikganj, Narshandi and Narayanganj. The northern boundary of the study area has been taken as the northern boundaries of the districts of Manikganj, Dhaka, Gazipur and Narshindi. A map of the study area is shown in Figure 1.1.

4.2 Rationale for selecting the study area

The main focus of the study area is the Dhaka Metropolitan City. But the boundary conditions of the lower geologic formations for setting up the groundwater model along the periphery of Dhaka City area are yet unknown. So the boundary of the model was taken far from the centre to have minimum or no influence on the results of the modeling study inside Dhaka City. The model external boundaries are selected along some well dominating features like rivers Padma, Meghna, Old Brahmaputra.

4.3 Geology of the study area

Dhaka metropolitan city by and large is occupied by the southern fringe of the Madhupur Tract. The rest of the area is covered by the flood plains of the Jamuna, Padma and Meghna rivers. Madhupur clay is the weathered product of Pleistocene clay, which stands higher than the surrounding flood plains. There is a great difference in the elevation throughout the Dhaka City. The elevation difference is reflected by the distinct land forms viz. high lands, low lands, abandoned channels and depressions.

4.4 Topography of the study area

The relief of the study area is entirely an alluvial deltaic plain. The alluvial plain falls south-eastward from a height of 17.3 m PWD at the Jamuna-Ganges confluence to 1.2 m PWD at the extreme south of the study area. The city area, the central part of Greater Dhaka is occupied by the southern half of the Modhupur Tract. Ground elevation in the city varies from 0.5 to 12 m PWD. About 60% to 70% of the city area includes low lands, abandoned channels and depressions and the elevation of these areas vary from 0.5 to 5 m PWD. The topographic elevation of the entire study area is depicted in Figure 4.1.

4.5 Use of land

The use of the land within the study area has important influence on the recharge of the groundwater. The potential recharge from rainfall has been calculated from the records of rainfall gauging stations within the study area. Previous studies conducted by EPC and MMP(1991) reveals that changes in cropping pattern have only a limited effect on natural recharge to the groundwater. However recharge from irrigation return flow can play a significant role. The pattern of land use for the urban and industrial development is an important factor to consider the amount of recharge from the natural sources. Obviously this will be greatly reduced in the densely built-up areas.

4.6 Climate

The study area being the central part of the country lies within the humid sub-tropical zone of moderately warm temperature, high humidity and high annual rainfall. The mean annual rainfall in the study area ranges from about 1800 mm in the western

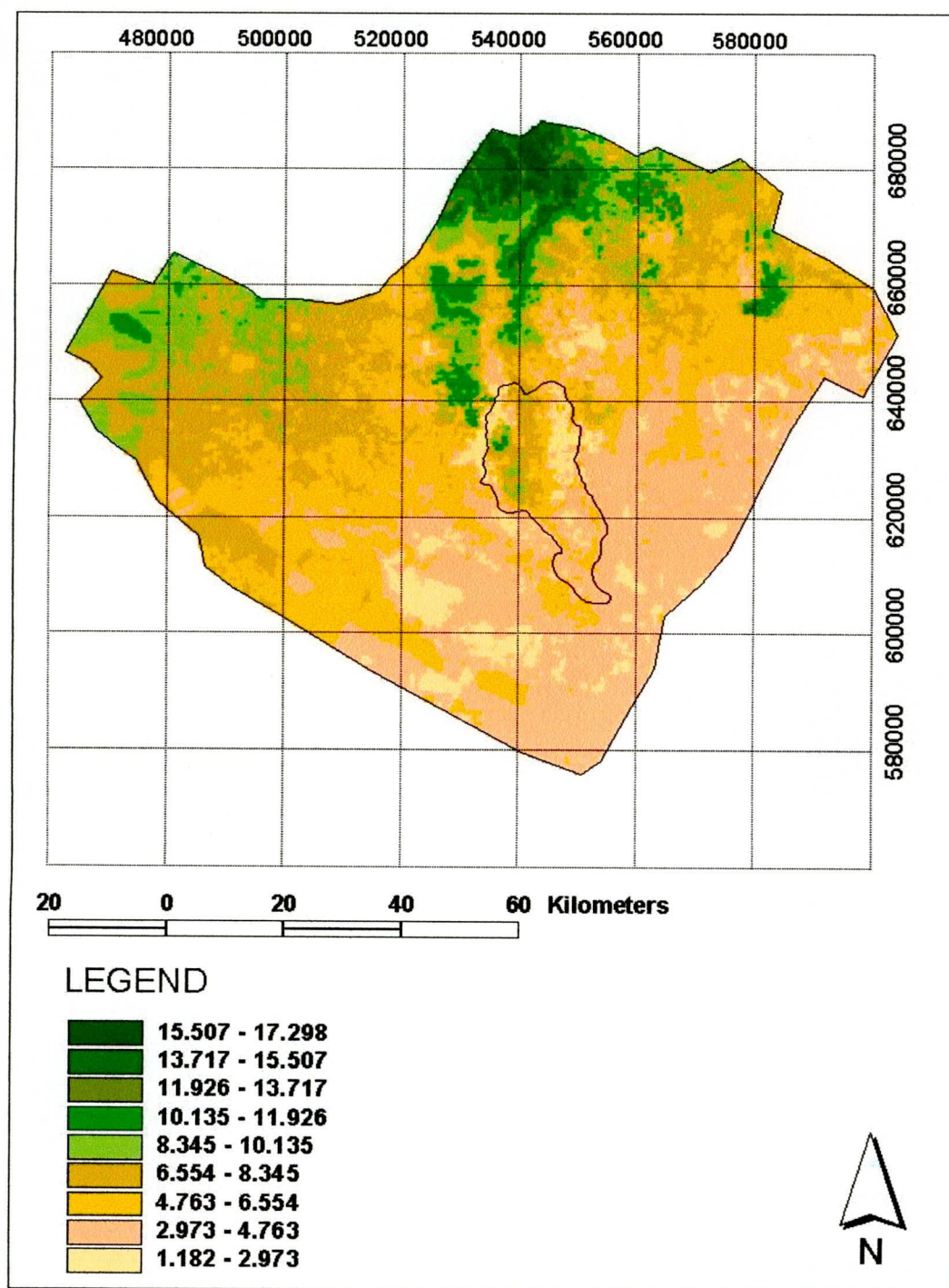


Figure 4.1 Topographic elevation of the study area

part to about 2400 mm in the eastern part. The long term areal average rainfall is 2130 mm, most of which falls in the months of June to September. Temperature varies from about 10 °C at night during December and January to over 35 °C in day during April and May. The annual evaporation of Dhaka Region ranges from 840 to 1020 mm. Table 4.1 shows the location and type of rainfall gauging stations in the study area.

Table 4.1 Rainfall stations in the study area

Sl	Station number	Station name	Station type	Easting(X)	Northing(Y)
1	R010	Daulatpur	RFL	482073	645921
2	R402/E43	Bhagyakul	RFLEVP	515558	608547
3	R412	Nawabganj	RFL	515763	617810
4	R365	Munshiganj	RFL	557027	601905
5	R519/E46	Shimrail	RFLEVP	544438	618072
6	R009/E13	Dhaka	RFLEVP	537707	628821
7	R020	Manikganj	RFL	500202	639831
8	R031	Savar	RFL	526254	637647
9	NCE1	Maona	RFLEVP	532148	674169
10	R017	Joydebpur	RFL	542690	654338
11	R037	Sreepur	RFL	548634	674087
12	R076	Narsingdi	RFL	571411	640804
13	R079	Shibpur	RFL	574774	662333

Note: RFL - Rainfall, RFLEVP - Rainfall and evapotranspiration

4.7 Rivers

A Large number of rivers flow through the study area. Some degree of hydraulic continuity exists between the rivers and the aquifer system. Only the major rivers have been included within the groundwater model as it is in regional scale. Rivers that have been considered in the study area are listed in Table 4.2. BWDB has number of water level gauging stations at various points along these rivers. The river water level is recorded periodically and maintain at these stations. List of the water level gauging stations in the study area and their locations are shown in Table 4.3 and Figure 4.2 respectively.

Table 4.2 Rivers in the study area

Sl	External Rivers	Internal Rivers
1	Jamuna	Balu
2	Padma	Bangshi
3	Upper Maghna	Buriganga
4	Old Brahmaputra	Dhaleshwari
5		Kaliganga
6		Lakhya
7		Tongikhal
8		Turag

Table 4.3 List of water level stations in the study area

Sl	Station ID	Station Name	River Name	Station Type	Easting	Northing
1	91.9L	Baruria	Padma	WLQ	478530	632379
2	137A	Taraghat	Kaliganga	WLQ	495998	638682
3	68	Tilli	Kaliganga	WLQ	496362	647288
4	50	Porabari	Jamuna	WL	480816	686103
5	93.5L	Mawa	Padma	WLQ	520501	594352
6	14.5	Nayarhat	Dhaleshwari	WLQ	523534	644258
7	70	Kalatia	Dhaleshwari	WLQ	526266	623960
8	42	Dhaka Mill Barak	Buriganga	WL	543407	619999
9		Savar	Dhaleshwari	WL	525657	634561
10	302	Mirpur	Turag	WLQ	534155	630331
11	200	Tongi Khal	Tongi Khal	WLQ	540836	641049
12	7.5	Demra Balu	Balu	WLQ	550121	625651
13	179	Demra lakhya	Lakhya	WLQ	552731	625651
14	7	Pubail	Balu	WLQ	550202	646603
15	301	Kaliakoir	Dhaleshwari	WLQ	521262	663199
16	9	Kaoraid	Old Brahmaputra	WLQ	551915	688646
17	230.1	Bhairab Bazar	Meghna	WL	601121	660162
18	S277	Chandpur	Meghna	WL	569696	565692
19	71A	Rekabibazar	Meghna	WL	574781	607880
20	275	Baidar Bazar	Meghna	WL	564812	614780

Note: WL – Water level, WLQ – Water level and discharge

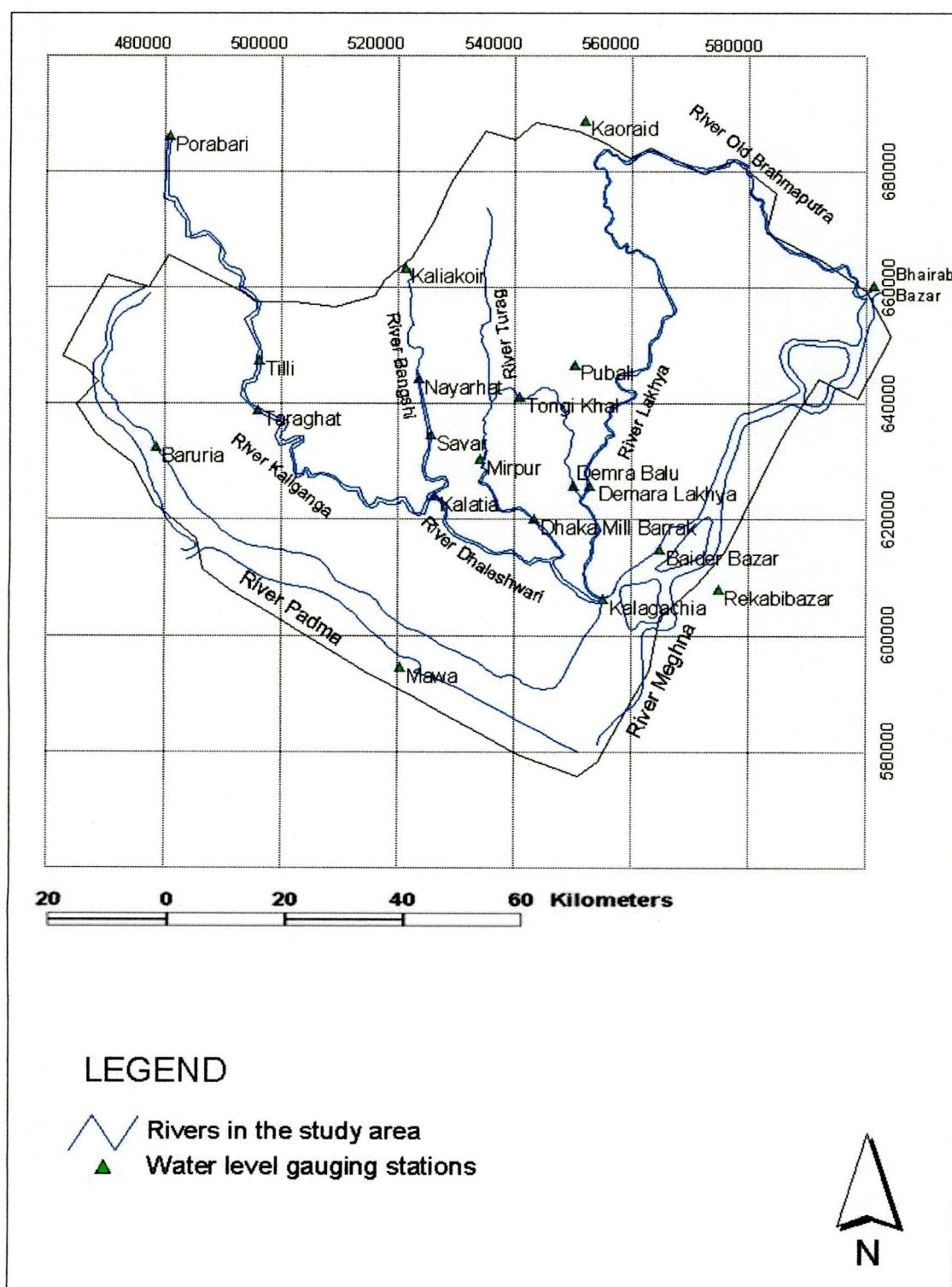


Figure 4.2 Rivers and water level stations in the study area

4.8 Hydrogeology

Occurrence of aquifer

Detailed information about the subsurface geology and aquifer system are available with the BWDB, WASA and IWM bore log data. The upper two aquifer system beneath the Dhaka City is complex in nature and function as a leaky confined aquifer. The thickness of different formation layers as well as the aquifer properties is found to vary greatly between places. A simplified configuration of this aquifer system is presented below:

Upper aquitard

This is the top most soil layer composed of finer plastic concentration of impervious clay and low permeable silt. The thickness ranges from 6 to 10 meter on average.

Upper aquifer

Below the upper aquitard, the formation layers are mainly composed of fine to medium fine sand to a depth of 30 to 45m. Aquifer test data indicate that the whole of the upper aquifer sequence behaves as a single aquifer system in which all the units are hydraulically connected. Shallow and hand pump tube wells extract water from this aquifer.

Intermediate aquitard

This may be considered as the bottom of the upper aquifer. It is composed of silt and clay with little thickness in some places of the study area.

Intermediate aquifer

Below the lower aquitard, the intermediate aquifer is composed of medium to coarse sand with a thickness from 90 to 120m depth. This is the main source of municipal

and irrigation water supply. It is found that in majority of places the main aquifer can be classified as semi confined in nature.

Deep aquitard

Recently DWASA has explored to a depth around 300 m beneath Dhaka City to extract groundwater from deep aquifer. Between the intermediate and deep aquifer there lies a thick clay layer the composition of which is nearly similar to that of the intermediate aquitard. Its thickness ranges from 7 to 73m throughout the study area.

Deep aquifer

Below the lower aquitard lies the deep aquifer, which is composed of medium to coarse sand and thickness ranging from 9 to 130m throughout the model area. The hydraulic head of the deep aquifer is quite encouraging and in Dhaka City area it is 16 to 18 m below the ground surface.

Chapter 5

METHODOLOGY

5.1 General

The methodology followed in the present study to fulfill the objectives is a blend of field data analysis and model application. The selected study area is a regional scale basin and required huge amount of field data to be collected, analyzed and processed for the model application process. The hydro-geology of the area is very complex in nature and the data available is not sufficient to make an accurate groundwater model. The general approach that has been followed in the current study can be summarized in the flowchart given in Figure 5.1.

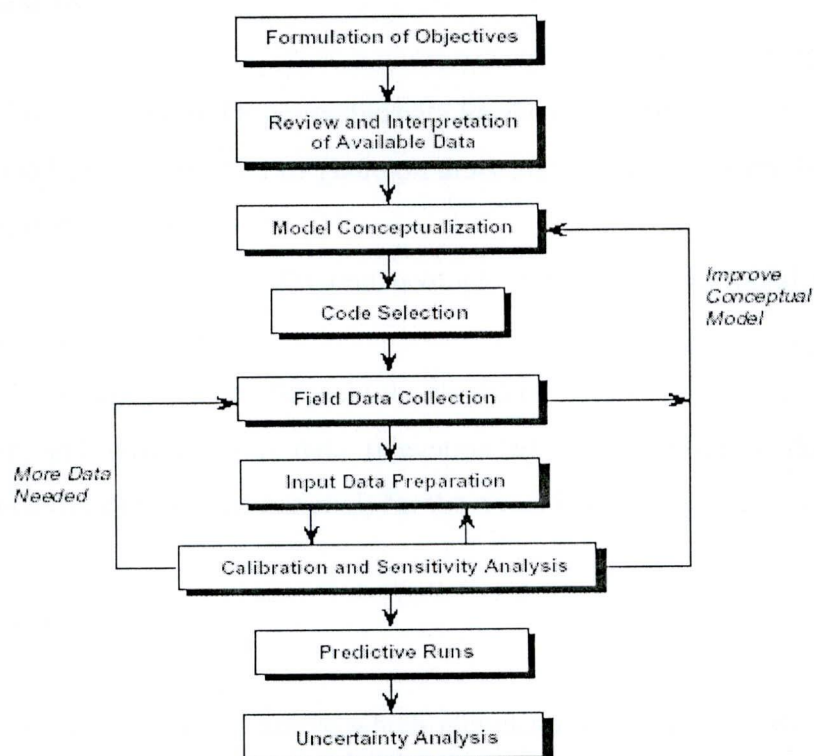


Figure 5.1 General methodology applied in present study

5.2 Data requirement

A large amount of data of different types had to be collected from various sources. Data was collected for the study and preparation of groundwater model mainly for the duration 2000 to 2004. All elevation data used in the model were converted to m PWD. The relations between m PWD and other established datum is as under:

New Mean Sea Level (NMSL) = Old Mean Sea Level (OMSL) – 0.40 m (approximate)

OMSL = m PWD – 0.338 m (approximate)

Data required for the present study and preparation of the groundwater model can be grouped under two categories as (a) Time invariant data and (b) Time variant data. Category wise data requirement for the groundwater model is furnished below:

Time Invariant Data

- Land use, soil type and topographic data for the study area.
- Top and bottom elevation of geologic units that defines the various layers of the groundwater model.
- Observation well data at different geologic units to set the initial condition and compare the model results.
- Specific storage and specific yield for all geologic units.
- Layout and cross-section data (elevation of river bottom, width, depth and conductivity of river bed material) for the rivers in the study area.

Time Variant Data

- Data for groundwater recharge which includes rainfall for the whole study area, urban and irrigation return flow.
- Water level data at the gauging stations along the external and internal rivers.

- Groundwater abstraction that includes DWASA abstraction, private abstraction and irrigation abstraction.

5.3 Data collection and analysis

5.3.1 Recharge

Recharge for groundwater and land subsidence model consists of following components.

- a) Recharge from rainfall
- b) Urban return flow and
- c) Irrigation return flow

Rainfall

Monthly rainfall data from 2000 to 2004 has been collected from IWM. Original source of the data is the Climate Division of BMD. There are total 13 rainfall gauging stations in the study area. Raw data in millimeters of rainfall is recorded at the stations on daily basis. Missing data were filled up by taking the averages of the data of times corresponding to other years.

Urban return flow

Urban return flow is due to leakage from water distribution and sewerage system. It forms an important component of ground water recharge. The total volume of urban return flow is estimated as a percentage of total volume of water supplied for the city dwellers. Total volume of supplied water is composed of DWASA and private abstraction and the surface water contribution from the treatment plants. The return flow from surface water supply is very less and therefore not included. Urban return flow is considered within the Dhaka City only. Due to variation in population density, urbanization and concentration of DTWs the amount of urban return flow is not uniform over the Dhaka City. Considering these factors the urban return flow is apportioned on the basis of sub-sector area as shown in Figure 5.2. Sub-sector wise return flow distribution factors have been kept same as BUET (2000) as shown in Table 5.1. The proportion factors were estimated considering density of distribution network, the

distribution of abstraction wells, industrial and populated area as well as the age of the distribution system.

Irrigation return flow

Irrigation abstraction and hence the irrigation return flow is assigned to the model area out side of Dhaka City. In this study 20% of the total irrigation abstraction was considered for irrigation return flow. It is distributed on the basis of thana area in the model.

Table 5.1 Sub-sector wise urban return flow proportion factors

Sub-sector no	Sub-sector	Urban recharge distribution proportion factors	
		Value used by DWASA(1990)	Value used by BUET (2000)
1	Mahallah	0.090	0.090
2	Lalbagh	0.090	0.090
3	Kotwali	0.070	0.070
4	Sher-e-Bangla Nagar	0.010	0.010
5	Dhanmondi	0.040	0.040
7	Mirpur West	0.020	0.030
8	Gabtali	0.040	0.040
9	Mirpur East	0.080	0.090
10	Shewrapara	0.080	0.090
11	Ramna	0.100	0.090
12	Motijheel	0.100	0.090
13	Rampura	0.080	0.080
14	Tejaon	0.080	0.080
15	Airport Road	0.020	0.020
16	Gulshan/Banani	0.050	0.040
17	Baridhara	0.025	0.020
27	Uttara	0.025	0.030
Total		1	1

5.3.2 River water level

River water level as maintained by BWBD water level gauging stations for the duration 2000 to 2004 has been collected from BWBD and IWM. From the raw data

monthly average data is obtained. Water level in the river reach between the gauging stations is set by linear interpolation.

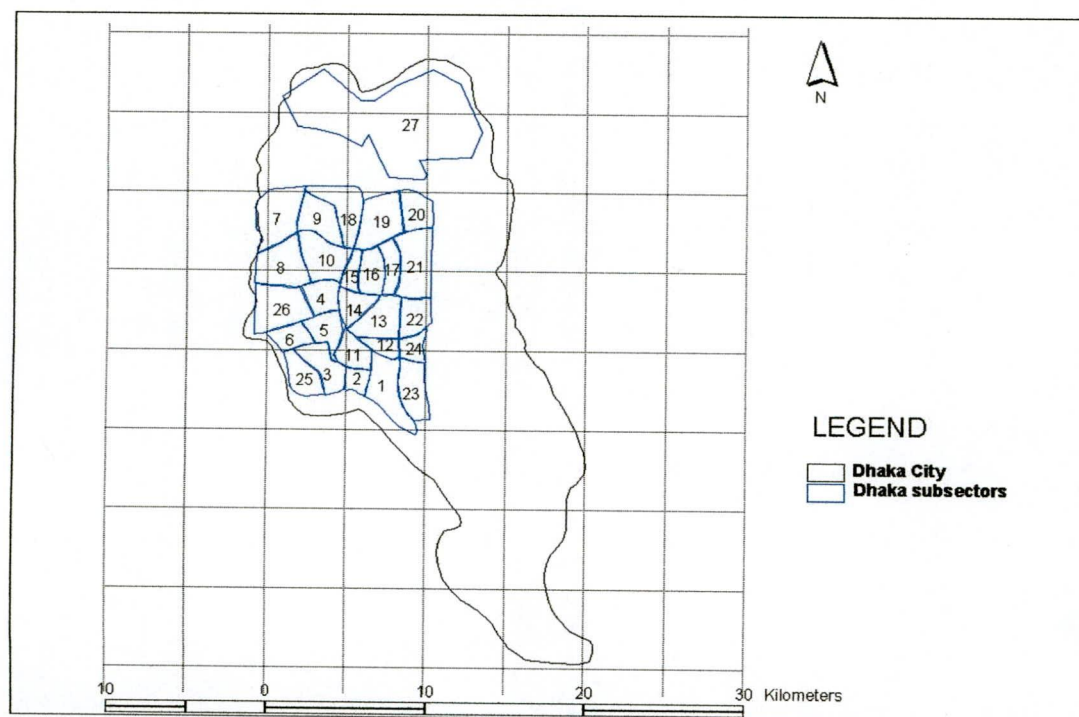


Figure 5.2 Division of sub-sectors in Dhaka City for proportioning urban return flow

5.3.3 River cross section

River cross section data for all the external and internal rivers has been collected from IWM. From these data river bottom elevation at various locations is obtained to be used in the model. Cross sections of rivers within the study area are shown in Appendix A. The data for the conductance of riverbed material has been collected from BUET (2000). All these data were used to define the external and internal boundaries of the groundwater model.

5.3.4 Groundwater observation data

All data regarding observation wells in the upper and intermediate aquifers in the study area has been collected from BWBD. Information regarding deep monitoring wells

was collected from IWM. There are total 85 monitoring wells within the study area out of which 19 wells are located within Dhaka district. But the water level records for these wells are not maintained properly. Water level found in raw data had to be converted into elevation with respect to m PWD. Again the location of screen pipes of these wells indicates that they belong to upper aquifer. Only 3 monitoring wells were identified having water level records up to 2003 that corresponds to the intermediate aquifer. Most of the monitoring wells that were installed by DWASA in intermediate aquifer have become inoperative.

DWASA is pumping groundwater from the upper and intermediate aquifers for more than four decades. Due to continuous pumping this aquifer system has become highly depleted with about 2 to 3 m declination in hydraulic head each year. This is evident from the observed hydrographs of some of the important locations in Dhaka City area as shown in Figure 5.3 to 5.13. It is revealed from observed hydrographs at Savar, Dohar, Singair, gazipur and Louhajong (observation wells at these locations stand close to the river as shown in Figure 5.28) that there is strong interaction between the river and aquifer near the river and the water table is at a much higher elevation in those areas than in the center of Dhaka City.

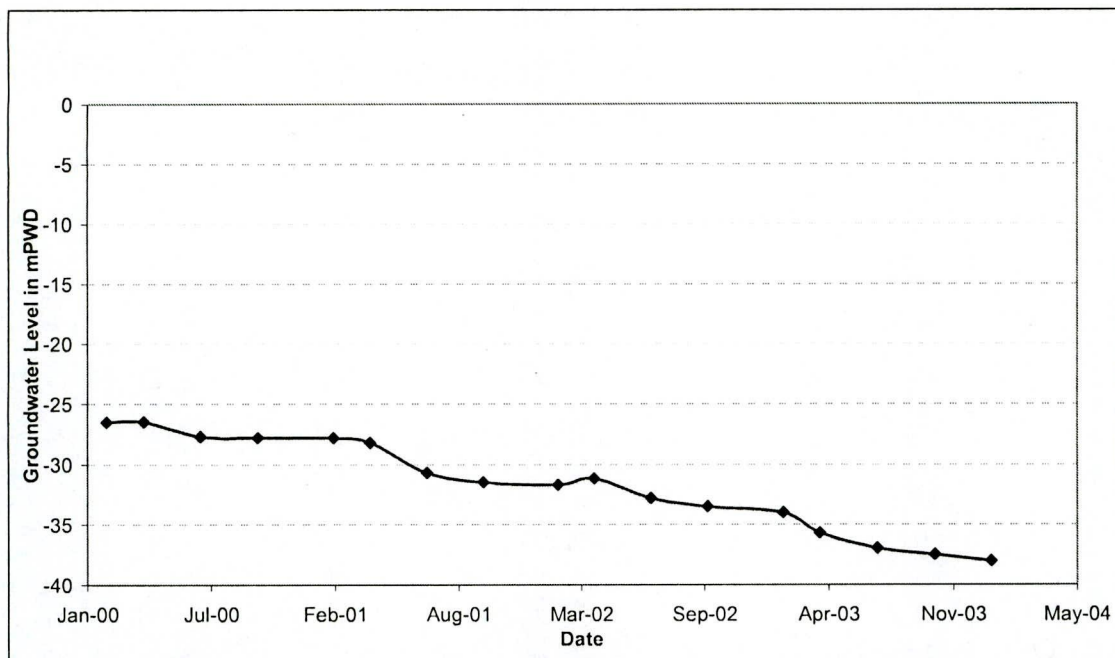


Figure 5.3 Observed hydrograph at Lalbagh 1 (intermediate aquifer)

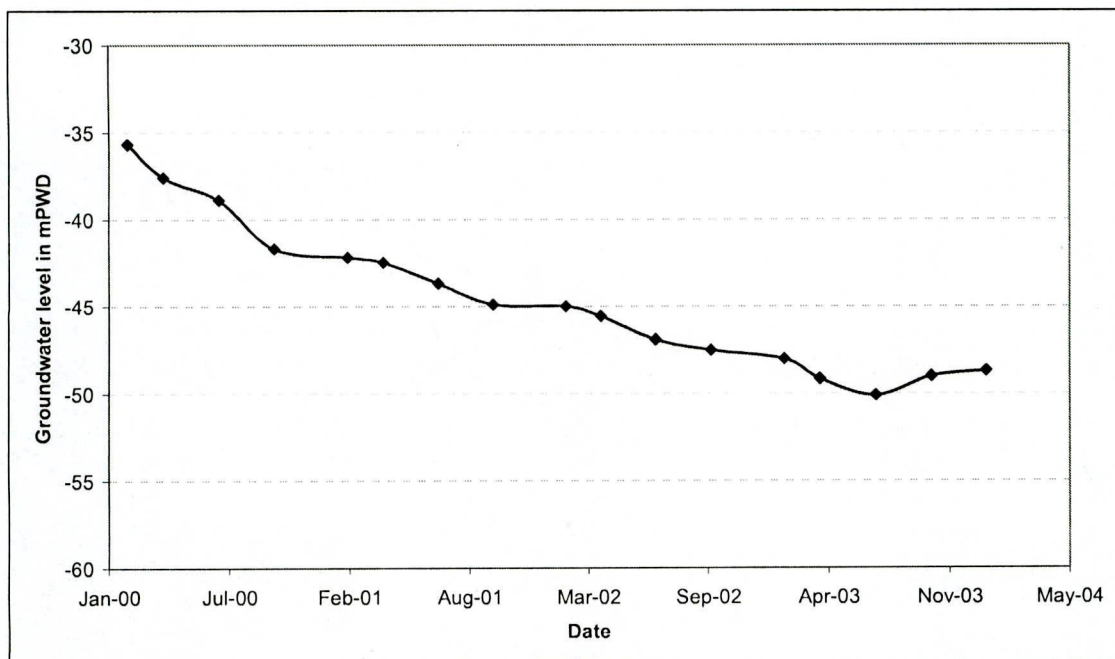


Figure 5.4 Observed hydrograph at Motijheel (intermediate aquifer)

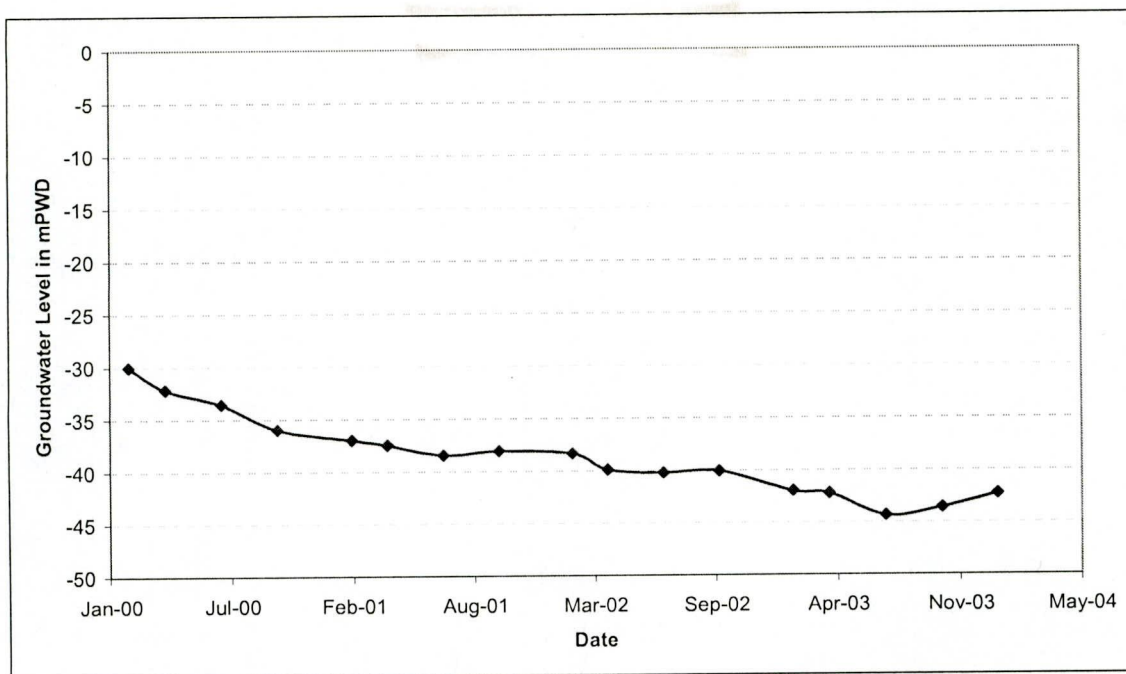


Figure 5.5 Observed hydrograph at Gulshan (intermediate aquifer)

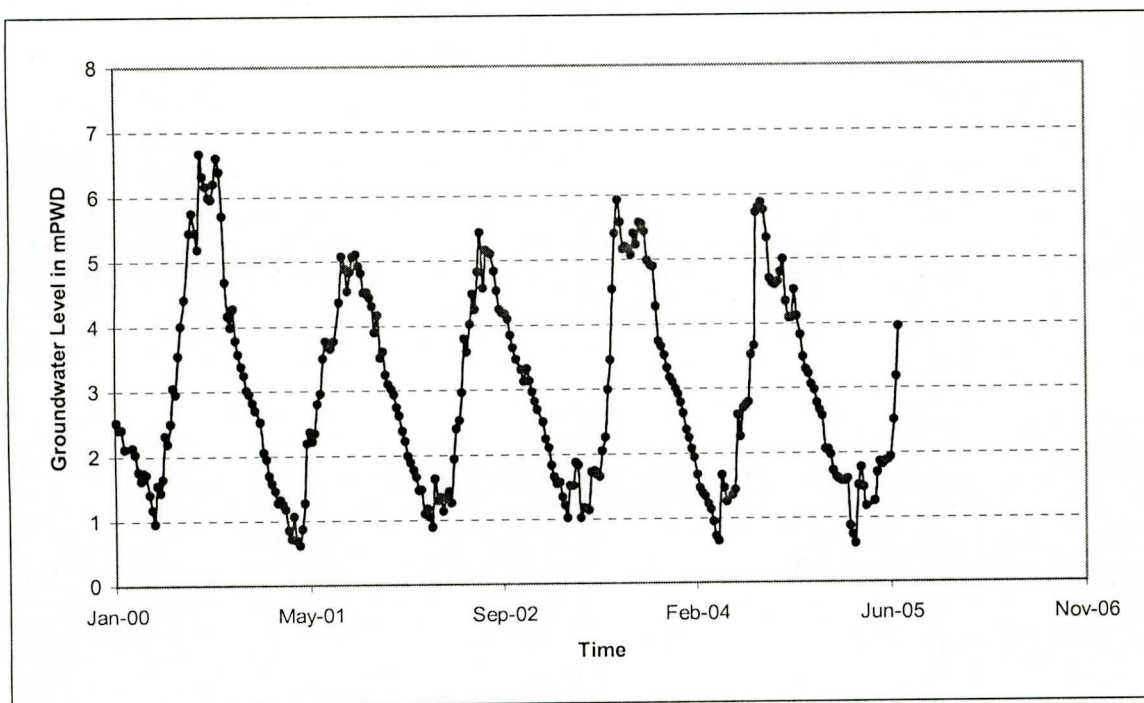


Figure 5.6 Observed hydrograph at Dohar (upper aquifer)

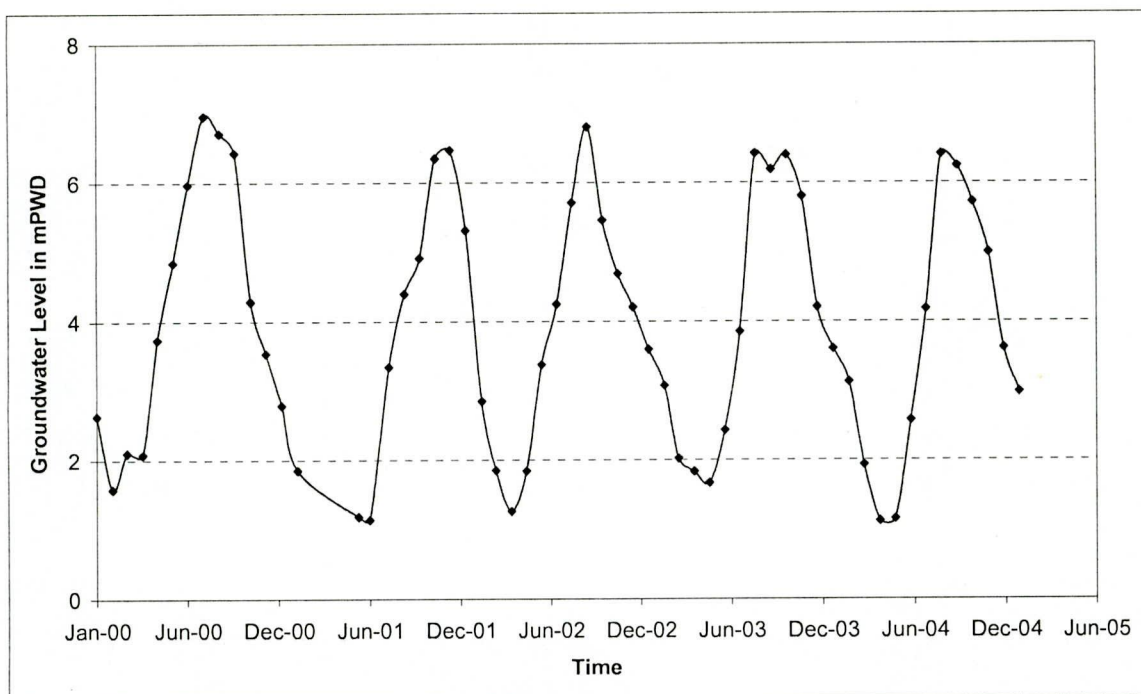


Figure 5.7 Observed hydrograph at Singair (upper aquifer)

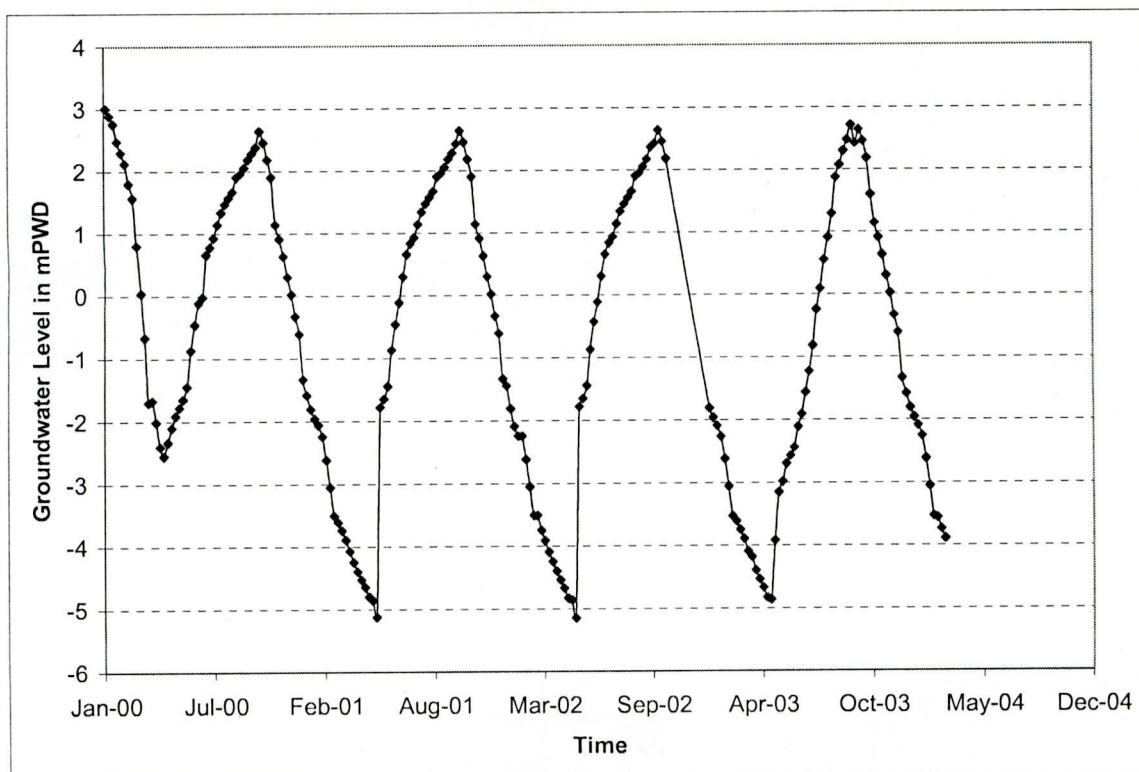


Figure 5.8 Observed hydrograph at Gazipur Sadar (upper aquifer)

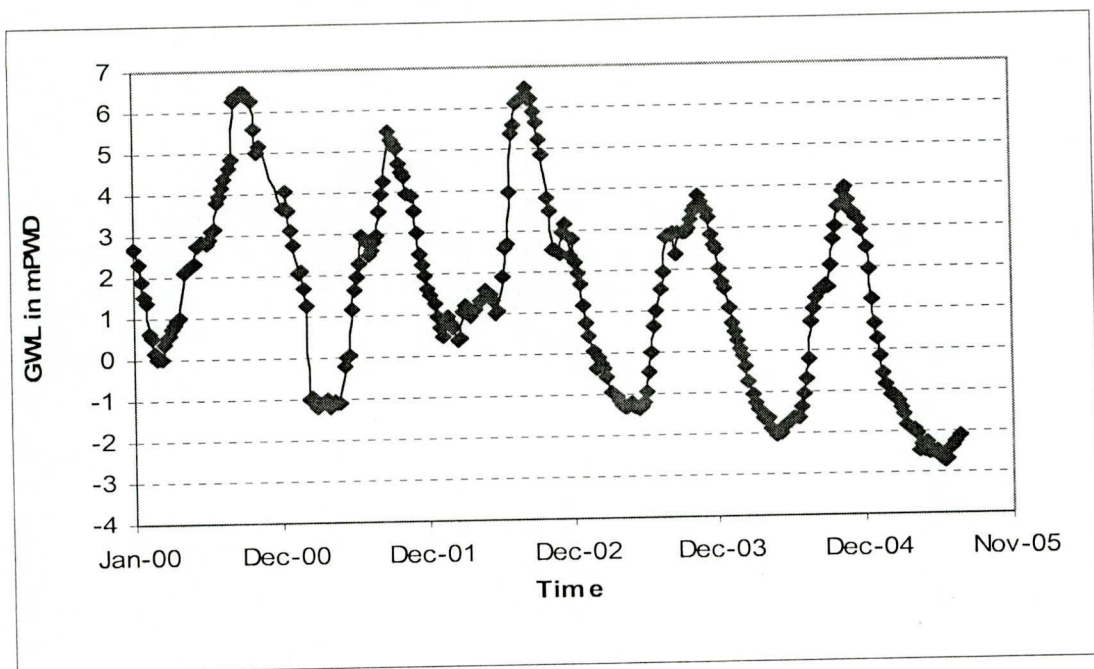


Figure 5.9 Observed hydrograph at Savar (upper aquifer)

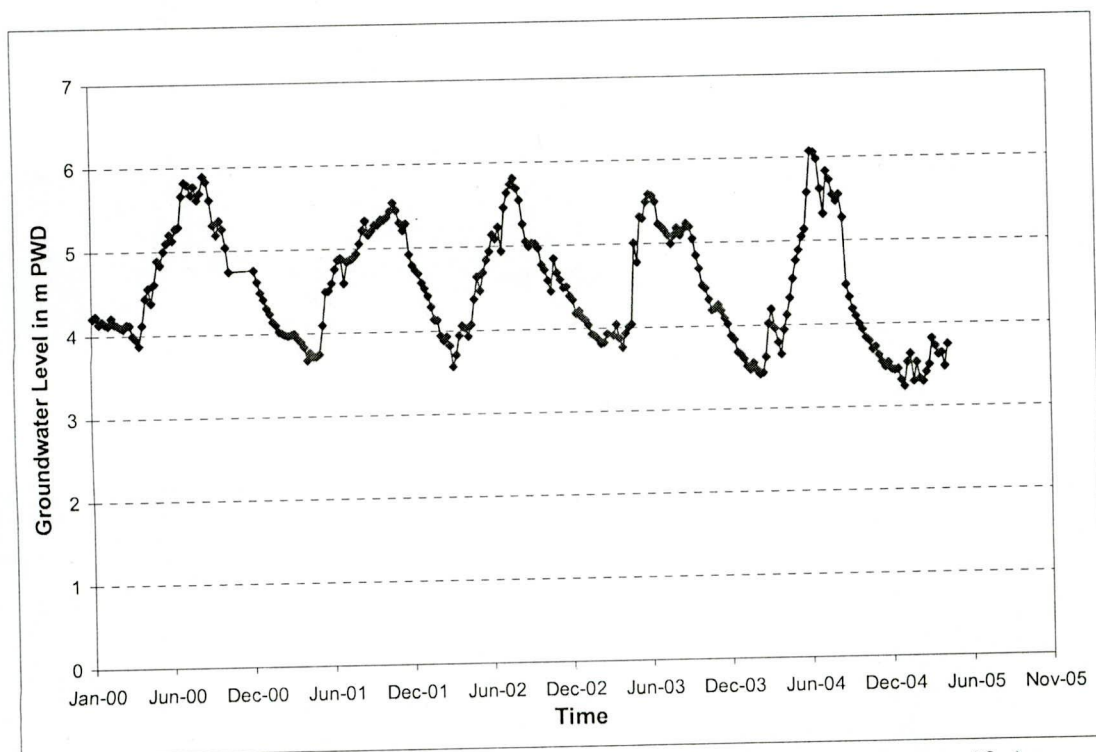


Figure 5.10 Observed hydrograph at Palash, Narshingdi (upper aquifer)

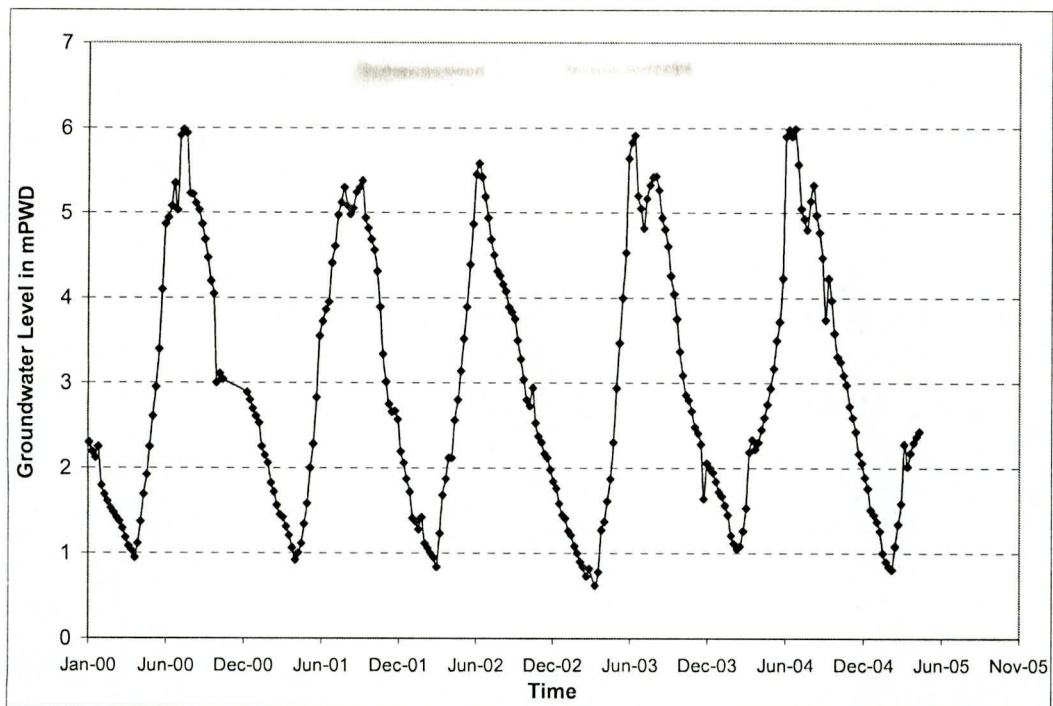


Figure 5.11 Observed hydrograph at Louhajong, Munshiganj (upper aquifer)

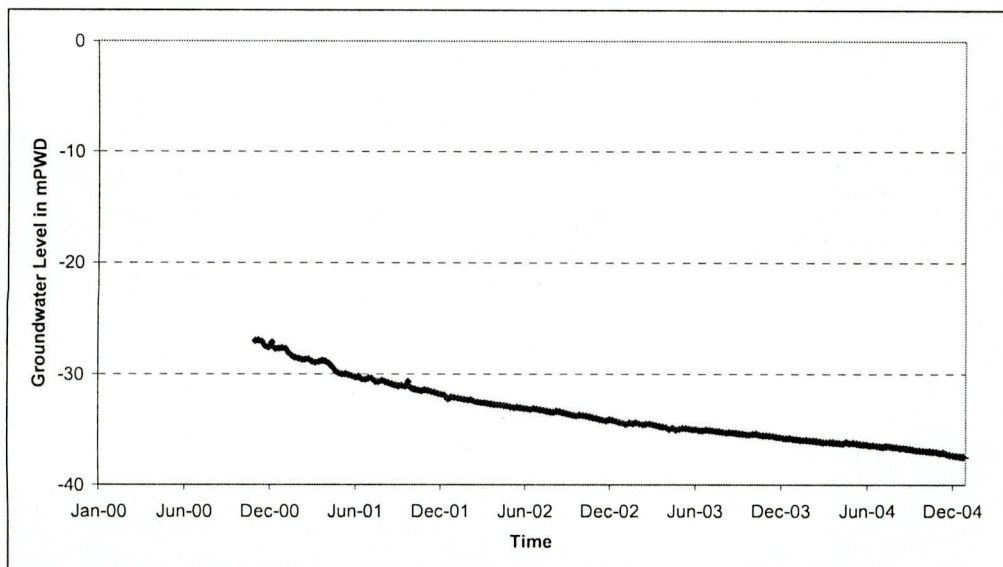


Figure 5.12 Observed hydrograph at Lalbagh 2 (upper aquifer)

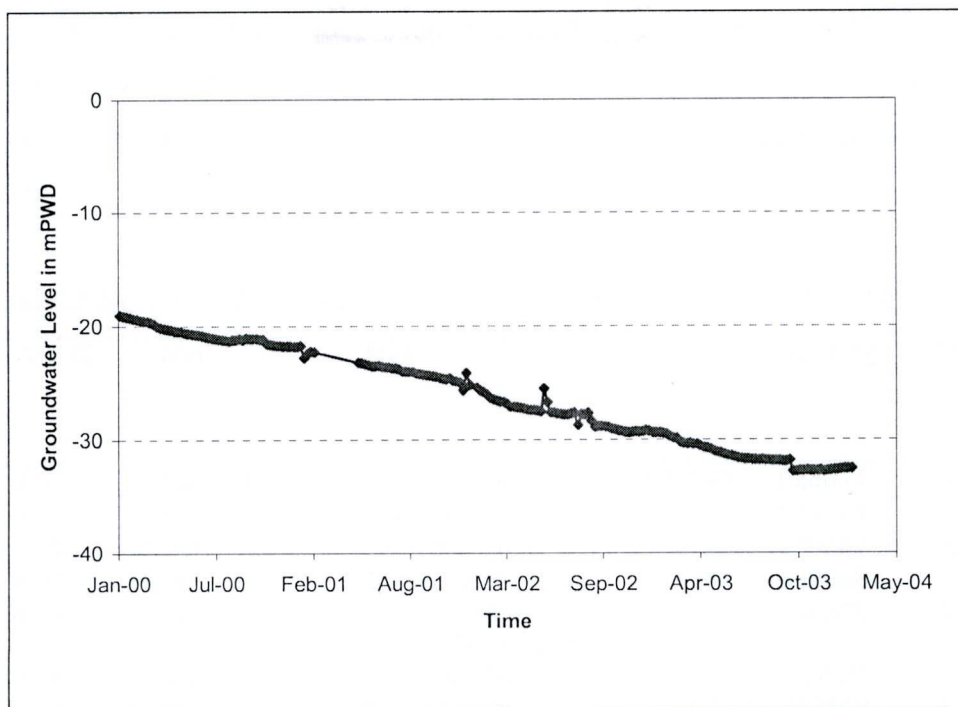


Figure 5.13 Observed hydrograph at Dhaka Cantonment (upper aquifer)

The critical situation regarding the upper Dupi Tila aquifer system triggered the necessity to look for alternate source to meet the increasing water demand. This prompted DWASA to explore the deep aquifer (lower Dupi Tila aquifer) since the beginning of year 2004. Water level in deep aquifer is being monitored by some newly installed monitoring wells in the study area as shown in Table 5.9. But those have started operating after mid of 2005. So, data was not available for a complete hydrologic cycle to compare the model out put that corresponds to deep aquifer.

5.3.5 Elevation data for setting model geometry

Topographical elevation data of the study area is obtained from the Digital Elevation Model prepared by IWM. The original source of the data is Survey of Bangladesh (SOB). Elevation data for top and bottom surface for top 4 layers of the model formation has been obtained form the groundwater model 'GLM 2000' of BUET (2000) and bore logs of DWASA wells installed in Dhaka and Manikganj. The location of data points were obtained by accurate geo-referencing. The surface elevations of

bottom geologic layers (deep aquitard and aquifer) has been collected and processed from the bore log data of DWASA and monitoring wells recently installed in the deep aquifer. List of newly installed DWASA wells (up to end of 2004) in deep aquifer is given in Table 5.2.

Table 5.2 New DTWs installed in deep aquifer(up to end of 2004) in Dhaka City

Ser	Well ID	Thana	Area	Easting	Northing	Fixture Depth in m PWD
1	3-51	Mohammadpur	Tajmahal Road	537243	628014	280.97
2	4-14	Mirpur	Shewrapara-1 West	538189	631181	276.88
3	4-15	Mirpur	Bangla College	536258	630087	280.49
4	4-34	Mirpur	Sangbadik Colony	538340	633998	300.3
5	4-44	Tejgaon	West Agargaon WASA Compound	537846	629375	304.8
6	4-78	Mirpur	Mirpur DOHS	536032	633008	271.27
7	4-79	Mirpur	Ahmadnagar	537945	633440	304.85
8	5-07	Gulshan	Mohakhali TB gate	542039	629638	274.85
9	6-02	Ramna	Noyatola Shishu Park	541855	626741	262.2
10	6-22	Shabujbag	Khilgaon-8	543437	626610	315.55
11	6-48	Ramna	Eskaton	540851	626117	276.83
12	6 - 44	Ramna	Siddeswari Boys High School, Siddeswari	542112	625767	290.78

5.3.6 Hydraulic conductivity and storage properties

Conductivity and storage data has been obtained accurately from the model 'GLM 2000' for the upper 4 model layers by the method of geo-referencing. These parameters are already calibrated and needed hardly any adjustment during the processing. The distribution of hydraulic conductivity of various layers is furnished at Appendix B. But there was no data to set the hydrogeology of the deep aquitard and aquifer until Sep 2005. During September and October 2005 two long term (72 hours) pumping tests in deep aquifer have been carried out in Dhaka City for the resource assessment project undertaken by IWM-DWASA. The aquifer transmissivity, storage coefficient and hydraulic conductivity of the area concerned as computed from aquifer test results are

shown in Table 5.3. The average transmissivity, storage coefficient and hydraulic conductivity are 1805 m²/day, 0.0024 and 27.09 m/day respectively.

Table 5.3 Long-term aquifer test results of deep aquifer system

Location	Method	Transmissivity(T) m ² /day	Storage Coefficient	Hydraulic Conductivity(K) m/day
Mirpur, DOHS	Jacob	2021.50	0.001890	25.50
	Chow	1642.00	0.002850	20.72
	Hantush	1343.00	0.003860	16.95
	Thies	1720.00		21.72
	Hantush- Jacob	1900.00		23.98
	Logan	1418.89		17.91
	Thies	2247.60		28.35
	Recovery			
Tejgaon Polytechnical compound	Jacob	2343.50	0.000531	40.46
	Chow	1781.00	0.002960	30.75
	Hantush	1589.00	0.002194	27.43
	Thies	1790.69		30.92
	Hantush- Jacob	1700.00		29.35
	Logan	1747.35		30.17
	Thies	2033.05		35.10
	Recovery			
Average Value		1805.54	0.0024	27.09

*Source DWASA-IWM

5.3.7 DWASA abstraction

DWASA has developed seven MOD zones to provide city dwellers with domestic water. Each zone operates a number of DTWs and maintains records of monthly abstraction of each well. Location of MOD zones and the DTWs under them is shown in Figure 5.14. Tube well wise monthly abstraction data of seven MOD zones were collected from the respective zonal offices. These are the monthly water production reports, which were collected in printed form. Data for some of the months were not

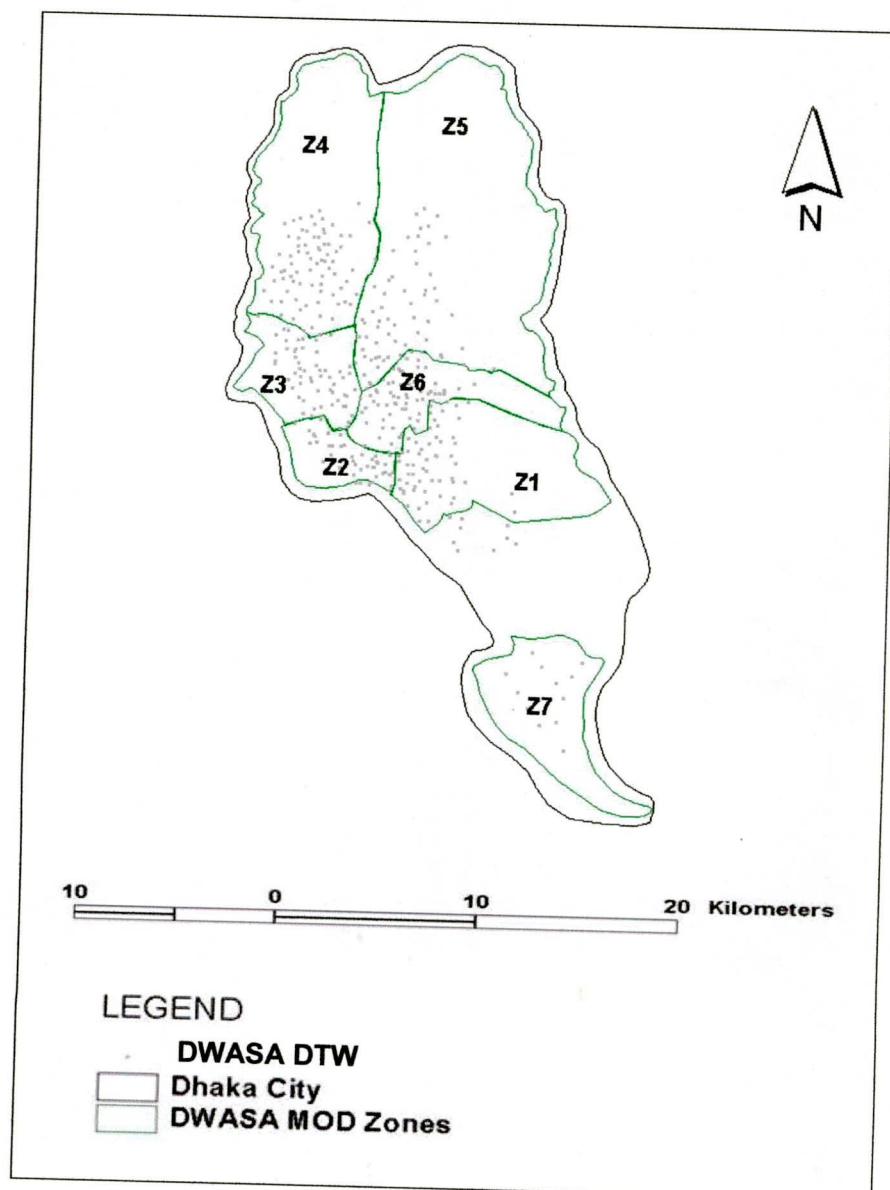


Figure 5.14 DWASA MOD zones and the location of DTWs under their jurisdiction

available. These data had to be converted into soft form and missing data were filled up taking the averages of water production data for preceding and following months. Monthly water production data was collected for the period of 2000 to 2004. During analysis some of the production data were found to be abnormally high and had to be adjusted by estimating the production basing on a standard operation time of 22 hours and 70% efficiency at the pump design capacity. The abstraction data collected was

compared with the abstraction record maintained by MIS DWASA as shown in Table 5.4.

Table 5.4 Year wise number of DWASA DTWs and their abstractions (Mm³)

Year	Zone-1	Zone-2	Zone-3	Zone-4	Zone-5	Zone-6	Zone-7	Total
1991	25	23	25	25	22	29	10	151
	35.42	31.41	338.22	29.71	28.07	40.63	2.05	205.52
1992	29	24	25	23	21	32	10	164
	46.10	35.64	39.11	33.48	31.37	42.17	2.41	230.88
1993	31	24	25	25	27	33	9	174
	45.88	37.71	39.68	35.37	37.29	43.57	2.55	240.00
1994	33	24	26	27	34	35	8	187
	49.37	36.25	41.96	38.29	42.95	46.88	2.25	257.95
1995	35	25	28	27	38	39	8	200
	52.28	37.15	44.03	38.41	46.14	47.49	2.21	267.61
1996	35	25	32	31	42	42	8	215
	55.67	38.64	50.67	44.29	51.57	44.47	2.05	287.41
1997	36	25	35	32	43	45	8	224
	55.73	37.06	47.65	46.47	55.21	50.92	2.04	294.07
1998	38	27	36	35	44	49	8	238
	55.77	38.48	50.12	50.51	48.25	51.41	2.39	296.91
1999	57	28	40	448	47	56	8	269
	61.25	42.03	56.29	59.87	65.30	58.97	2.33	346.04
2000	60	32	46	55	52	67	8	320
	72.25	46.04	62.68	70.50	73.25	63.50	2.60	390.92
2001	67	34	40	64	49	73	8	335
	78.3	44.97	66.31	76.32	80.32	66.18	4.39	416.8
2002	70	37	60	72	66	77	8	390
	77.17	46.53	69.83	96.27	83.37	66.84	4.02	432.96
2003	67	37	61	76	68	72	9	390
	76.24	47.39	68.39	86.39	81.95	55.99	4.64	420.99
2004	67	42	63	81	72	66	9	400
	77.08	48.40	67.02	87.69	87.34	56.32	7.25	431.11

5.3.8 Private abstraction

Huge amount of groundwater is being abstracted for industrial, commercial and residential use from the aquifer systems in different MODS zones including area Tongi and Keraniganj by a large member of privately owned DTWs. But unfortunately there is no suitable record of the specifications, numbers and abstractions of these DTWs. In the previous model study BUET (2000) DWASA provided the number of zone wise record of DTWs up to year 2000. During the present study it is found that DWASA has the record of privately owned DTWs only for the year 2004. From 2001 to 2003, no data is available regarding number of private wells. Also there is no accountability regarding the DTWs which are installed in numerous high rise buildings for domestic water supply. But

MIS DWASA has shown an approximate figure of total annual private abstraction. So we had to rely on this information and the abstraction per DTW was obtained from the number of DTW and total annual abstraction shown in 2004. Number of DTWs and corresponding abstraction for the missing years has been obtained by linear interpolation from the yearly data available in BUET(2000) and the data provided by DWASA for the year 2004. Number of private wells for December 2004 is shown in Table 5.5. Table 5.6 shows the Year wise private abstraction up to 2004.

Table 5.5 Privately owned DTWs under DWASA jurisdiction as in December 2004

Category	Zone-1	Zone-2	Zone-3	Zone-4	Zone-5	Zone-6	Zone-7	Total
Industrial & Commercial use (Authorised)	65	129	19	108	124	23	2	470
Residential, Social & mixed use (Authorised)	11	5	61	41	34	55		207
Total	76	134	80	149	158	78	2	677
Unauthorised	75	8	7	28	35	6	490	649
Grand Total	151	142	87	177	193	84	492	1326

Table 5.6 Annual private abstraction in Mm³

Year	Zone1	Zone2	Zone3	Zone4	Zone5	Zone6	Zone7	Total
2000	14.87	4.71	28.36	59.18	52.56	15.60	124.78	300.06
2001	16.11	5.10	30.72	64.11	56.94	16.90	135.18	325.06
2002	18.79	5.50	33.09	69.04	61.32	18.20	145.58	351.52
2003	23.49	5.89	35.45	73.98	65.70	19.50	155.98	379.99
2004	31.32	6.28	37.81	78.91	70.08	20.80	166.37	411.57

5.3.9 Irrigation abstraction

Irrigation abstraction includes abstraction by DTWs and STWs from groundwater outside Dhaka City area. DTW abstracts groundwater from intermediate aquifer where as the STW abstraction is assigned to the upper aquifer. Almost all the DTWs are installed

by BADC. For modeling purpose thana wise data was collected from BADC and DWASA.

Information regarding the numbers, operating hours and capacities of DTWs and STWs was necessary to compute the amount of irrigation abstraction in the model area. The irrigation abstraction takes place during dry season in the months of December, January, February, March, April and May. Operating hours for those months were considered to be 6, 8, 10, 14, 10 and 2 hours per day respectively (BUET, 2000). The capacity of DTWs was considered to be 56 liters/sec and the capacity of an STW was taken to be 25% of DTW (BUET, 2000). Table 5.7 and 5.8 shows the year wise numbers of DTWs and STWs in different districts in the study area. Figure 5.15 shows that total number of DTWs is decreasing, while the number of STWs is increasing. So irrigation abstraction from the upper aquifer has an increasing trend while that from the lower aquifer has a decreasing trend. But total irrigation abstraction has an over all increasing trend as shown in Figure 5.16.

Table 5.7 Year-wise numbers of DTWs in different districts within study area

Year	Dhaka	Gazipur	Manikganj	Munshiganj	Narayanganj	Narshingdi	Total
1999/2000	305	842	226	12	56	103	1544
2000/2001	308	840	224	14	57	105	1548
2001/2002	310	845	222	15	48	104	1544
2002/2003	298	771	220	12	43	80	1424
2003/2004	286	703	218	10	39	62	1318

Table 5.8 Year-wise numbers of STWs in different districts within study area

Year	Dhaka	Gazipur	Manikganj	Munshiganj	Narayanganj	Narshingdi	Total
1999/2000	6526	4296	11412	1522	1295	8452	33503
2000/2001	6916	4315	11581	1536	1389	8615	34352
2001/2002	7508	4325	11736	1565	1490	8884	35508
2002/2003	7329	5479	12156	1625	1518	9473	37580
2003/2004	7154	6941	12591	1687	1547	10101	40021

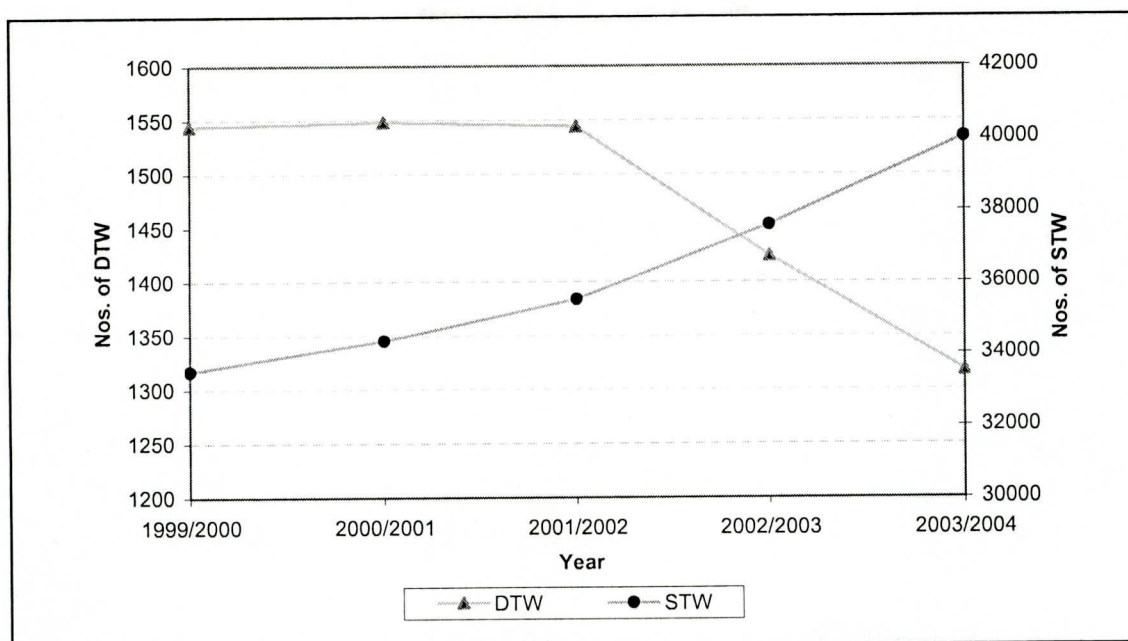


Figure 5.15 Year-wise comparison of total DTWs and STWs within study area

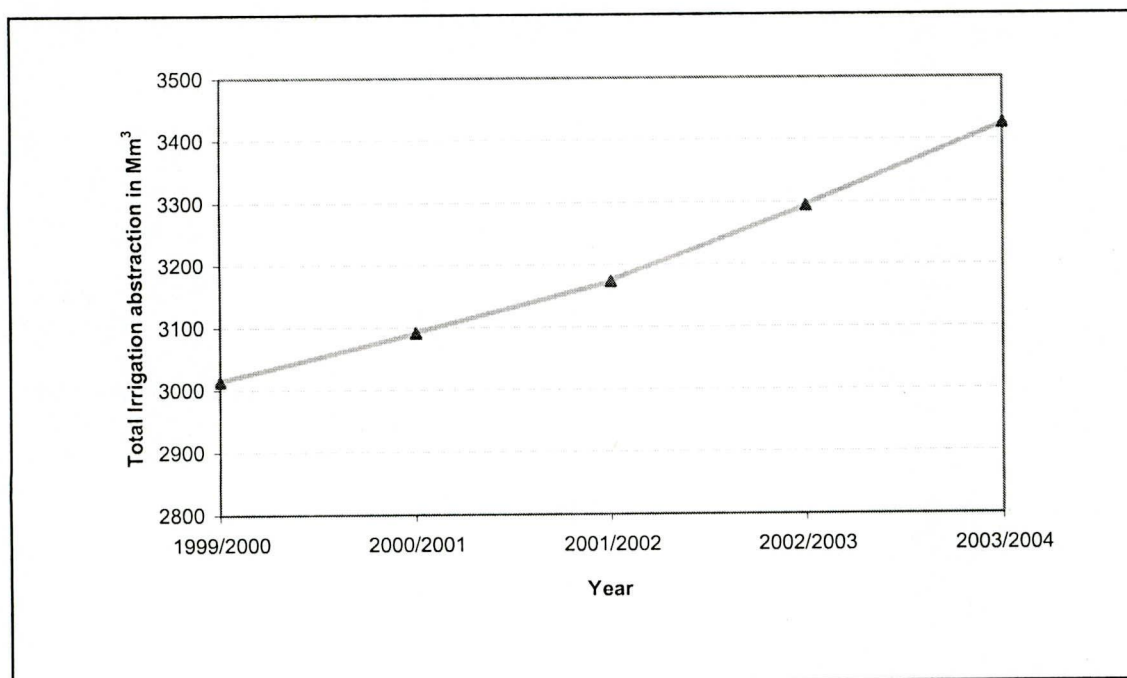


Figure 5.16 Year-wise variation of total irrigation abstraction within study area

5.4 Model setup and description of the groundwater model

The model is set up using Argus ONE and MODFLOW GUI. The preprocessing of input data is done in two stages. First, with the help of MS Excel and Arcview GIS (A widely used GIS application) before entering data into Argus ONE and second, after entering data into Argus ONE. The data files are processed to match the parameters of Argus ONE layers. Processed excel data files are then saved as DBF (Data Base Files), spreadsheet or text files. All these data files contain the location of data points in terms of BTM (Bangladesh Transverse Mercator) coordinates. The geographical locations (latitude and longitude) regarding the field data are converted into BTM coordinates with a small application named Geowin. Argus ONE supports the input of data in the form of DBF, text, spreadsheet and Arcview GIS shape files of specified format. The type of file to be used depends on the type of data input to the model. Spatial data entered into the model are basically of two types. Those are data related to point or area locations. Only shape files supports data related to both point and area locations. Point Shape files are generated with the help of Arcview GIS after importing the DBF or text files into it. For area shape files the data imported are added to the attributes of the generic shape files and a new shape file is created whose fields are in exact match (sequentially) with the parameters of respective Argus ONE layers. Stage two preprocessing is done in Argus ONE itself by necessary interpolation, parameter linking and using Argus ONE expressions. Preprocessing of raw data is shown in Figure 5.17. Further details of model setup are described in following paragraphs.

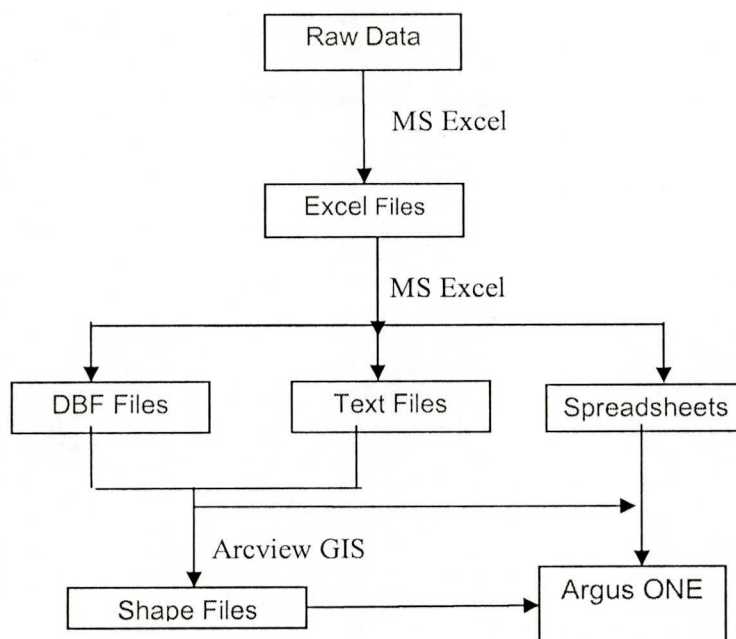


Figure 5.17 Flowchart showing processing of data

5.4.1 Spatial discretization

The groundwater model covers an area of 8778 km². The spatial discretization of the model area is set in two types of density. Outside Dhaka City the model grid cell size is 1000X1000 m² and inside Dhaka City it is 500X500 m². The discretization consists of 141 rows and 148 columns. No. of cells inside the model area is 15874. Spatial discretization of the model area is shown in Figure 5.18.

5.4.2 Temporal discretization

The model is set up for calibration for a period of 2000 to 2004. In the time discretization every month is selected as a stress period. Length of the stress period is kept exactly as the number of days as appears in the calendar month. Every stress period is further sub-divided into two time steps.

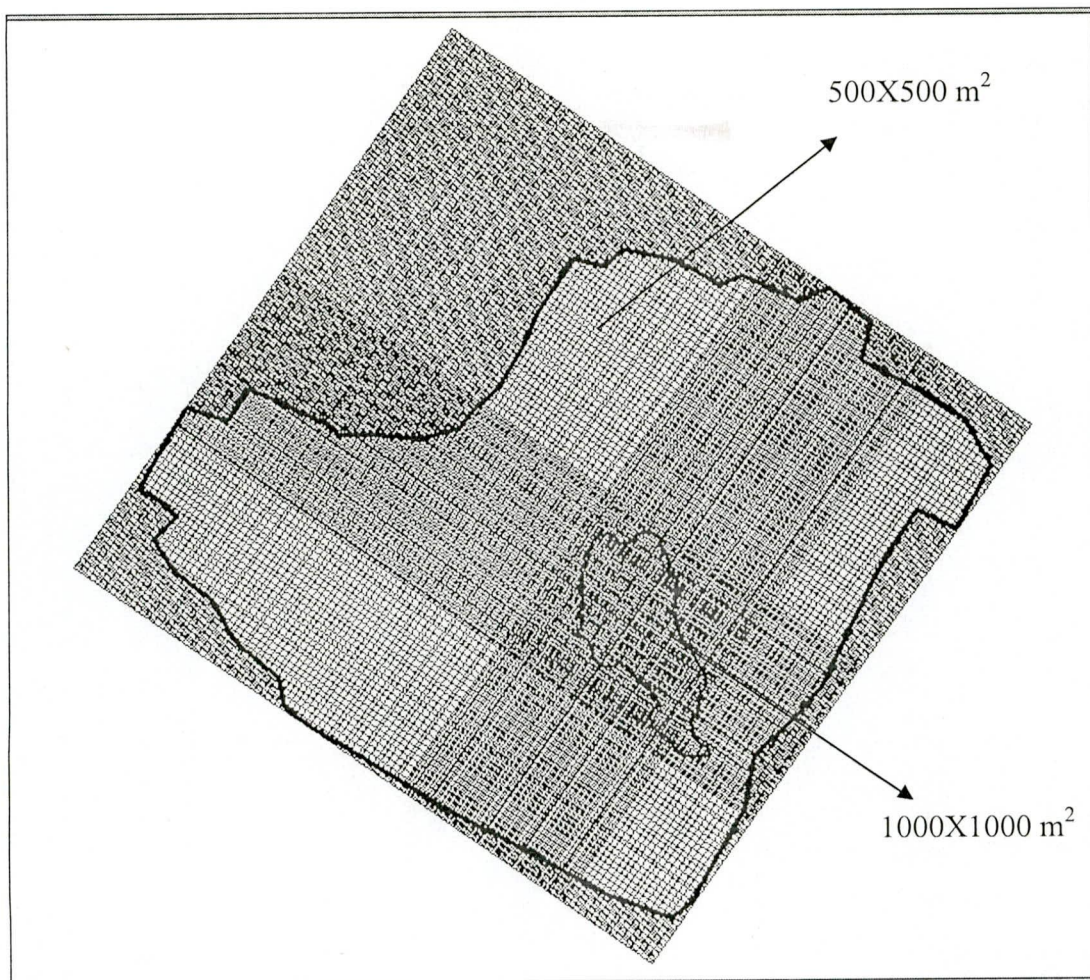


Figure 5.18 Model area and grid showing spatial discretization

5.4.3 Model geological formation

The model has 6 geological formations as shown in Figure 5.20. Topography of the model area has been defined from the data obtained from DEM as mentioned previously. The text files containing the elevation data of geologic units 1 to 4 was collected from BUET (2000) and updated with bore logs of newly installed DTWs (Table 5.2) and monitoring wells as listed in Table 5.9. The cross sections of model geologic formation along various directions are shown in Figure 5.19 to 5.23. Monitoring wells installed in deep aquifer of Dhaka City are shown in Figure 5.24.

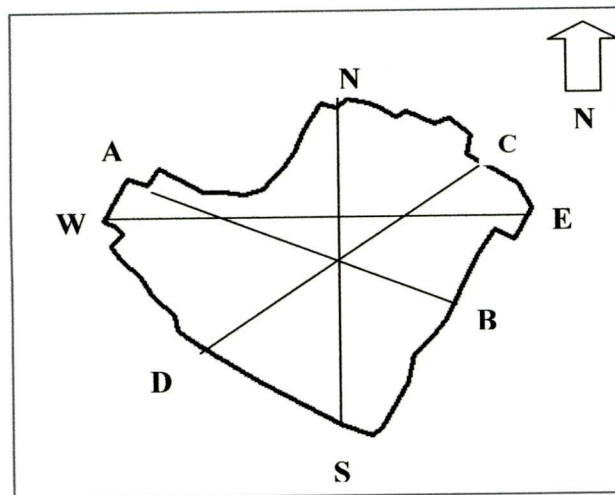


Figure 5.19 Outline of study area and the cross section lines for model formations

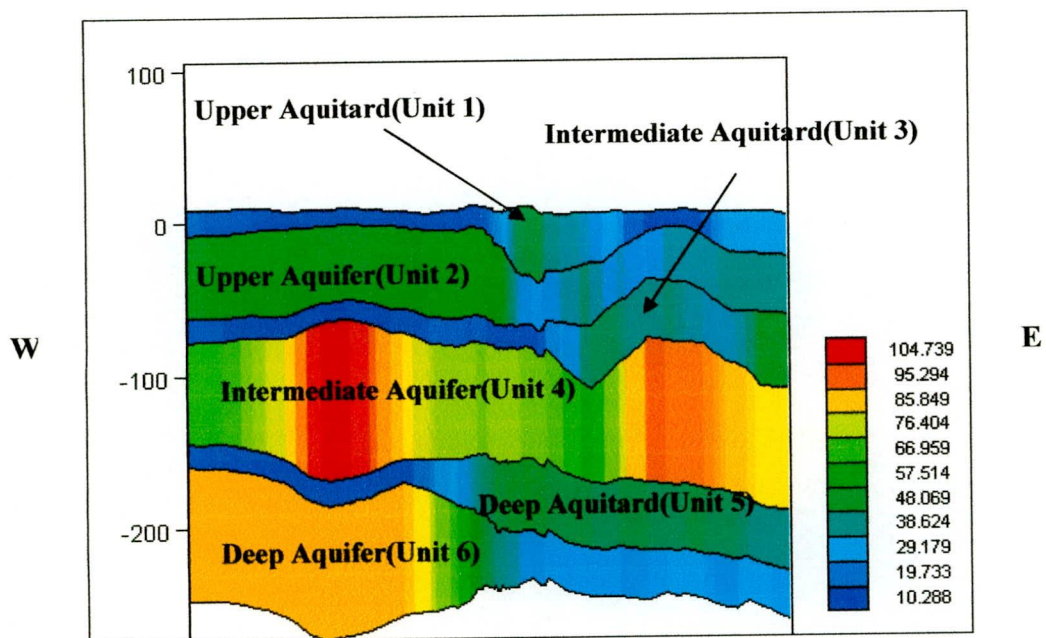


Figure 5.20 Cross section of model formation along E-W

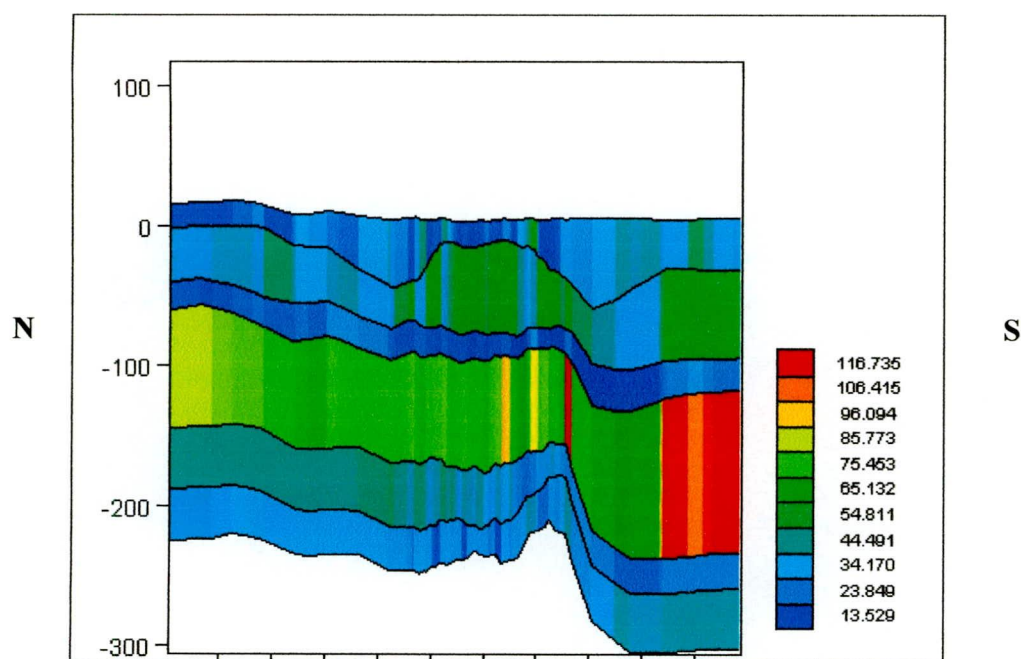


Figure 5.21 Cross section of model formation along N-S

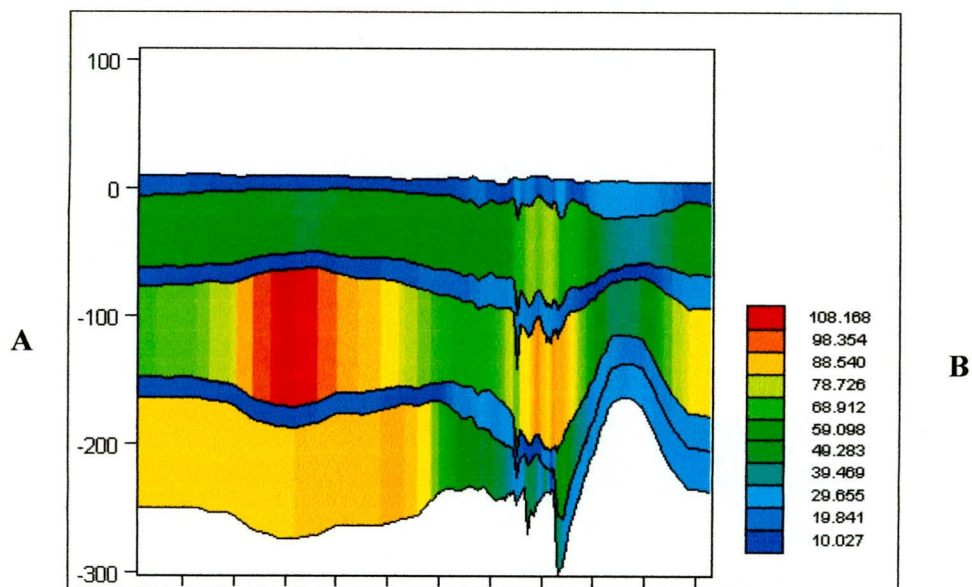


Figure 5.22 Cross section of model formation along A-B

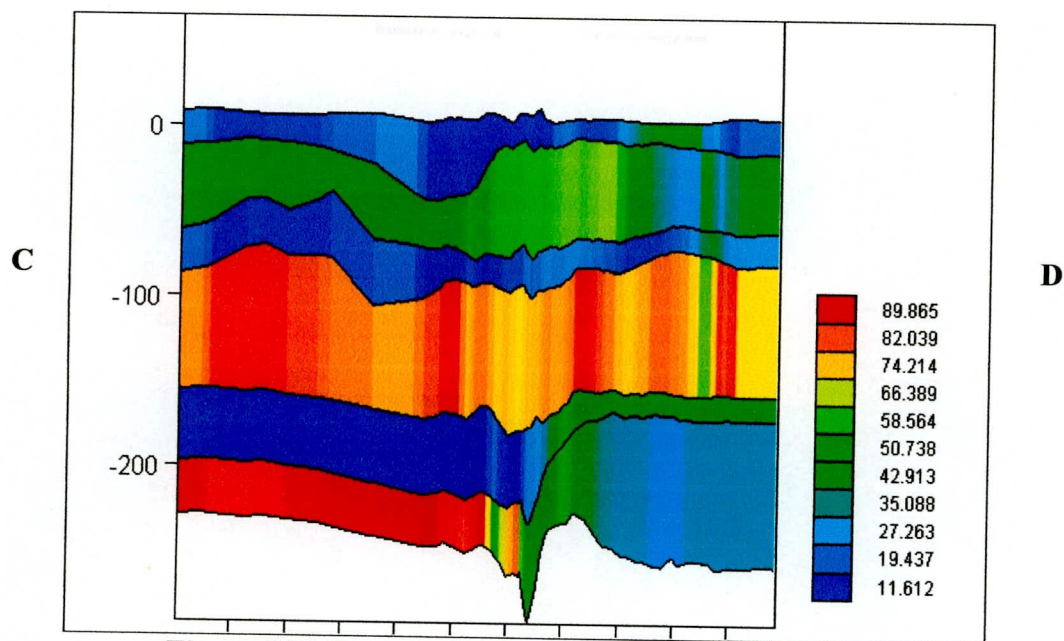


Figure 5.23 Cross section of model formation along C-D

Table 5.9 Recently installed monitoring wells in deep aquifer

Ser	Well ID	Vill/Location	Upazilla and District	Easting	Northing	Fixture Depth (m)	Parapet Height (m)
1	DDMW-1	Moinertek	Uttar Khan, Dhaka	546166	640854	220.52	0.6
2	DDMW-2	Diabari	Uttara, Dhaka	537554	640331	274.5	0.6
3	DDMW-4	Mastul	Dumni, Dhaka	549308	634935	274.45	0.6
4	DDMW-5	Rahmatulla Degree College	Uttar Badda, Dhaka	548083	631702	266.25	0.6
5	DDMW-6	Mirpur Bangla College	Mirpur, Dhaka	537206	631273	241.86	0.6
6	DDMW-8	Ashraful Madrasa	Mohammadpur, Dhaka	535871	628260	254.05	0.6
7	DDMW-10	Khilgaon Primary School	Khilgaon, Dhaka	544095	626264	257.1	0.6
8	DDMW-12	Tengra Primary School	DND area(near Demra main Canal)	550352	622643	274.45	0.6
9	DDMW-13	NA	DND area(near Pagla Khal), Dhaka	549376	617446	289.7	0.6
10	DDMW-14	Bhuiyapara	Fatullah, Narayanganj	552567	615504	220.52	0.6
11	DDMW-15	Sumilpara Union Parishad	Narayanganj	553103	617665	220.52	0.6
12	DDMW-16		Bandar, Narayanganj	552738	611304	274.5	0.6
13	SDMW-1	kasta	Bangala	506839	629089	268.4	0.6
14	SDMW-2	Boira	Boira	508526	634216	247.05	0.6
15	SDMW-3	Irta Kashimpur	Char Dighulia	513158	636966	224.79	0.6
16	SDMW-4	Pilot High School	Pilot High School	515120	633102	226.62	0.6
17	SDMW-5	Madhabpur	Madhabpur.	520862	627313	226.62	0.6
18	SDMW-6	Sayesta	Sayesta	517525	627213	217.47	0.6
19	SDMW-7	Joymondap	Joymondap	520862	627313	217.99	0.6
20	SDMW-8	Kamura	Kamura	521466	633622	304.88	0.6
21	SDMW-9	Shekhpara	Fordnagar	524088	634609	256.2	0.6
22	SDMW-10	Hatni	Jamirta	521880	630174	212.29	0.6

Note: DDMW- Dhaka deep monitoring wells, SDMW- Singair deep monitoring wells

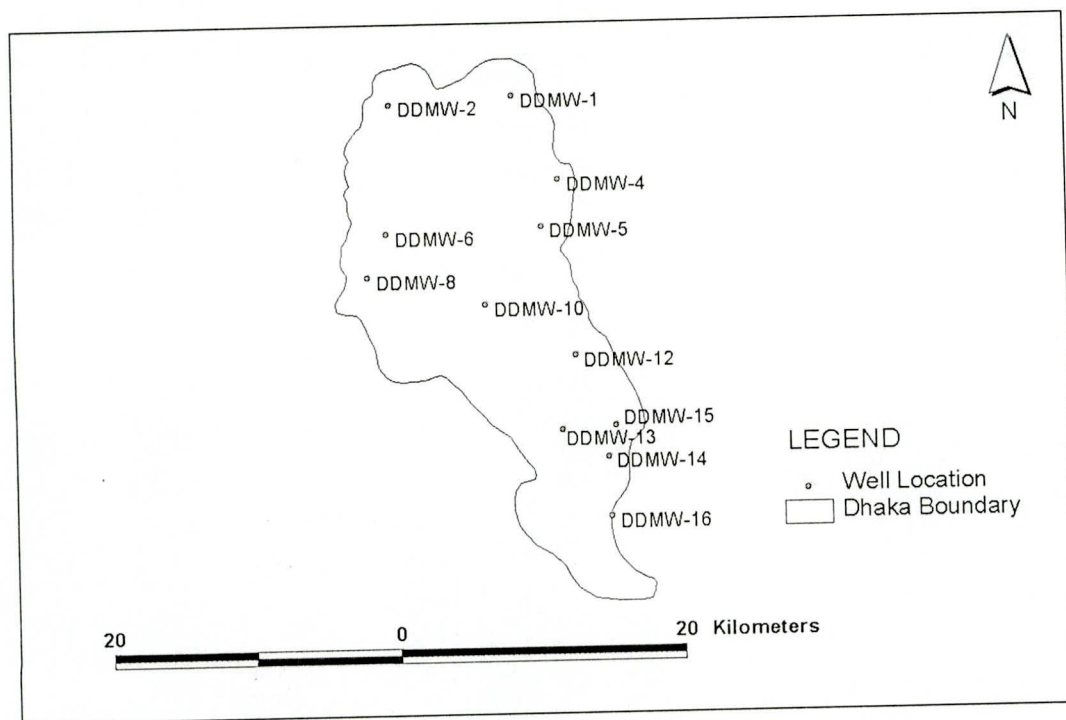


Figure 5.24 Recently installed deep monitoring wells in Dhaka City area

5.4.4 Input of time invariant data

The most basic way of entering time invariant data using Argus One is in the form of text files. In this model time invariant data has been obtained from BUET (2000), DEM, old and recent borelog data of DWASA DTWs and monitoring wells installed in the intermediate and deep aquifer. These data were further augmented and verified using the results of the investigation conducted by dept of geology, Dhaka University (Khan, 2005). The map of entire model area of BUET (2000) has been used to extract all the data accurately to be used in the current model through a process called geo-referencing. Data obtained in this process includes the following

- i) Top and bottom elevation of geologic units.
- ii) Horizontal and vertical Hydraulic conductivity.
- iii) Specific storage and specific yield.

After necessary input, these data were distributed in the model area by interpolation method with the help of Argus ONE.

5.4.5 Initial conditions

Initial conditions in terms of hydraulic head of groundwater have been specified in the model. Initial conditions for top four geological layers within the model area has been obtained from the BWBD and WASA monitoring well data corresponding to January 2000 and interpolated into model cells. Initial condition for deep aquifer system has been obtained as the static water level (SWL) as recorded in the bore log data of newly installed DTWs and monitoring wells by DWASA and IWM at the time of installation.

5.4.6 Boundary conditions

Rivers in the study area forms external and internal boundaries of the model except along the northern side. The northern boundary is formed by the boundaries of the districts and river Old Brahmaputra as can be seen in Figure 1.1. The water level of the external and internal rivers provides time varying head boundary conditions in this model.

External Boundary

Along the eastern and western side of the model area river ways of upper Meghna and Padma respectively forms the external boundaries. The northern side is aligned with the northern edge of Manikganj, Dhaka, Gazipur and Narshingdi Districts and part of River Old Brahmaputra. These features simulate the external boundary in following ways:

- (a) For the upper aquifer River Padma, Meghna and Old Brahmaputra are defined as time varying head controlled boundaries of the model. For these boundaries water

levels are specified for each model cell along these rivers at the beginning of each stress period.

- (b) For the northern part of the external boundary a prescribed head is used basing on the water level data of monitoring wells located along the northern boundary of the model.
- (c) For the intermediate and deep aquifer, the boundaries that coincide with the external rivers are considered to be flow divides and thus a zero gradient is specified. River water level at various stations within the study area has been obtained for the duration of model run. The water level between two stations has been set by interpolation along the river reaches.

Internal Boundaries

Inside the model area major rivers are incorporated as internal boundaries. These rivers are in direct or indirect contact with the upper aquifer and may contribute or gain water basing on the head difference with the connecting aquifer. MODFLOW-2000 defines the river-aquifer interaction in the following ways:

$$Q_{RIV} = C_{RIV} (H_{RIV} - h)$$

where, Q_{RIV} = Flow rate from or into river, C_{RIV} = Riverbed conductance = $\frac{KLW}{M}$, H_{RIV} = river stage, h = head in the connecting aquifer, K = Hydraulic conductivity of the riverbed material, L = Length of the river reach that is specified by the length of the cell along the river way and W = width of the river.

Now if the head in the aquifer is below the bottom of the river bed then the flow rate from the river into the aquifer becomes constant and given by,

$$Q_{RIV} = C_{RIV} (H_{RIV} - R_{BOT})$$

where, R_{BOT} = Elevation of the river bottom. Otherwise it is a variable quantity. So while using the river package the modeler needs to specify the H_{RIV} and C_{RIV} .

5.4.7 Recharge

The model calculates the volumetric recharge as given below:

$$\Delta Q = I \Delta x \Delta y$$

where, ΔQ = volumetric recharge rate (L^3/T), I = Recharge flux (L/T) and $\Delta x \Delta y$ = Cell area. In MODFLOW 2000 user needs to specify the recharge flux (I).

Recharge from rainfall is estimated considering 15% of total rainfall in the area and distributed as shown in Figure 5.25. A recharge reduction factor (0.5) was used while computing recharge from rainfall for Dhaka City area. The percentage of rainfall that formed the recharge to the groundwater model is used as a calibrated parameter. Urban return flow and irrigation return flow is assigned to the model as 15% and 20% respectively of the corresponding abstraction.

5.4.8 Abstraction

The monthly water production data was converted to m^3/day for each tube well. From the study of specification booklet of all DTWs installed by DWASA it was found that the screens of DWASA DTWs were placed both in upper and intermediate aquifer. Accordingly the abstraction was distributed both to intermediate (65%) and upper aquifer (35%) basing on the ratio of saturated thickness at the initial condition.

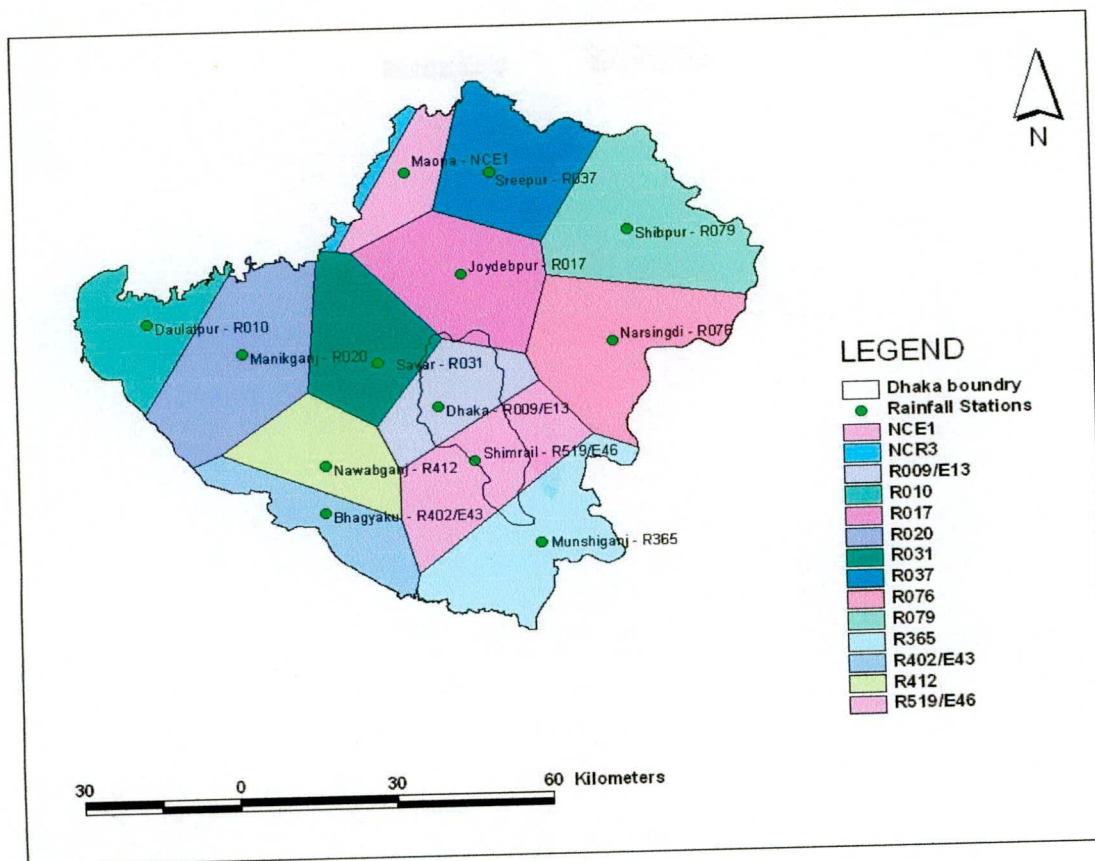


Figure 5.25 Rainfall distribution by thiessen polygon method

Abstraction data has been incorporated in the model in following ways:

- i) DWASA Abstraction in Dhaka City area by point well method since the location of individual well is known in this case.
- ii) Private abstraction in Dhaka City by area well method. The area corresponds to the MOD zones in which the private wells are located.
- iii) Irrigation abstraction in out side Dhaka City by area well method. The area corresponds to the thana areas where the irrigation wells are located.

Both DWASA and private abstractions are assigned to the upper and intermediate aquifers as a percentage of the corresponding saturated layer thickness. Irrigation abstraction is divided into two types. These are DTW abstraction and STW abstraction and assigned to intermediate and upper aquifers respectively. The irrigation return flow

data is processed on monthly basis and applied to the model on thana area basis. Urban return flow is computed as 15% of total abstraction and distributed in Dhaka sub-sectors (Figure 5.2) proportionately (Table 5.1) by area well method. Model takes abstraction as negative values and return flow as positive values.

5.5 Estimating land subsidence using groundwater model

5.5.1 General

The Subsidence module (SUB) simulates the drainage, changes in groundwater storage, compaction of interbeds and confining units that constitute an aquifer system. The program calculates net compaction in individual model layers and sums those values to calculate changes in vertical position of land surface. Only vertical component of displacement is simulated using SUB. The horizontal displacements are highly localized and occur near pumping wells, local heterogeneities and near the margins of groundwater basins. At regional scales and for regional groundwater flow and aquifer system compaction models the local horizontal displacement contribute little to the overall change in groundwater storage and is ignored in this study.

5.5.2 Setting up groundwater model to compute land subsidence

When the groundwater model setup and calibration is complete then the SUB package can be used to compute the land subsidence within the model area. In the calibrated groundwater model under this study the following model layers (Figure 5.26) are considered susceptible to compaction due to groundwater withdrawal:

- i) Upper aquitard (unit 1)
- ii) Intermediate aquitard (unit 3)
- iii) Deep aquitard (unit 5)

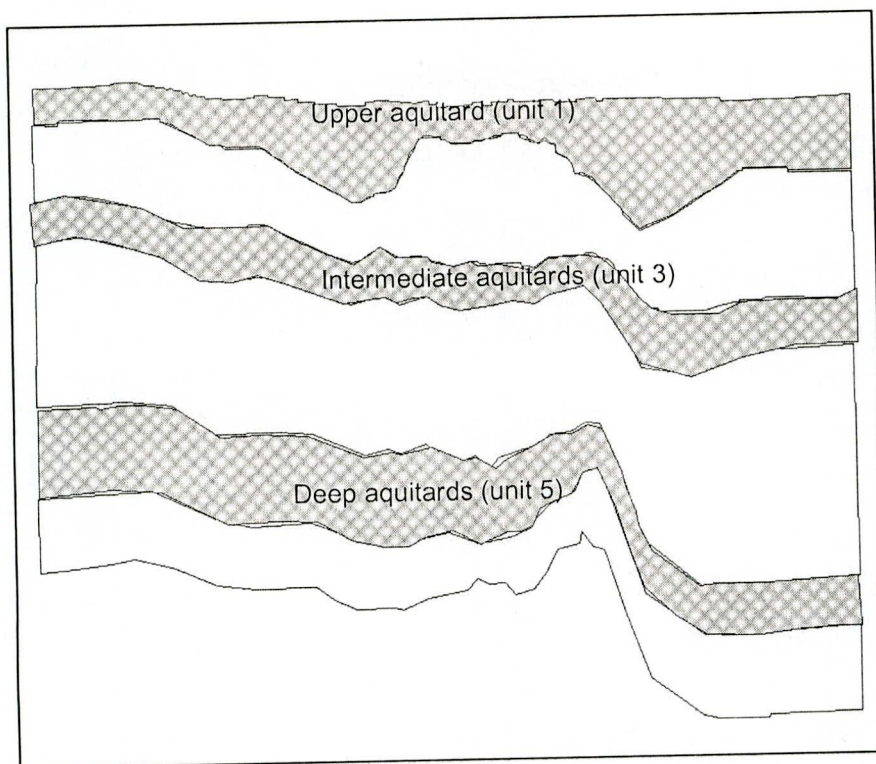


Figure 5.26 Compressible layers in the model formation

The SUB package is embedded in MODFLOW GUI. After the SUB package is activated the user need to specify the model layers for which compaction is to be measured. Then MODFLOW GUI generates required Argus ONE layers for subsidence computation under the respective geologic units. Model under this study is a regional scale groundwater model and aquitards are simulated as confining units (Figure 3.2) using single model layers (Figure 3.3 B) extended over the model area. In each Argus ONE layer generated there are 4 parameters as shown below for which data input is necessary:

- i) Preconsolidation head or stress
- ii) Skeletal elastic storage coefficient
- iii) Skeletal inelastic storage coefficient
- iv) Starting compaction

During the model run Argus ONE exports the input data and SUB package calculates the layer compaction (using Eq 3.30) and subsidence at the centre of model cell. The model output can be obtained in the form of contour map or text file by using the MODFLOW postprocessor.

Preconsolidation head

Data for preconsolidation stress is collected from BUET (2000) as shown in Table 5.10. Preconsolidation head is obtained by dividing the preconsolidation stress with unit weight of water. From Table 5.10 the average value is taken and specified in the model area for respective subsidence computation units as shown in Table 5.11. Figure 5.27 shows the locations of SCUs in the model area.

Table 5.10 Estimates of preconsolidation pressure (kPa)

Geotechnical sub-area	Modhupur clay	Lowland alluvium	Highland alluvium
Dhaka City	150 – 500	0 – 80	50 – 500
Savar	100 – 700	0 – 100	100 – 800
Tongi-Kaliganj	150 – 500	–	100 – 300
Narayanganj	–	50 – 500	50 – 500
Keraniganj	–	0 – 150	0 – 100

Table 5.11 Average parameter values for respective SCU (BUET, 2000)

SI	SCU	Easting	Northing	Compression Index C_c		Void Ratio		Preconsolidation stress(kPa)	
				Unit 1	Unit 3	Unit 1	Unit 3	Unit 1	Unit 3
1	1A	541000	631658	0.24	0.19	1.26	1.20	275	325
2	1B	536614	628405	0.23	0.19	1.35	1.20	300	325
3	1C	542357	622671	1.20	0.20	1.20	1.20	150	200
4	1D	538374	625760	0.23	0.22	1.35	1.30	300	325
5	1E	542559	625842	0.20	0.20	1.25	1.13	275	325
6	1F	541981	631921	0.15	0.15	0.97	0.97	275	325
7	1G	542645	637294	0.20	0.16	1.30	0.96	325	325
8	1H	543598	621964	0.17	0.18	1.00	1.00	300	325
9	2	530269	630861	0.21	0.15	1.20	0.93	325	400
10	3	542587	641434	0.35	0.22	1.66	1.15	350	325
11	4	549311	635963	0.20	0.25	1.00	1.20	200	300
12	5A	550726	622835	0.26	0.15	1.30	1.10	250	325
13	5B	548879	614028	0.24	0.20	1.33	1.10	275	325
14	6	540654	621176	0.32	0.22	1.34	1.15	75	150

Note: SCU – Subsidence Computation Unit

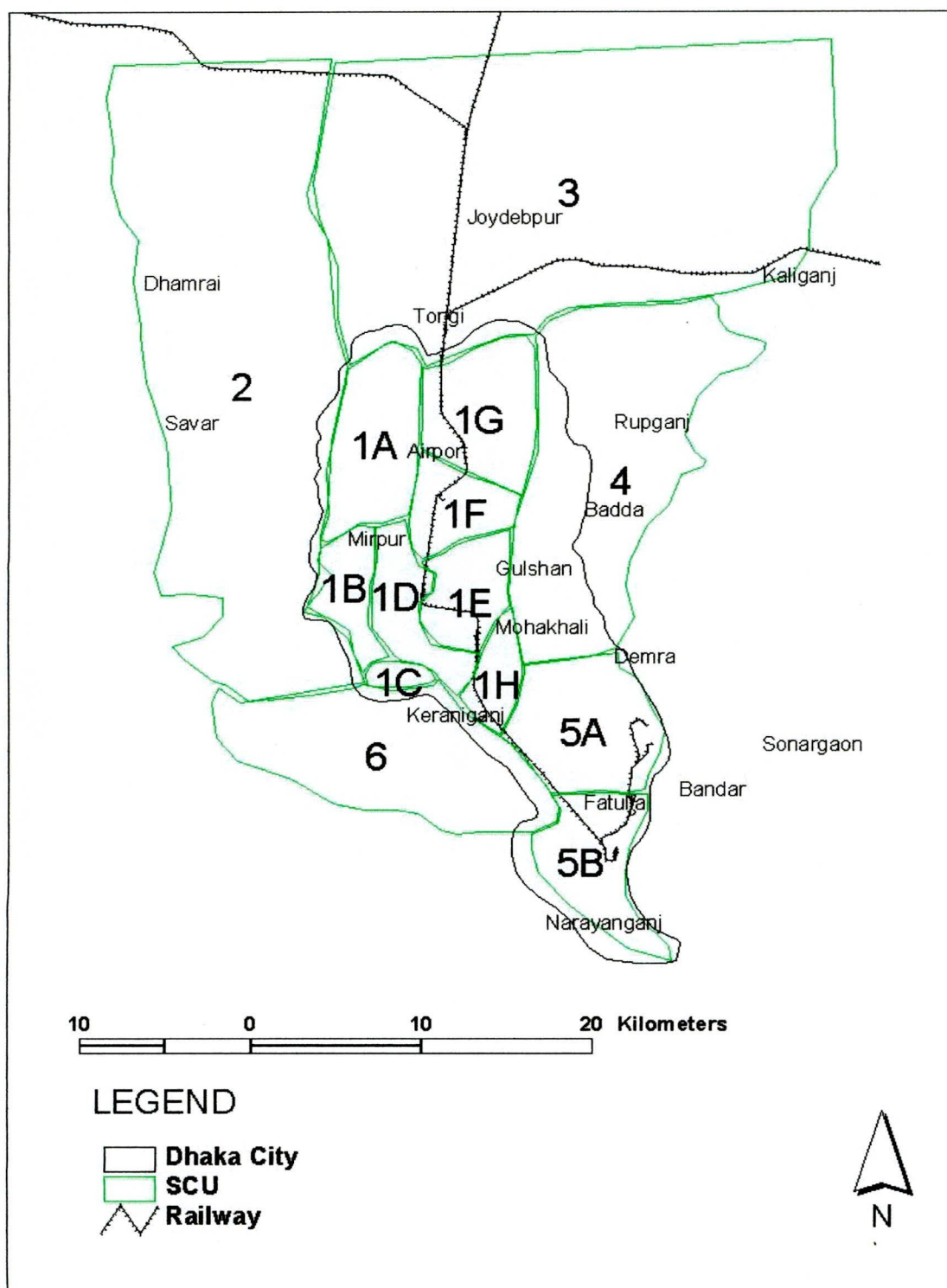


Figure 5.27 Subsidence Computation Unit (SCU) areas for data input in the groundwater model

Elastic and inelastic skeletal storage coefficient

For setting up the groundwater model storage properties for different layers are incorporated as specific storage. But for setting up the model for subsidence computation skeletal storage coefficient of the respective model layers need to be specified. Because using this method release of water from storage of these aquitards is the basis of subsidence computation. Since the difference between skeletal storage coefficient and storage coefficient is the component of storage due to compressibility of water, it can be considered negligible (Poland, 1984). So the storage coefficient data is set by multiplying the specific storage data of the respective model layers with their corresponding thickness. There was no data available regarding the inelastic storage coefficient. The inelastic storage coefficient is a function of the effective stress. The model input value for this parameter is obtained using Eq (3.27). Additional data required to compute inelastic storage coefficient using Eq (3.27) are the compression index and void ratio of the respective layers. Data for unit 5 was not available and has been kept the same as unit 3. These data were obtained from BUET (2000) as shown in Table 5.11.

Starting compaction

The model considered starting compaction value as zero and the result of subsidence is obtained in terms of absolute vertical displacement.

5.6 Model calibration

Model calibration is an iterative process through which simulated results (e.g., calculated heads) are matched with the measured head values by adjusting aquifer parameters, boundary conditions and stresses within plausible ranges. The number of input parameters that can be adjusted and the number of variables available for calibration targets complicate this process.

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

There are 6 geologic layers and the adjustable model inputs are recharge, boundary conditions, abstraction, storage, hydraulic conductivity and conductance of rivers. The calibration of the model was done manually. The calibration was based on the comparison between the calculated and observed head on original observation well data. A set of 11 observation wells was selected for matching of hydrographs.

Matching of historical hydrograph

To measure the performance of the model, calibrated water levels were compared with the observed water levels for 11 observation wells as shown in Table 5.12. Historic data for these observations wells from January 2000 to December 2004 period was required for the calibration purposes. The water level record for all these wells were not available for the total duration of model run. During the calibration process hydraulic conductivity, specific yield, specific storage, vertical leakage, abstraction and recharge values were adjusted until reasonable matches were obtained between the observed and simulated water levels for all observed hydrographs. The locations of the comparison points are shown in the Figure 5.28.

Table 5.12 List of observation wells used for model calibration

Sl	Location	ID	Model Layer	Easting (X)	Northing (Y)
1	Lalbagh 1	DA-110	Intermediate aquifer	541938	622661
2	Motijheel	DA-112	Intermediate aquifer	542576	625490
3	Gulshan	DA-123	Intermediate aquifer	541221	630511
4	Cantonment	GT2608001	Upper aquifer	542289	632843
5	Lalbagh 2	GT2642009	Upper aquifer	542755	622819
6	Singair	GT5682015	Upper aquifer	501846	632343
7	Dohar	GT2618006	Upper aquifer	514091	607823
8	Savar	GT2672018	Upper aquifer	527454	637904
9	Gazipur	GT3330001	Upper aquifer	541903	653171
10	Narshingdi	GT6863005	Upper aquifer	544454	622907
11	Munshiganj	GT5924002	Upper aquifer	559903	604787

5.7 Sensitivity analysis

Sensitivity analysis is a procedure for quantifying the impact on an aquifer's simulated response due to an incremental variation in a model parameter or a model stress. The purpose of sensitivity analysis is to identify parameters that are most important in determining aquifer behavior. First parameters have been ranked in order of importance, and then priorities have been set for focusing field investigations on key parameters to reduce model uncertainty. Sensitivity analysis was carried out for the aquifer properties K_x (horizontal hydraulic conductivity), K_z (vertical hydraulic conductivity) and S_s (specific storage). Results of the sensitivity analysis are furnished in chapter 6.

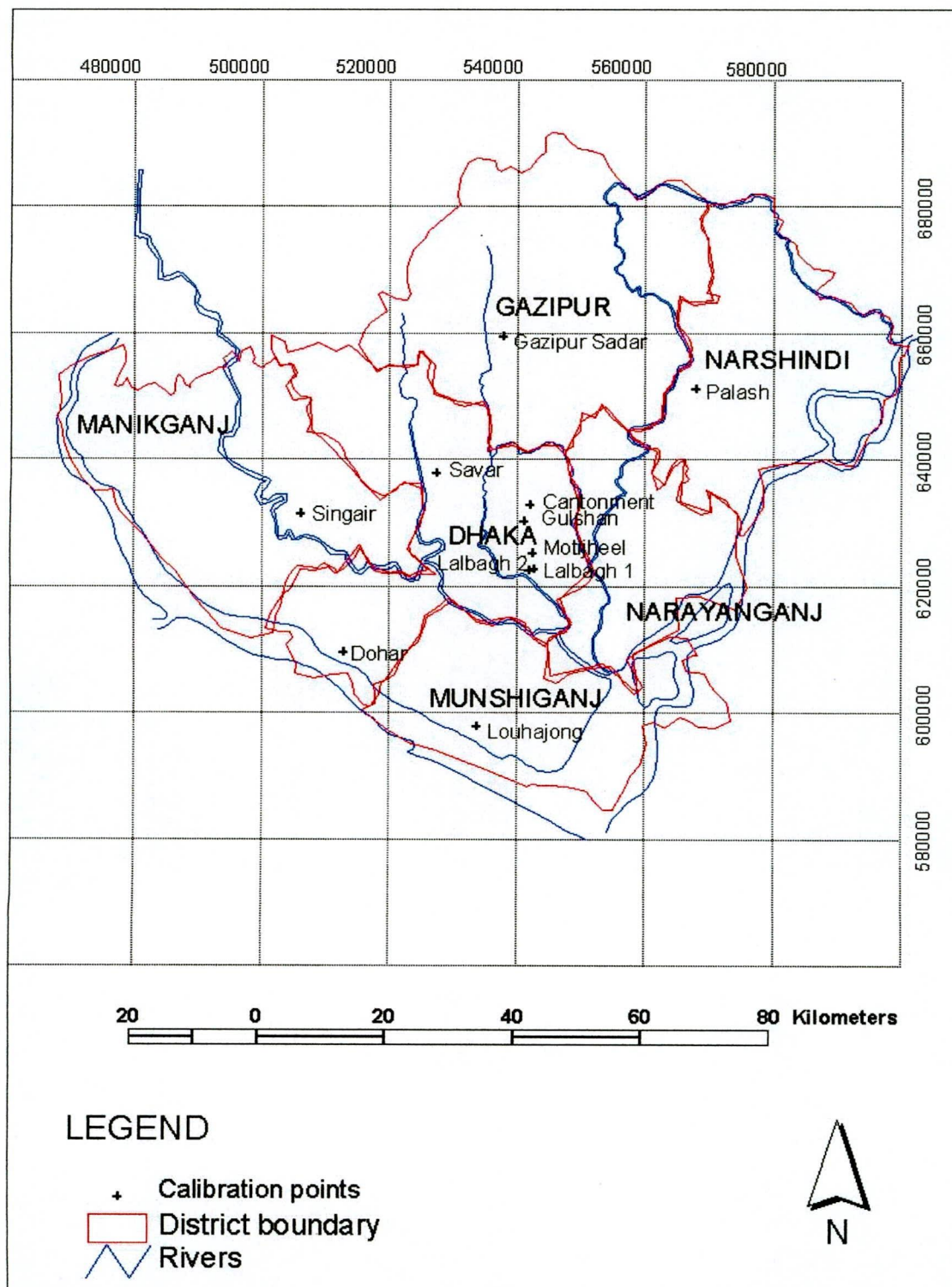


Figure 5.28 Locations of the observation wells used for model calibration

5.8 Scenario runs

The calibrated groundwater model was used to test a variety of potential development scenarios to simulate the future dynamic response of the aquifer systems. The simulation results were obtained both in terms of predicted GWL and land subsidence in Dhaka City area. The possible future scenarios were selected and corresponding data files were prepared accordingly keeping in mind the following few factors:

- (a) Increase/decrease in number of number of DWASA and private DTWs over the current years in Dhaka City area.
- (b) Increase/decrease in number of number of irrigation DTWs and STWs during the calibration period of the model in the study area.
- (c) Current number and future plan of installing DTWs in recently explored deep aquifer by DWASA.
- (d) Current rate of mining/recharge and rate of declination of water table in aquifers of Dhaka City area.

Basing on the data analysis and consideration of relevant factors following scenarios have been selected and tested during the current study:

Scenario 1 Continuation of rate of abstraction until 2020 as existed during the year 2004.

Scenario 2 An annual increase of private abstraction at the rate of 10% from 2005 until 2020.

Scenario 3 Continuation of 10% annual increase of private abstraction up to 2010 and then keeping it fixed (abstraction rate of 2010) until 2020.

Scenario 4 Increasing abstraction from the deep aquifer with 94 wells in operation from 2005 and continuing up to 2020.

Data Preparation for the Scenario Runs

For Scenario 1 the input of abstraction data from 2005 to 2020 has been kept same as the input of year 2004. It has been assumed that year 2003 would be appropriate as representative for long term rainfall as 2004 was a year of unusual rainfall and flood. For the boundary conditions and other time series, the data for the year 2004 has been used for 2005-2020. For Scenarios 2 to 4 all other inputs less the abstraction was kept the same as Scenario 1. For Scenario 2 the private abstraction data (for only upper Dupi Tila aquifer system since there is no record of private abstraction from deep aquifer so far) was increased at a yearly rate of 10% of the previous year from 2005 to 2020. The abstraction from deep aquifer was kept same as 2004 for the simulation period 2005-2020. For Scenario 3 the only change is that the 10% increase in abstraction continued only up to 2010 and then kept constant until 2020. For Scenario 4 the only change in abstraction from deep aquifer is that the number of wells was increased to 94 from 2005 and continued up to 2020.

Chapter 6

RESULTS AND DISCUSSIONS

6.1 Groundwater flow calibration results

The upper and intermediate aquifer system of Dhaka City is already under stressed condition due to continuous pumping by DWASA and private wells. This critical condition and ever increasing water demand of the city has rendered DWASA to explore the deep aquifer boring up to a depth of more than 300 m. The concentration of deep tube wells is so high that many of these (mainly private wells) are located within the radius of influence of each other. So, observed water levels of those monitoring wells are continuously affected by the pumping wells. Groundwater level (as recorded in December 2003) observed at monitoring wells in the Dhaka City area ranges approximately from -20 to -52 m PWD. With the statistics available from MIS DWASA, the number of production wells were 1726 (DWASA 400 and private 1326 as from Tables 5.4 and 5.6) during year 2004. These tube wells are concentrated within an area of 400 km² (area of Dhaka City less DND area). This makes a density of over 4 DTWs per Km² if they are assumed to be evenly distributed. But in reality the density is much higher in areas of high rise buildings and industries.

Groundwater level data from observation wells have been used to compare the model simulated results. During the calibration, it was essential to determine which parameters most strongly influence the hydraulic head pattern of the area. Existing data of monitoring wells reveal that hydraulic head in the intermediate aquifer decreases towards the center of the city and increases towards the periphery of the rivers. Observation well data also shows that water table is still much higher in the outside of Dhaka City beyond the river boundaries. Also it is evident that the water table fluctuations near the rivers have similarity with the seasonal river level fluctuations and this diminishes rapidly away from the rivers. So the surrounding rivers are hydraulically connected to the upper Dupi Tila Aquifer system and the flow towards the city is coming from the high water levels beyond

the river boundaries. In effect, when the rivers are taken as no-flow boundaries to the modeled area, it is assumed that the rivers supply virtually the whole amount of water necessary to balance the water tables close to its required observed positions. On the other hand, aquifer recharge also occurs by the direct vertical transfer of water from the precipitation and return (urban and irrigation) flows. Thus horizontal as well as vertical hydraulic conductivities are the important parameters of aquifers and aquitards used to control the lateral and vertical flow rates into the modeled area. Other calibration parameters that may control the hydraulic head output under the existing pumping conditions are the storage coefficients of the aquifers and aquitards of the geological formations.

For calibration from January 2000 to December 2004 with a set of values of parameters the model was run repetitively following trial-and error approach. In each run, the simulated water levels of the monitoring wells were plotted to check the variation with observed levels for that time period. Figure 6.3 to 6.13 show the comparison between the observed and simulated water levels after final calibration. These figures show that there is a satisfactory agreement between the observed and the simulated results. Contour map on simulated groundwater levels (m PWD) of the model area for December 2004 is shown in Figure 6.1 and 6.2. The simulated head projects the pronounce cone of depression in Dhaka City which is induced by large scale groundwater abstraction. The head pattern over the study area is in close agreement with the analysis of observed GWL data.

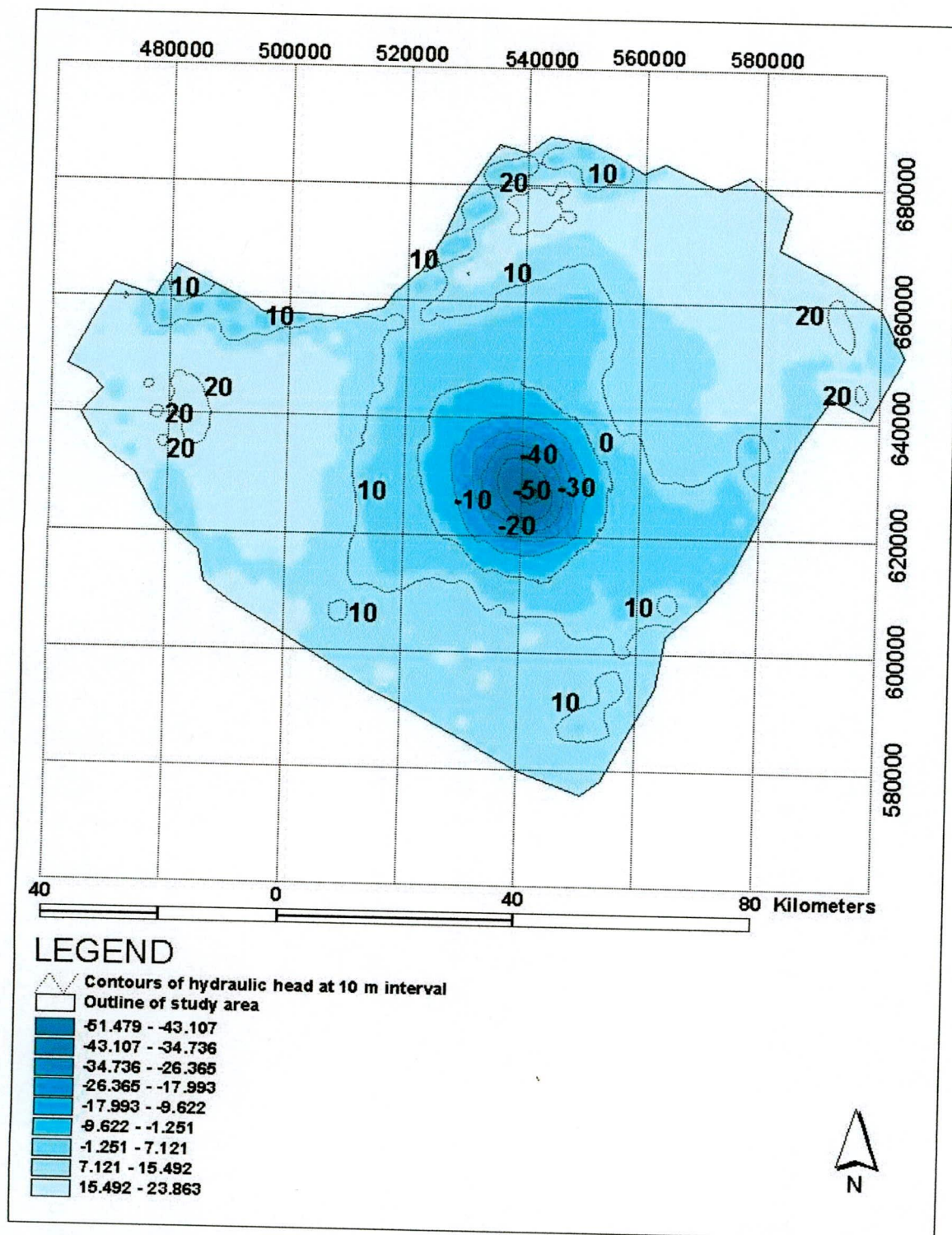


Figure 6.1 Contour of simulated head (m PWD) over study area as on 31 December 2004

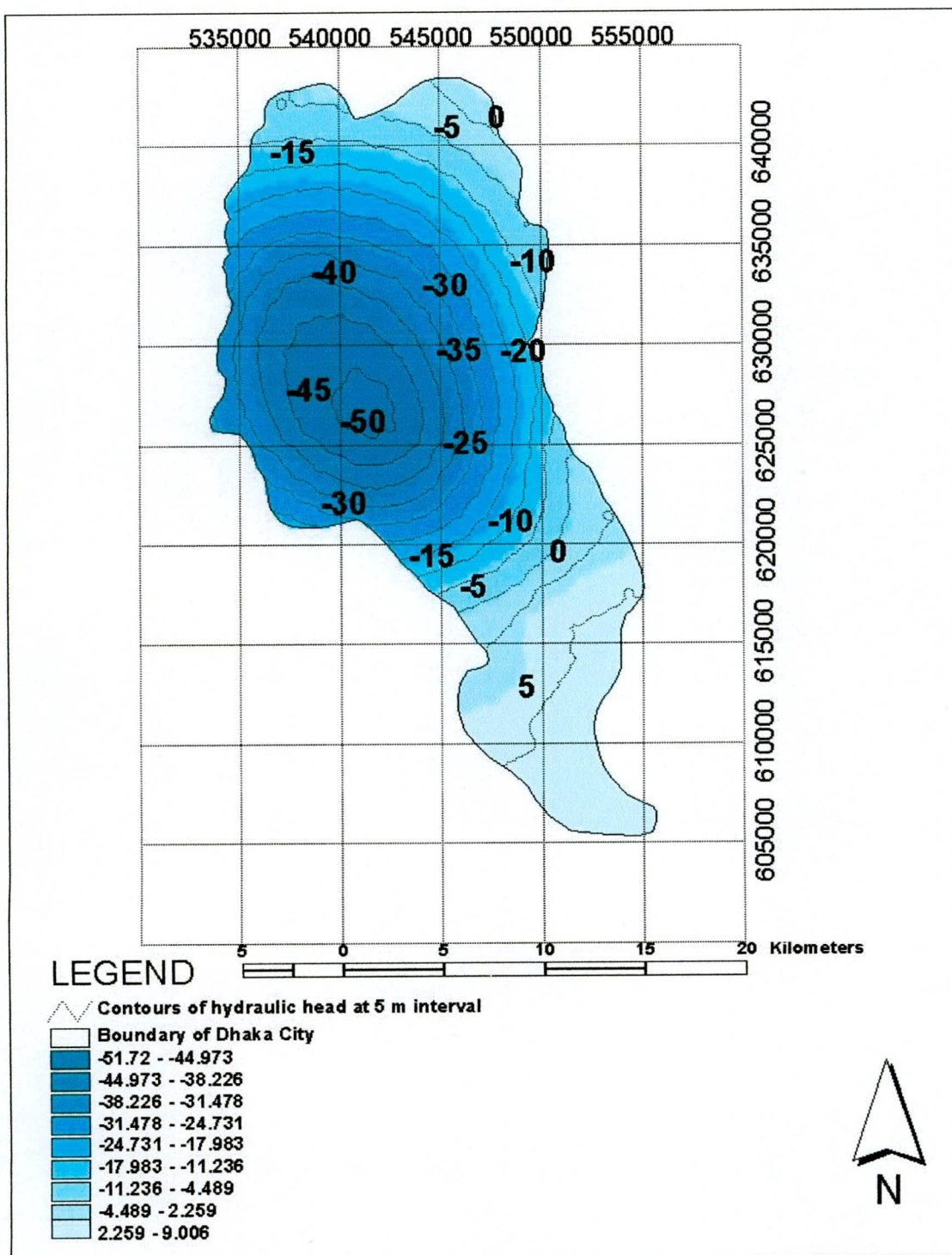


Figure 6.2 Contour of simulated head (m PWD) over Dhaka City as on 31 December 2004

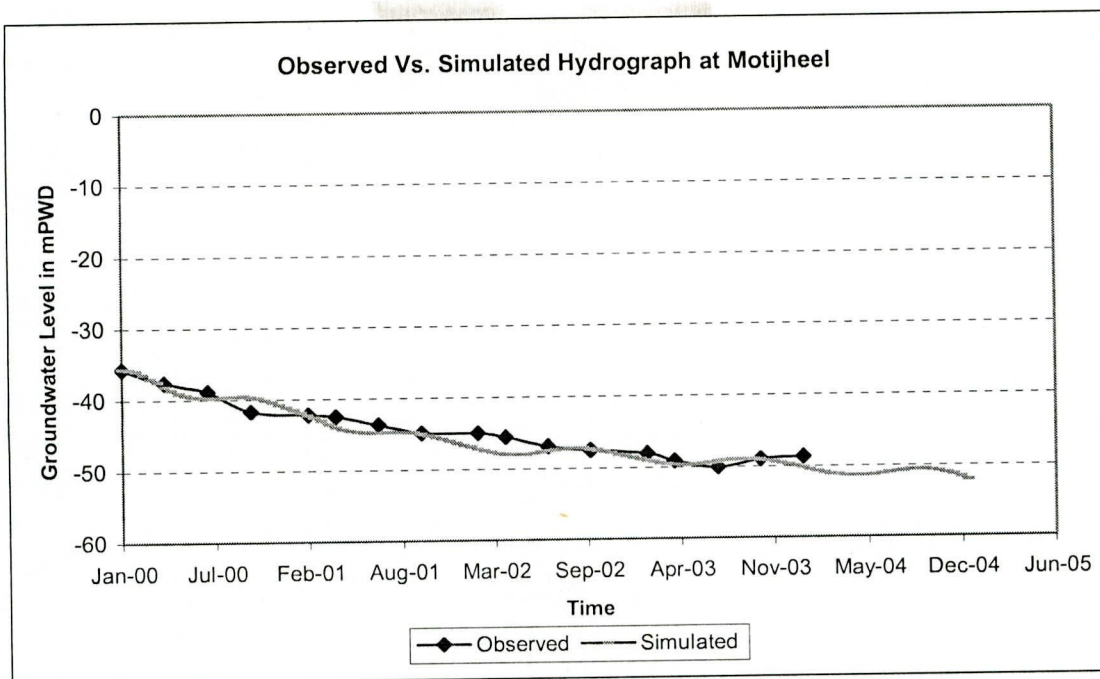


Figure 6.3 Simulated and Observed Hydrographs at Motijheel

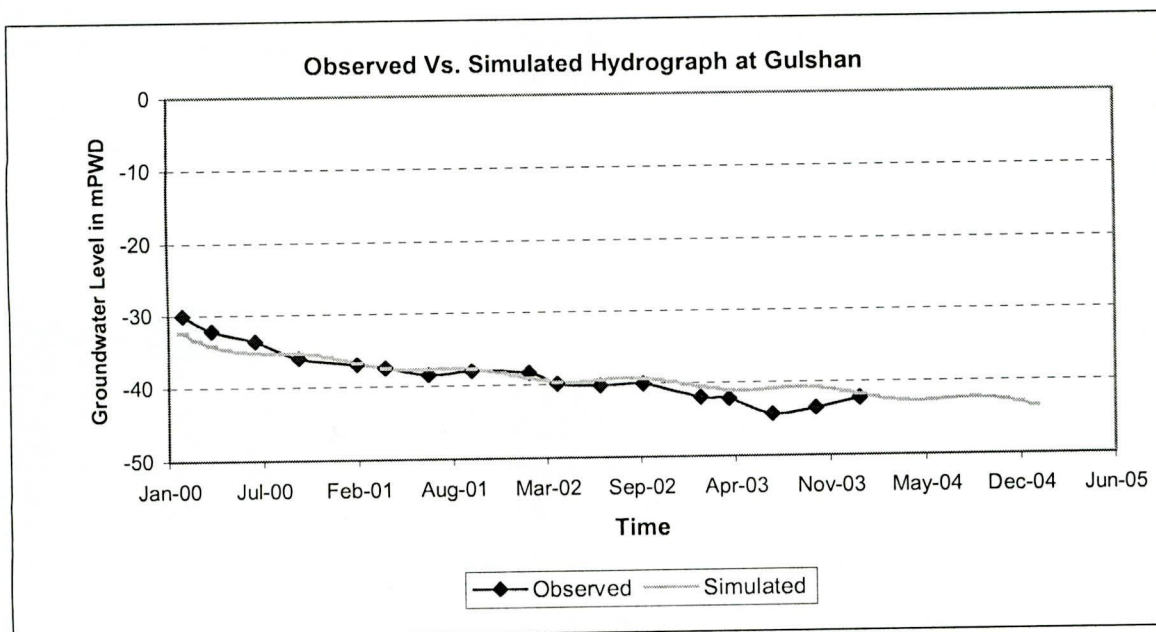


Figure 6.4 Simulated and observed hydrographs at Gulshan

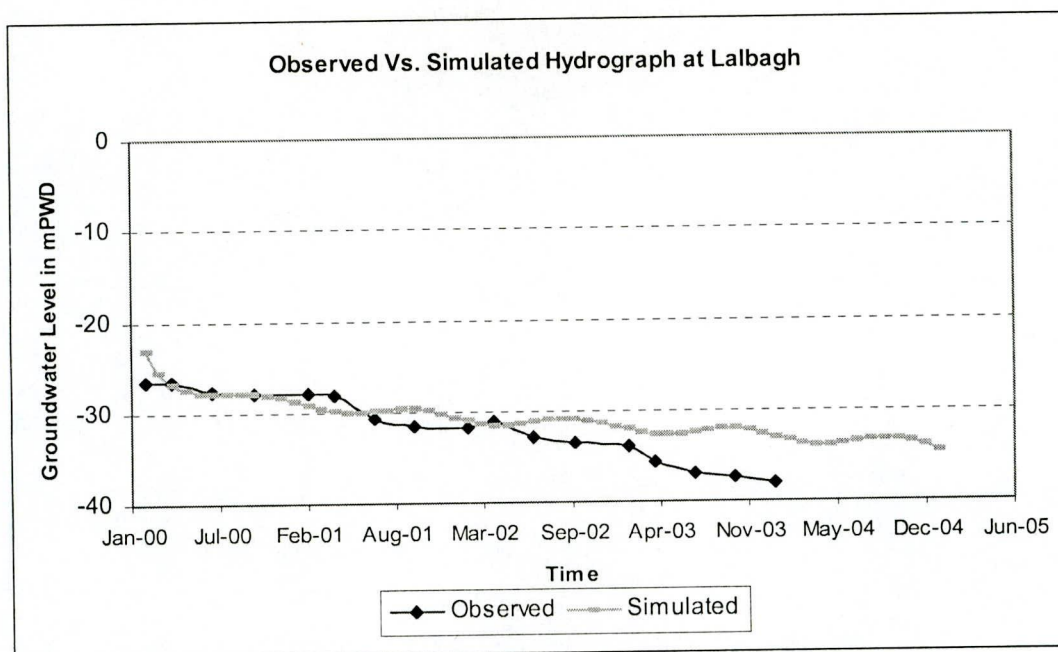


Figure 6.5 Simulated and Observed Hydrographs at Lalbagh

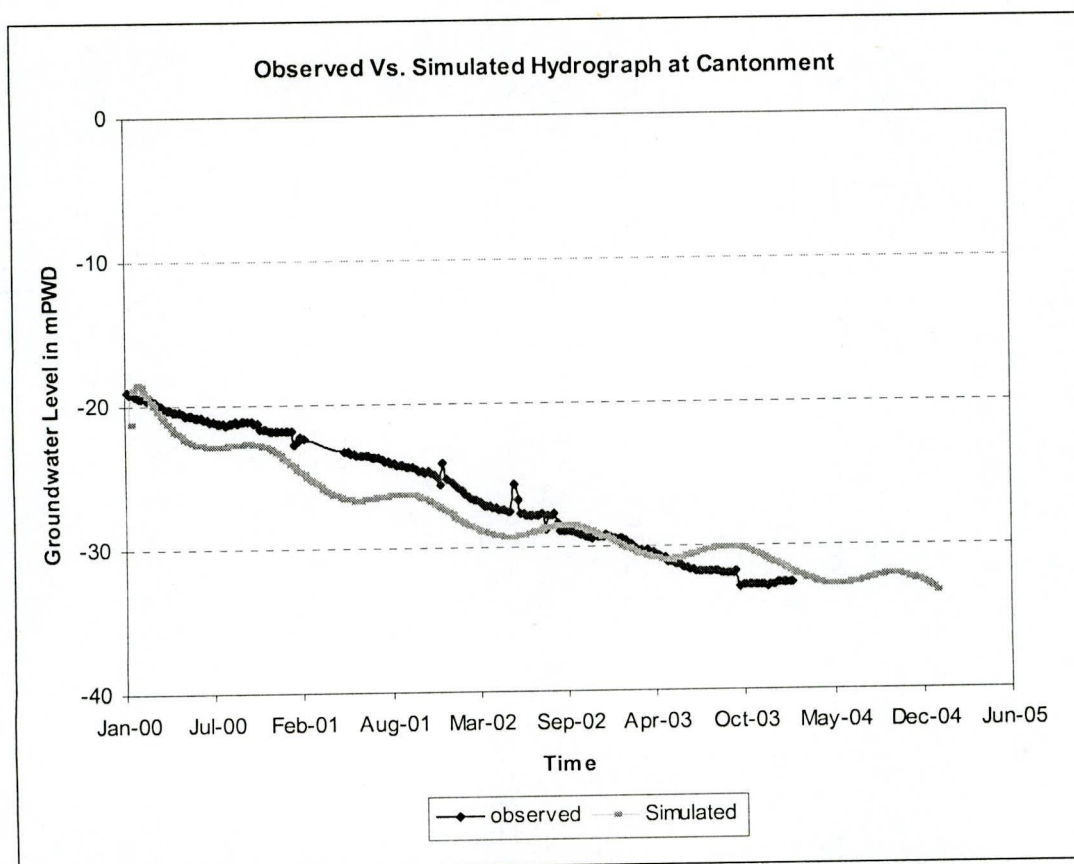


Figure 6.6 Simulated and observed hydrographs at Cantonment

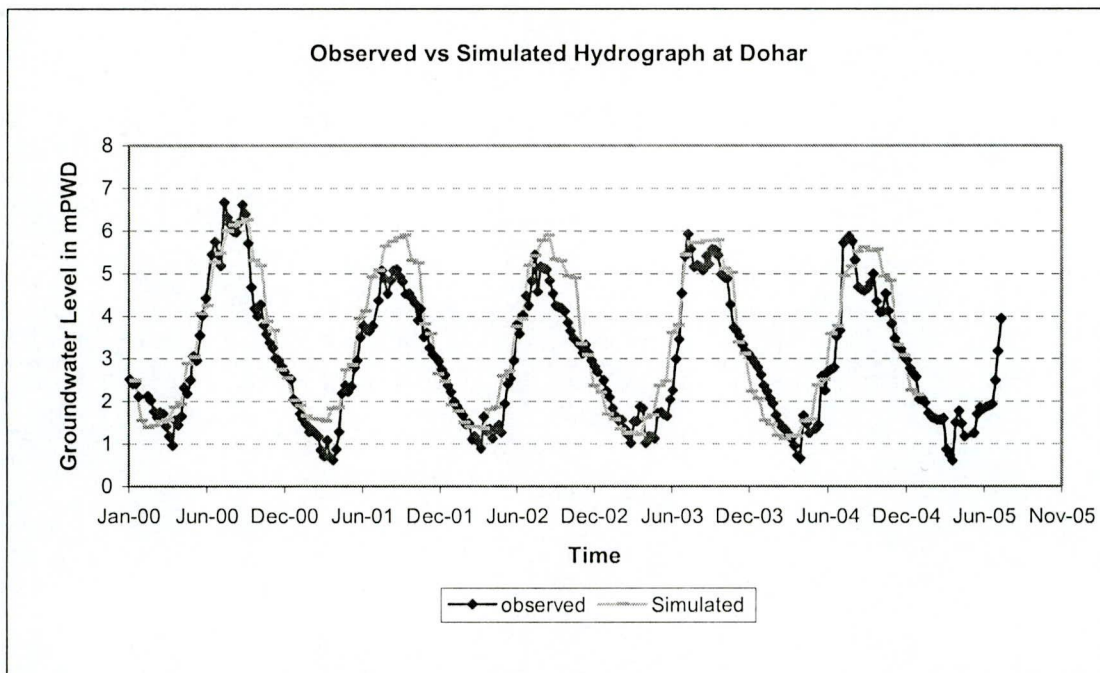


Figure 6.7 Simulated and Observed Hydrographs at Dohar (upper aquifer)

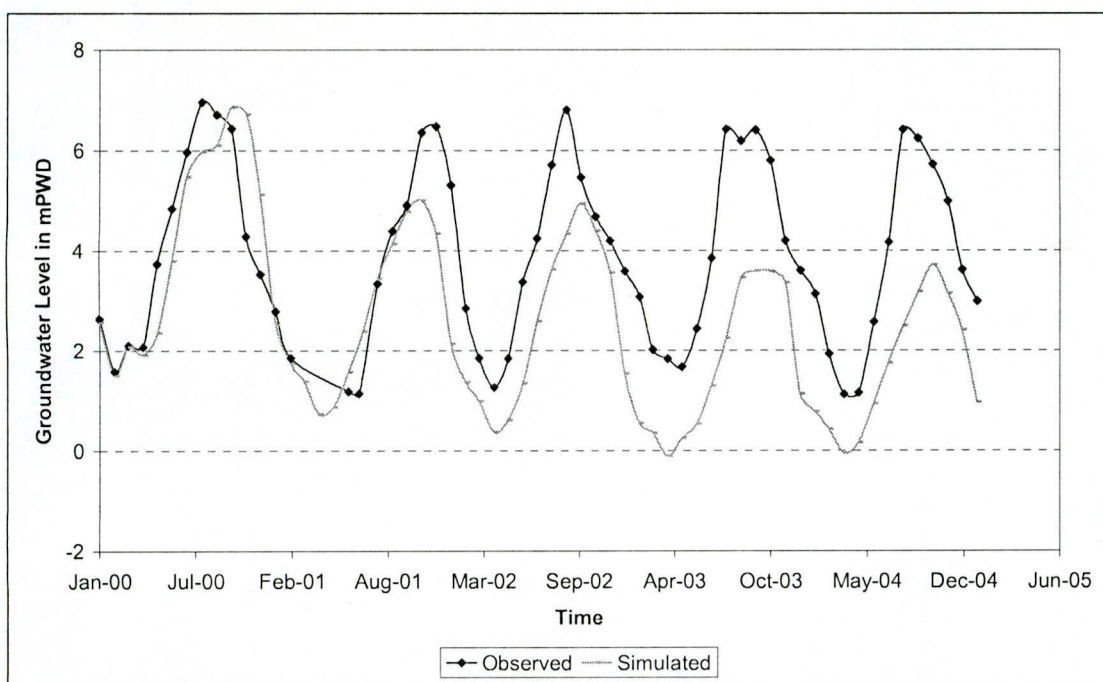


Figure 6.8 Simulated and Observed Hydrographs at Singair (upper aquifer)

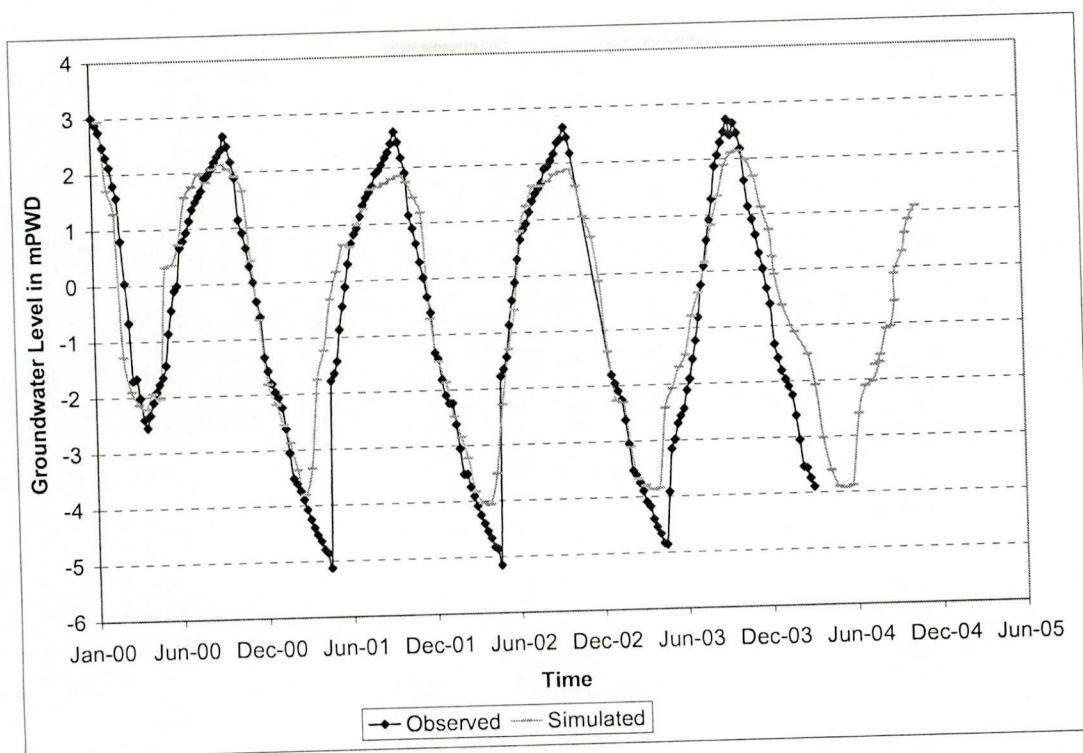


Figure 6.9 Simulated and Observed Hydrographs at Gazipur (upper aquifer)

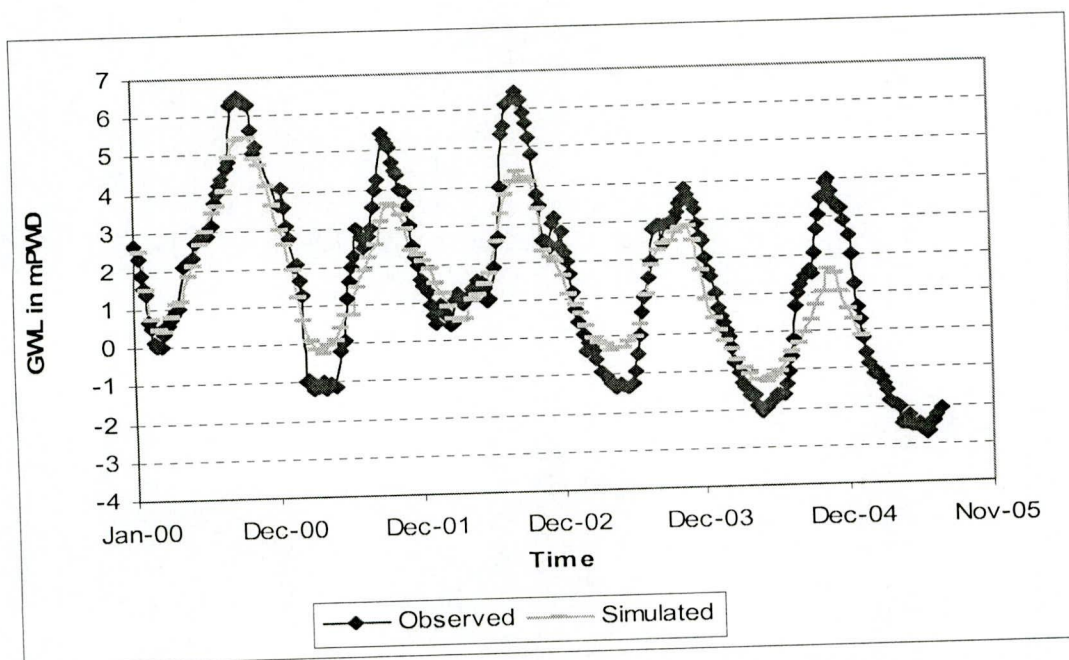


Figure 6.10 Simulated and Observed Hydrographs at Savar (upper aquifer)

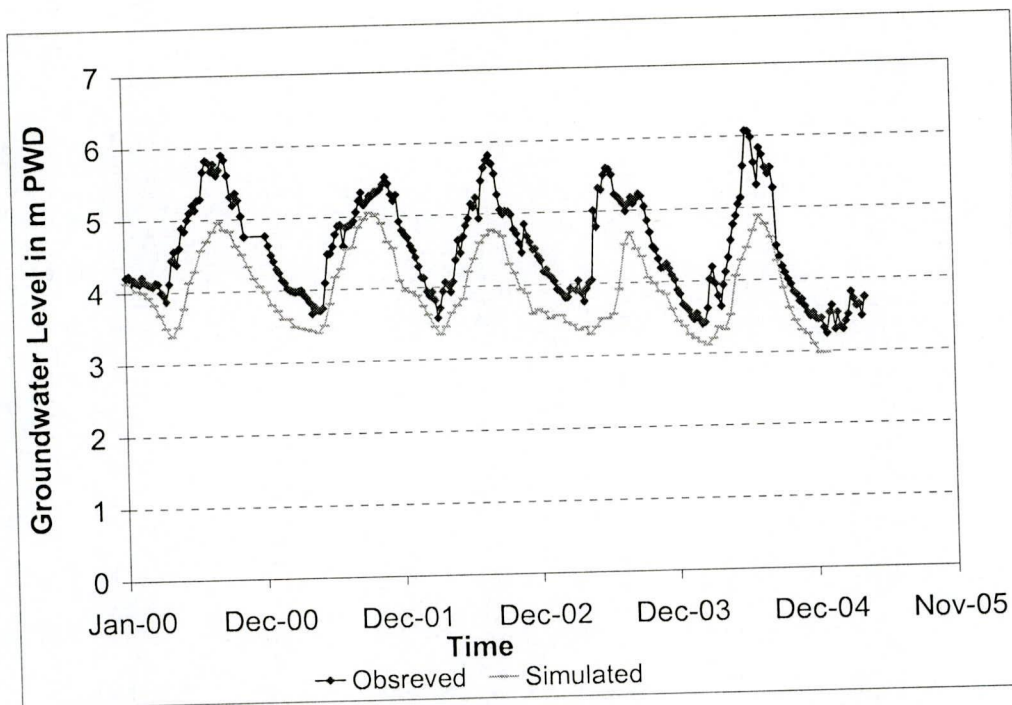


Figure 6.11 Simulated and Observed Hydrographs at Narshingdi (upper aquifer)

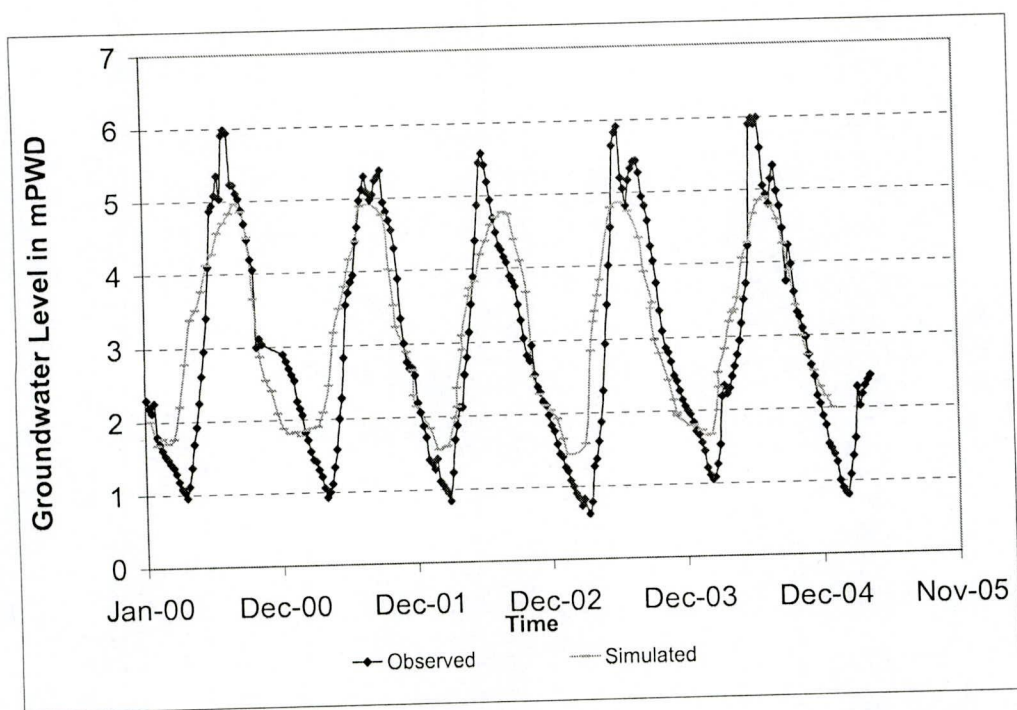


Figure 6.12 Simulated and Observed Hydrographs at Munshiganj (upper aquifer)

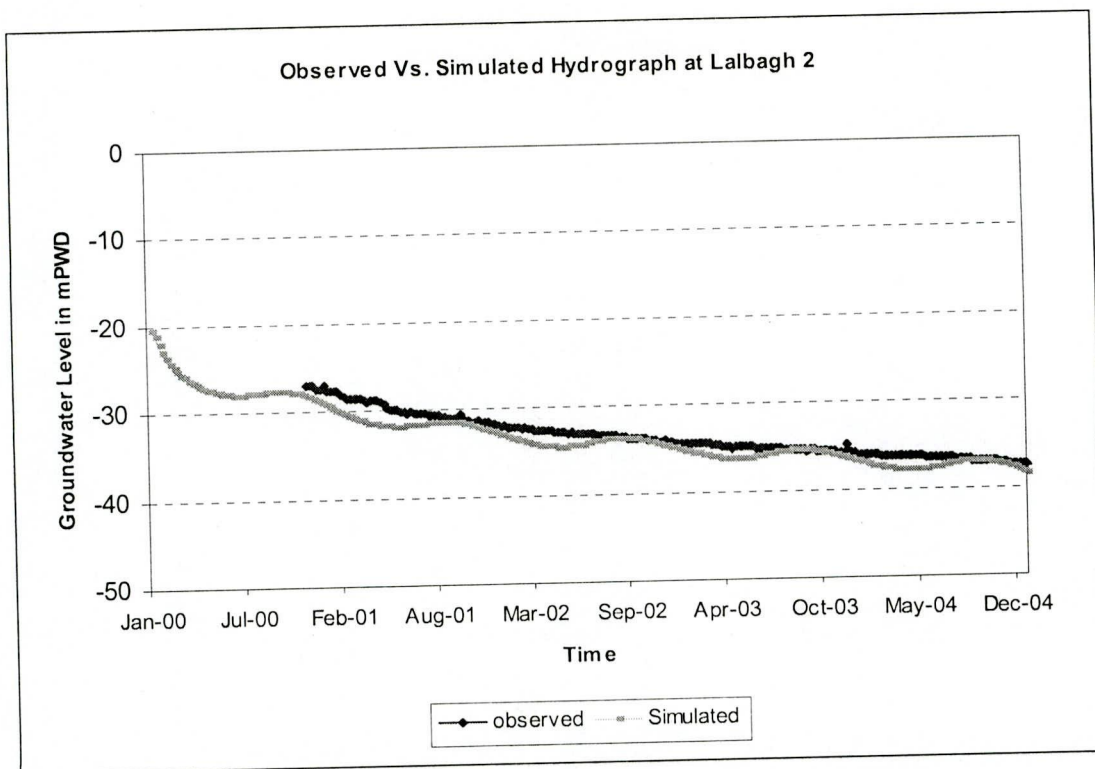


Figure 6.13 Simulated and observed hydrographs at Lalbagh 2

6.2 Calibrated aquifer parameters

The calibrated spatial aquifer parameter distributions are shown in Appendix B and can be summarized in the following section.

Horizontal hydraulic conductivity (K_h)

The calibrated horizontal hydraulic conductivity has been summarized in the Table 6.1 and the distribution of horizontal hydraulic conductivity among different layers have been presented in Appendix B.

Table 6.1 Calibrated horizontal hydraulic conductivity, K_h (m/day)

Statistics	Layers					
	Upper Aquitard	Upper Aquifer	Intermediate Aquitard	Intermediate Aquifer	Deep Aquitard	Deep Aquifer
Maximum	0.00	27.00	0.00	54.00	0.00	54.00
Minimum	0.00	9.00	0.00	27.00	0.00	25.34
25% Tile	0.00	11.56	0.00	27.00	0.00	27.00
75% Tile	0.00	18.19	0.00	34.92	0.00	39.80
Mean	0.00	14.45	0.00	32.58	0.00	35.53

The results of the calibrated model indicate that the horizontal hydraulic conductivity of upper aquifer ranges between 9.00 – 27.00 m/day. The twenty five percent area of this layer comprises of K_h less than 11.56 m/day and for the other 25% the values of K_h are greater than 18.19 m/day. The K_h values range between 11.56 – 18.19 m/day for the remaining 50% of the layer while the average horizontal conductivity of the whole formation is 14.45 m/day. The horizontal hydraulic conductivity of the intermediate aquifer ranges between 27.00 – 54.00 m/day. One-fourth area of this layer has K_h less than 27.00 m/day and other one fourth has values of K_h greater than 34.45 m/day. The remaining half of the layer contains K_h ranges between 27.00 – 34.45 m/day and the average horizontal conductivity of the whole formation is 32.58 m/day. The horizontal hydraulic conductivity of the deep aquifer ranges between 25.34 – 54.00 m/day. One-fourth area of this layer has K_h less than 27.00 m/day and other one fourth has values of K_h greater than 39.80 m/day. The remaining half of the layer contains K_h ranges between 27.00 – 39.80 m/day and the average horizontal conductivity of the whole formation is 35.53 m/day.

Vertical hydraulic conductivity (K_v)

The calibrated vertical hydraulic conductivity has been summarized in the Table 6.2 and the distribution of vertical hydraulic conductivity among different layers has been presented in the Appendix B.

Table 6.2 Calibrated vertical hydraulic conductivity, K_v (m/day)

Statistics	Layers					
	Upper Aquitard	Upper Aquifer	Intermediate Aquitard	Intermediate Aquifer	Deep Aquitard	Deep Aquifer
Maximum	0.025	20.00	0.173	24.00	0.15	19.20
Minimum	0.025	6.67	0.173	12.00	0.15	9.60
25%Tile	0.025	8.56	0.173	12.00	0.15	9.60
75% Tile	0.025	13.47	0.173	15.52	0.15	14.84
Mean	0.025	10.71	0.173	14.48	0.15	12.89

The results of the calibrated model show that the vertical hydraulic conductivity of aquitards is uniform throughout the model area. K_v of upper aquifer ranges between 6.67 – 20.00 m/day. The values of K_v is less than 8.56 m/day for 25% area of the formation and K_v values greater than 13.47 m/day represent other 25% of the layer. The K_v values range between 8.56 – 13.47 m/day for the remaining 50% of the layer and the average vertical conductivity of layer-1 is 10.71 m/day where as for the intermediate aquifer the vertical hydraulic conductivity ranges between 12.00 – 24.00 m/day. The values of K_v is less than 12.00 m/day for 25 percent area of the formation and K_v values greater than 15.52 m/day represent other 25% of the layer. The K_v values range between 12.00 – 15.52 m/day for the remaining 50% of the layer and the average vertical conductivity is 14.48 m/day. Like wise the distribution of K_v in deep aquifer can be analysed as the values K_v of different model layers have been summarized in the Table 6.2.

Specific storage (S_s)

From the statistics as shown in Table 6.3 it can be analysed that the areal distribution of calibrated specific storage in different layers are more or less uniform in nature.

Table 6.3 Calibrated specific storage, S_s (m^{-1})

Statistics	Layers					
	Upper Aquitard	Upper Aquifer	Intermediate Aquitard	Intermediate Aquifer	Deep Aquitard	Deep Aquifer
Maximum	1.5E-07	2.65E-05	1.25E-07	6.25E-05	1.00E-07	6.25E-04
Minimum	1.5E-07	7.35E-08	1.25E-07	5.64E-06	1.00E-07	5.64E-05
25%Tile	1.5E-07	8.74E-06	1.25E-07	6.25E-06	1.00E-07	6.25E-05
75% Tile	1.5E-07	8.76E-06	1.25E-07	6.25E-06	1.00E-07	6.25E-05
Mean	1.5E-07	8.96E-06	1.25E-07	6.37E-06	1.00E-07	6.37E-05

6.3 Results of estimated land subsidence from the calibrated groundwater model

The SUB package of MODFLOW-2000 simulates both elastic and inelastic compaction of compressible layers (unit 1, 3 and 5 as shown in Figure 5.26) in the model formation located adjacent and within the aquifers.

Once the groundwater model is calibrated it can be used to estimate the amount of subsidence. Table 6.4 shows the model computed land subsidence at selected places (Figure 6.15) of subsidence computation units. Subsidence contour map (Figure 6.14) shows that the model computed subsidence over a period of 5 years (from 2000 to 2004) is maximum 4.9 cm. The subsidence results indicate that due to groundwater pumping a gentle subsidence bowl develops slowly and can extend over large area. Figure 6.16 shows that land subsidence has increased sharply during the initial 6 month and thereafter followed a constant increasing trend. The consequences of land subsidence may be dangerous in both cases when the amount of subsidence is very high and if not distributed over a large area. From Figure 6.14 it is also evident that the estimated subsidence is higher in areas where density of wells is maximum.

Table 6.4 Model estimated subsidence at selected places

Sl	SCU	Easting	Northing	Estimated Subsidence(m)
1	1A	541000	631658	0.0323
2	1B	536614	628405	0.0415
3	1C	542357	622671	0.0324
4	1D	538374	625760	0.0455
5	1E	542559	625842	0.0429
6	1F	541981	631921	0.0276
7	1G	542645	637294	0.0012
8	1H	543598	621964	0.0255
9	2	530269	630861	0.0002
10	3	542587	641434	0.0024
11	4	549311	635963	0.0003
12	5A	550726	622835	0.0003
13	5B	548879	614028	0.0003
14	6	540654	621176	0.0167

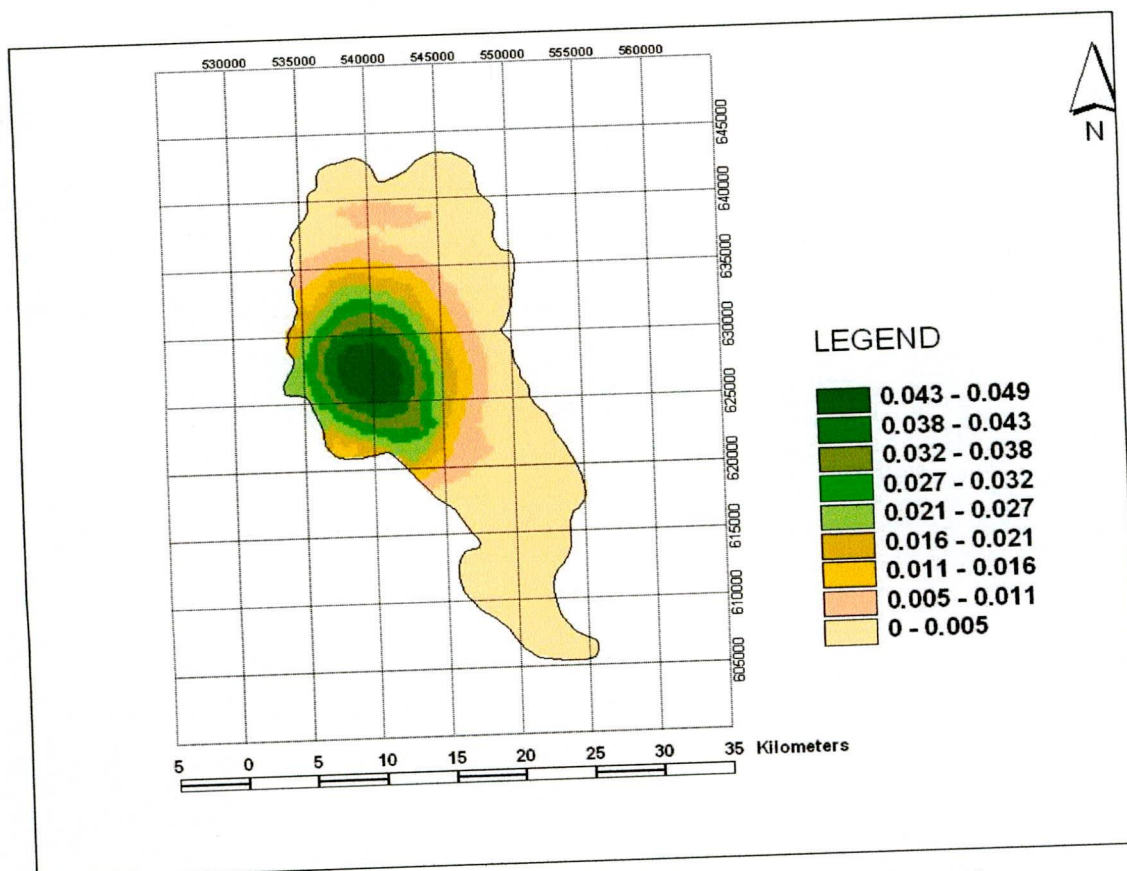


Figure 6.14 Land subsidence (m) in December 2004 over Dhaka City area

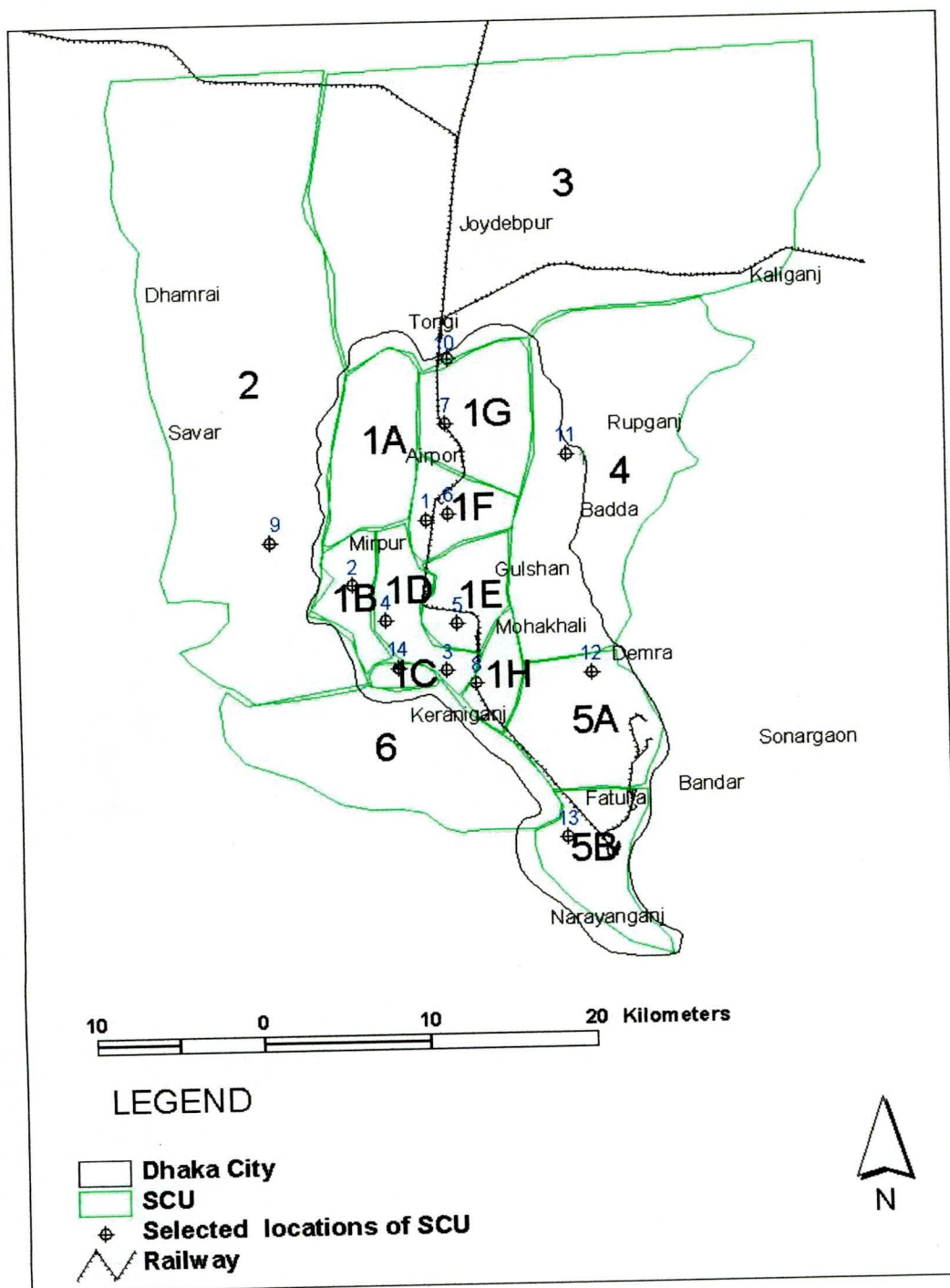


Figure 6.15 Map showing selected places in the SCU for subsidence computation (Number above the location symbol refer to the sl of Table 6.4)

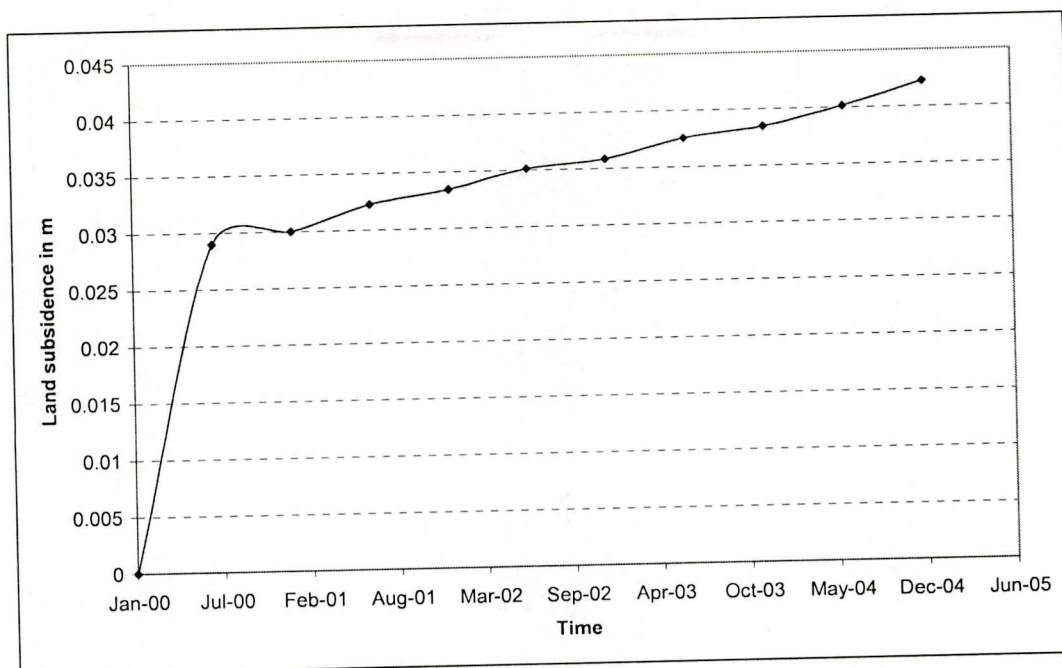


Figure 6.16 Time series result at the point (SCU 1D in Figure 6.15) of maximum subsidence)

6.4 Sensitivity analysis

Sensitivity analysis was carried out for the following aquifer parameters:

- Horizontal conductivity unit 4
- Vertical conductivity unit 4
- Specific storage unit 4
- Specific Yield unit 4
- Vertical conductivity unit 3
- Prescribe head boundary condition unit 4

Results of the sensitivity analysis were obtained in terms of hydraulic head in unit 4 at the observation well location of area Motijheel. For test of sensitivity the parameter values were varied within a range of 25% to 175% as shown in results of the sensitivity test summarized in Table 6.5.

The sensitivity analysis shows that horizontal hydraulic conductivity has a great influence in the model calibration. There is a significant amount of increase and decrease of GWL if the horizontal conductivity is varied in the range 0.25 to 1.75 times. Due to the increase of vertical conductivity of the same layer (layer for which simulated head is obtained) there is a negligible rise in head. But the increase of vertical conductivity of the upper layer makes a little more response than the conductivity of the same layer. The variation of specific storage and specific yield has no influence on the model result. It is also substantiated that the external boundary condition (prescribed head unit 4) along the northern edge of the model has no impact on the head output inside Dhaka City. This was one of the reasons for taking the model boundary far away from Dhaka City. So from the results, it has been found that the model is least sensitive to storage properties and most sensitive to horizontal conductivity. This makes the horizontal conductivity the key parameter in calibrating the model.

Table 6.5 Results of sensitivity analysis

Simulated Groundwater Level at Motijheel (m PWD)							
Factor	Min	1 st Quartile	Median	3 rd Quartile	Max	Mean	SD
Horizontal Hydraulic Conductivity Unit 4							
0.25	-177.79	-168.65	-161.14	-149.20	-115.94	-157.86	14.63
0.5	-98.87	-94.07	-90.15	-84.88	-69.85	-88.73	7.29
0.75	-67.03	-63.26	-60.94	-58.11	-49.78	-60.39	4.18
1	-51.03	-48.27	-46.51	-44.43	-39.31	-46.20	2.92
1.25	-41.11	-38.96	-37.50	-35.84	-32.92	-37.33	2.22
1.5	-34.26	-32.38	-31.12	-29.75	-28.30	-31.09	1.76
1.75	-29.21	-27.62	-26.49	-25.30	-24.18	-26.54	1.43

Table 6.5 Results of sensitivity analysis (continued)

Vertical Hydraulic Conductivity Unit 4							
0.25	-51.040	-48.279	-46.523	-44.440	-39.318	-46.210	2.918
0.5	-51.034	-48.273	-46.516	-44.433	-39.311	-46.204	2.917
0.75	-51.031	-48.272	-46.514	-44.430	-39.309	-46.202	2.917
1	-51.032	-48.271	-46.513	-44.429	-39.308	-46.203	2.919
1.25	-51.031	-48.270	-46.512	-44.429	-39.307	-46.202	2.918
1.5	-51.031	-48.270	-46.512	-44.428	-39.307	-46.202	2.918
1.75	-51.030	-48.269	-46.511	-44.428	-39.306	-46.201	2.918
Specific Storage Unit 4							
0.25	-51.030	-48.269	-46.511	-44.428	-39.306	-46.201	2.918
0.5	-51.030	-48.269	-46.511	-44.428	-39.306	-46.201	2.918
0.75	-51.030	-48.269	-46.511	-44.428	-39.306	-46.201	2.918
1	-51.032	-48.271	-46.513	-44.429	-39.308	-46.203	2.919
1.25	-51.030	-48.269	-46.511	-44.428	-39.306	-46.201	2.918
1.5	-51.030	-48.269	-46.511	-44.428	-39.306	-46.201	2.918
1.75	-51.030	-48.269	-46.511	-44.428	-39.306	-46.201	2.918
Specific Yield Unit 4							
0.25	-48.414	-45.883	-44.186	-42.219	-37.254	-43.904	2.731
0.5	-48.414	-45.883	-44.186	-42.219	-37.254	-43.904	2.731
0.75	-48.414	-45.883	-44.186	-42.219	-37.254	-43.904	2.731
1	-48.414	-45.883	-44.186	-42.219	-37.254	-43.904	2.731
1.25	-48.414	-45.883	-44.186	-42.219	-37.254	-43.904	2.731
1.5	-48.414	-45.883	-44.186	-42.219	-37.254	-43.904	2.731
1.75	-48.414	-45.883	-44.186	-42.219	-37.254	-43.904	2.731
Vertical Hydraulic Conductivity Unit 3							
0.25	-48.624	-46.051	-44.369	-42.381	-37.386	-44.061	2.774
0.5	-48.507	-45.956	-44.267	-42.286	-37.334	-43.972	2.753
0.75	-48.468	-45.923	-44.231	-42.258	-37.297	-43.944	2.739
1	-48.442	-45.905	-44.212	-42.241	-37.278	-43.927	2.736
1.25	-48.429	-45.896	-44.200	-42.231	-37.267	-43.916	2.733
1.5	-48.420	-45.888	-44.192	-42.224	-37.259	-43.909	2.732
1.75	-48.414	-45.883	-44.186	-42.219	-37.254	-43.904	2.731
Prescribed Boundary Condition Unit 4							
0.25	-48.415	-45.883	-44.186	-42.219	-37.254	-43.904	2.731
0.5	-48.414	-45.883	-44.186	-42.219	-37.254	-43.904	2.731
0.75	-48.414	-45.883	-44.186	-42.219	-37.254	-43.904	2.731
1	-48.414	-45.883	-44.186	-42.220	-37.254	-43.905	2.731
1.25	-48.414	-45.883	-44.186	-42.219	-37.254	-43.904	2.731
1.5	-48.414	-45.883	-44.186	-42.219	-37.254	-43.904	2.731
1.75	-48.414	-45.882	-44.186	-42.219	-37.254	-43.904	2.730

6.5 Water balance

One of the methods of expressing model results is through a water balance. Water Balance data provide both an indication of the relative magnitude of flow components within the study area, as well as a means to check that the model solution has remained stable. If there is an error in the iterative solution then it is likely to show up in the water balance. For that reason it has been checked whether the model change in aquifer storage is equivalent to the total inflow minus outflow. The aquifer characteristics as well as recharge pattern and the groundwater abstraction rate vary spatially within the whole study area. To find the variability of the aquifer characteristics and to calculate the water balance of Dhaka City the study area has been divided into two zones as shown in the Figure 6.17 and the exchange of flows between the zones has been calculated separately. The model has been set up to calculate the water balance considering the entire thickness of model formation. External stresses such as wells, areal recharge and rivers are simulated to calculate the water budget of Dhaka City area for the calibration period (January 2000 to December 2004). In the water balance diagrams as shown in Figure 6.18 and 6.19, storage changes are referred to as Δs with plus or minus sign. A minus sign refers to the water released from storage of the layer and plus sign refers to the water added to the storage of the layer. The water balance results have shown discrepancies of less than 0.01%, which is generally considered an acceptable error.

After calibration of the model the water balance of the area Dhaka City for the whole year of 2004 shows that total abstraction of 731 Mm^3 is higher than the total contribution from rivers, precipitation and return flows. So there is a deficit of 134 Mm^3 that is coming from the storage of the aquifer system for that period and causing the water table lowering. Abstraction history of Dhaka City shows (Figure 5.10 and Table 5.3) that it has been increasing every year to meet the required demand of water. In this regard the aquifer system under Dhaka City is always under increasing stress and there is no chance to get back to previous year's level.

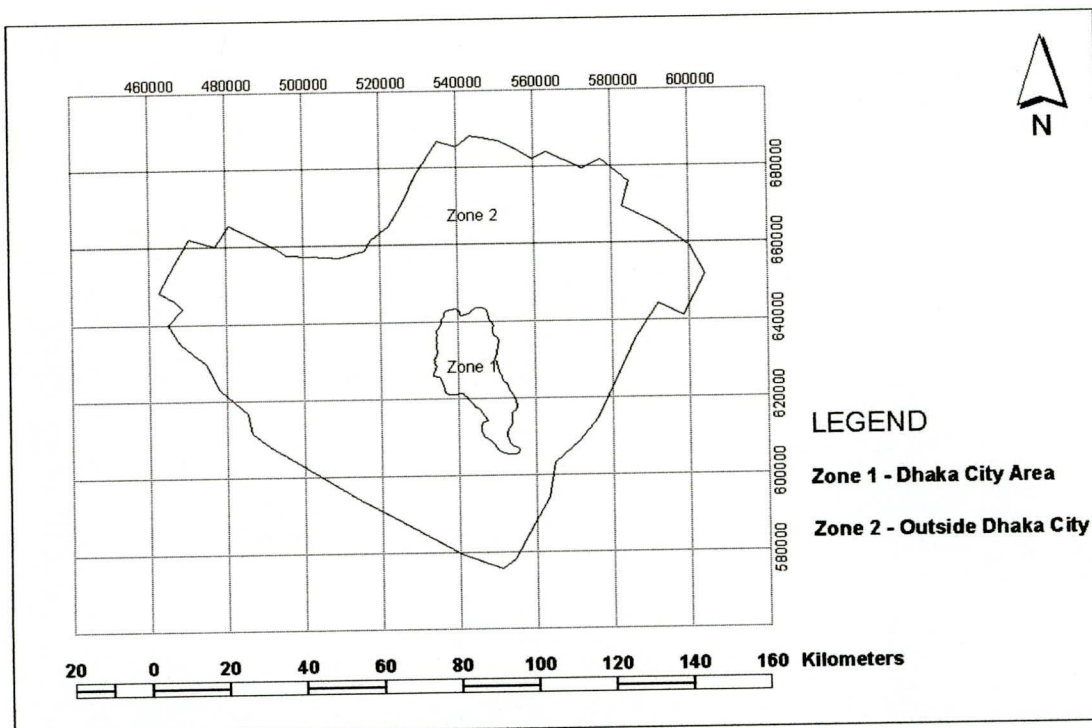


Figure 6.17 Zoning of model area for water balance study of Dhaka City

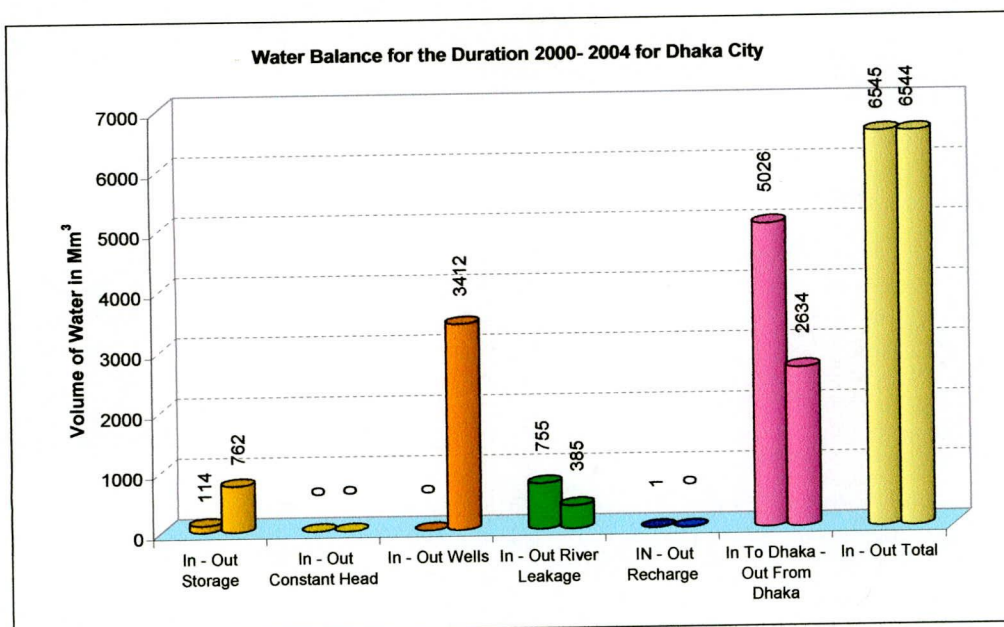


Figure 6.18 Water balance for the duration Jan 2000 to Dec 2004 for Dhaka City

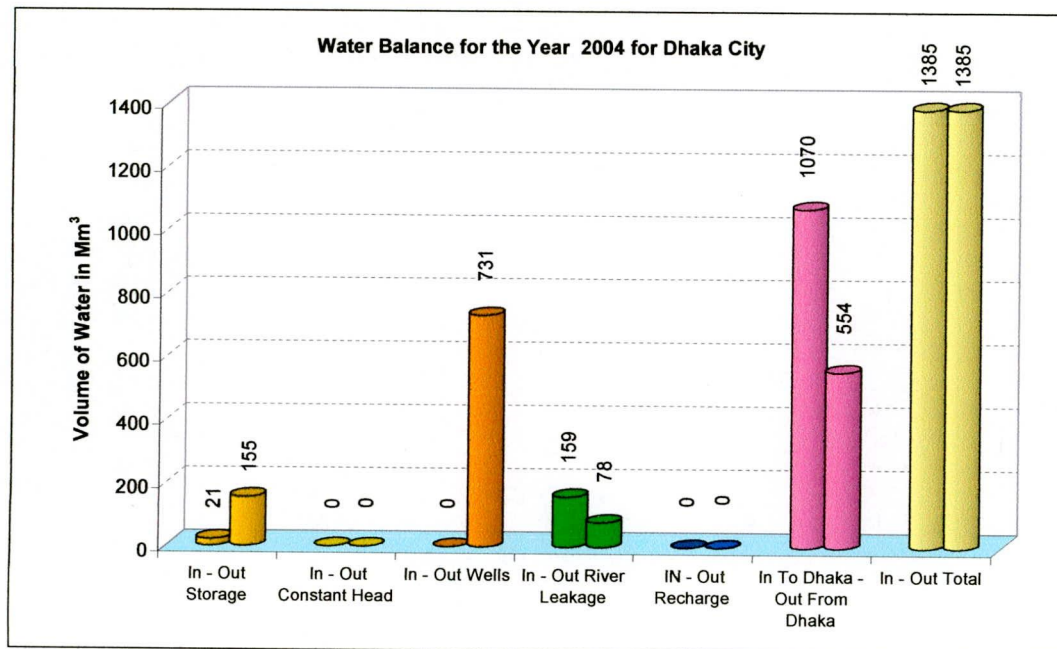


Figure 6.19 Water balance for the duration Jan 2004 to Dec 2004 for Dhaka City

From Figure 6.18 and 6.19 it can be analyzed that there is no change inside aquifers of Dhaka City due to the effect of constant head boundary which is set along the northern edge of the study area. Well abstraction is the most important stress component of the model. The change in storage ($\Delta S = \text{Storage in} - \text{Storage out}$) is negative because of the excessive pumping from the Dhaka aquifers though it is gaining water both from the surrounding rivers and inflow from zone 2. The recharge component over the Dhaka City is very small as evident from the Figures showing the water balance. From Figure 6.19 the annual average declination of head during 2000-2004 over Dhaka City area can be computed as shown below:

$$\begin{aligned}
 \text{Average head declination} &= \frac{\text{Storage out} - \text{Storage in}}{\text{Area of Dhaka City}} \\
 &= \frac{(762 - 11463) \text{ Mm}^3}{448 \text{ Km}^2} \\
 &= 1.446 \text{ m} \cong 1.5 \text{ m}
 \end{aligned}$$

From Figure 6.19 ΔS for the year 2004 can be obtained as given below:

$$\Delta S = \text{Storage in} - \text{Storage out}$$

$$= 21 - 155$$

$$= - 134 \text{ Mm}^3$$

6.6 Results of scenario analysis

While selecting future development scenarios following assumptions were made:

- All the parameters/assumptions used on hydrogeological characteristics of the aquifer remain the same.
- Groundwater conditions computed by the calibrated flow model for December 2004 have been used as “initial condition”.
- It is assumed that recharge from the irrigation system will remain unchanged during the next 15 years.
- No dramatic changes in the hydro-climatic conditions or flows of rivers in future.
- Model was run for 252 stress periods for the total 20 years.

6.6.1 Predicted GWL at the calibration points

Using the simulated groundwater conditions at December 2004 as initial conditions, few scenarios were studied to simulate the future dynamic response of aquifers. Results of scenario runs (shown in Figure 6.20 to 6.29) are obtained in terms of predicted GWL (of intermediate aquifer) at Lalbagh 1, Gulshan and Motijheel observation well locations. The groundwater model was used to simulate the hydrodynamics of groundwater for the next fifteen years based on these future development scenarios:

Scenario 1 Results : Continuation of rate of abstraction until 2020 as existed during the year 2004.

It is observed from scenario 1 results (Figure 6.20 to Figure 6.22) that if groundwater pumping is continued at rate as existed during 2004 then GWL will reach a steady state condition by April 2006. The setup and result of this scenario run is important in the sense that DWASA might think of controlling groundwater abstraction from upper Dupi Tila aquifer system by not allowing further increase in abstraction using both

DWASA and private DTWs. This would allow a sustainable condition for the total abstraction from the upper Dupi Tila aquifers of around 730 Mm^3 per year.

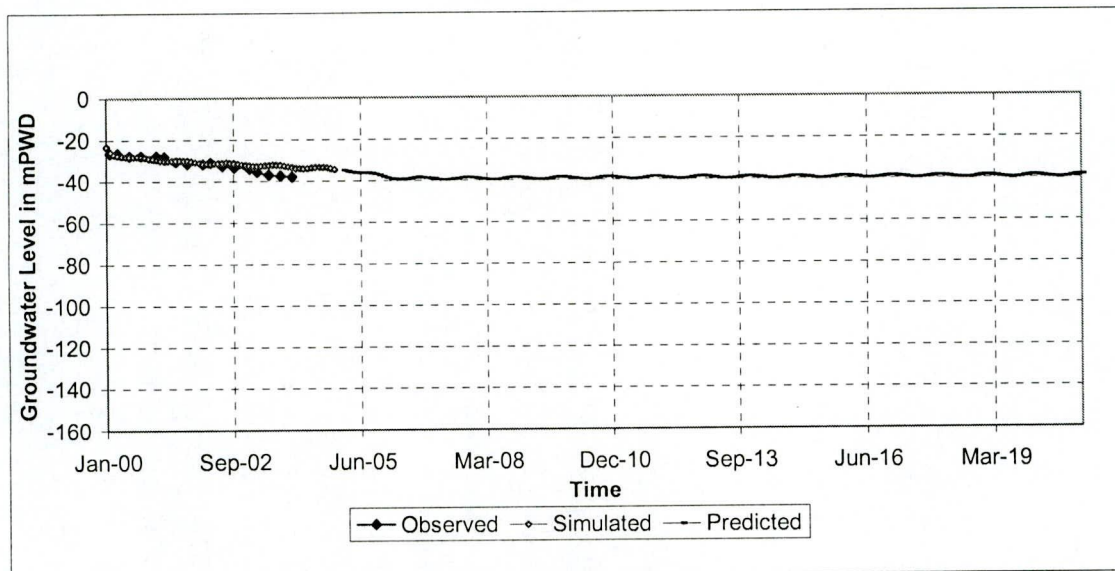


Figure 6.20 Predicted groundwater level at Lalbagh 1 for scenario 1

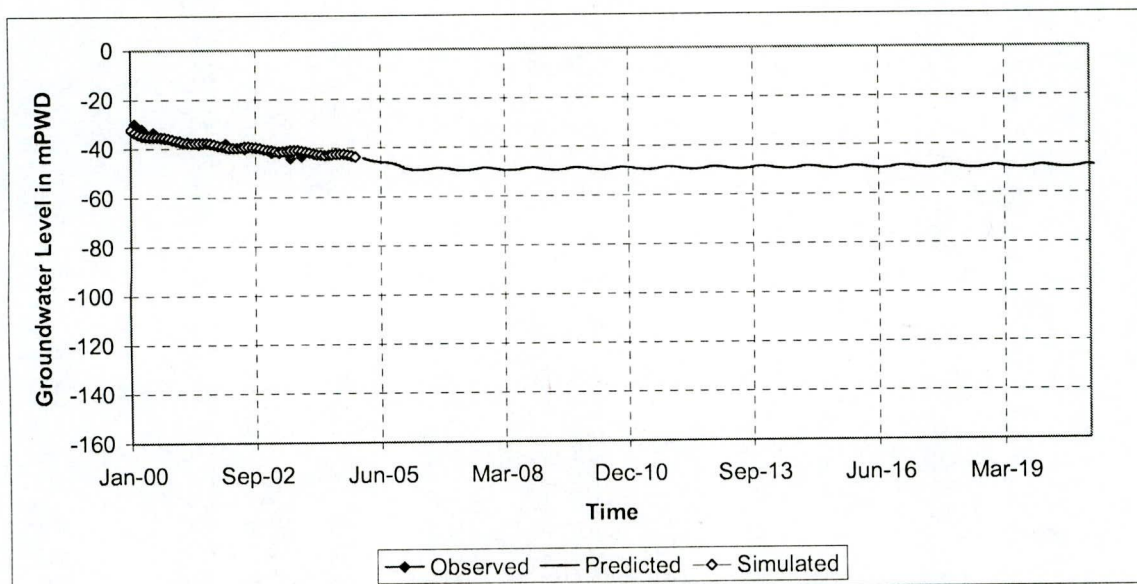


Figure 6.21 Predicted groundwater level at Gulshan for scenario 1

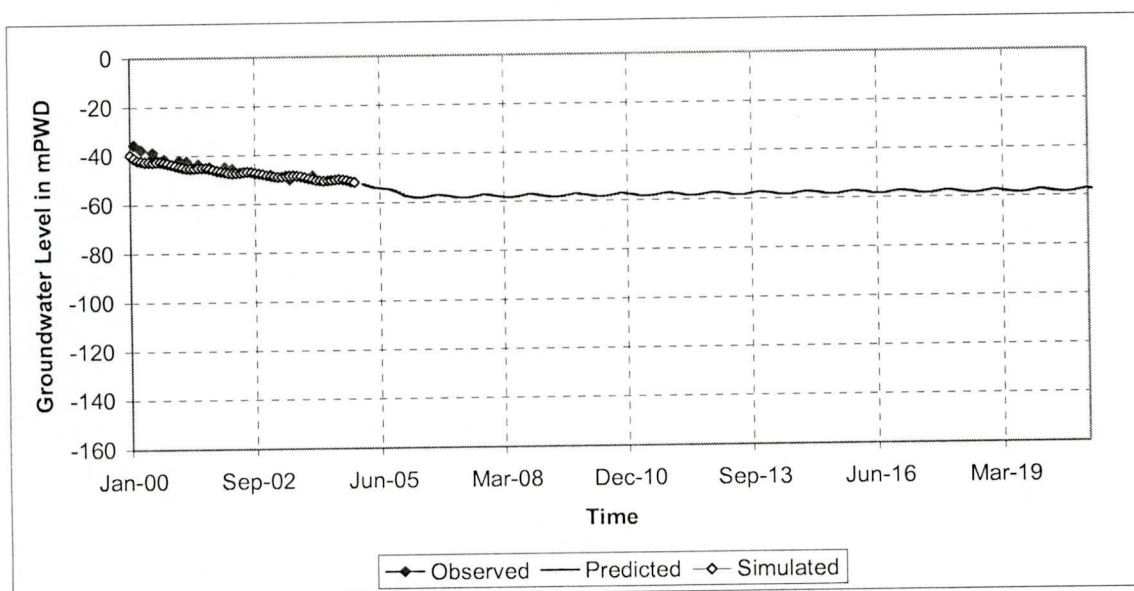


Figure 6.22 Predicted groundwater level at Motijheel for scenario 1

- **Scenario 2 Results: An annual increase of private abstraction at the rate of 10% from 2005 until 2020.**

This option was chosen in conformity with DWASA policy to not to install new DTWs in the upper Dupi Tila aquifer system. Because further depletion of GWL of this aquifer would render many wells inoperative. There can be severe impact on the geological environment of the area concerned amongst which land subsidence is the one that is most feared. In the recent past there has been only replacement of DTWs that has screens in the upper Dupi Tila aquifers. New DTWs has been installed mainly in the deep (lower Dupi Tila) aquifer. But there has been little control on the increase of private wells that still abstract water from the upper Dupi Tila aquifer system. So this option considers the only increase of private abstraction at an annual rate of 10% from 2005 until 2020. The predicted GWL shows that (Figure 6.23 to Figure 6.25) this would result in a continuous downfall of water table to about -160 m PWD by 2020. So, result of this option indicates that it could create the worst possible condition of the groundwater resources under Dhaka City area.

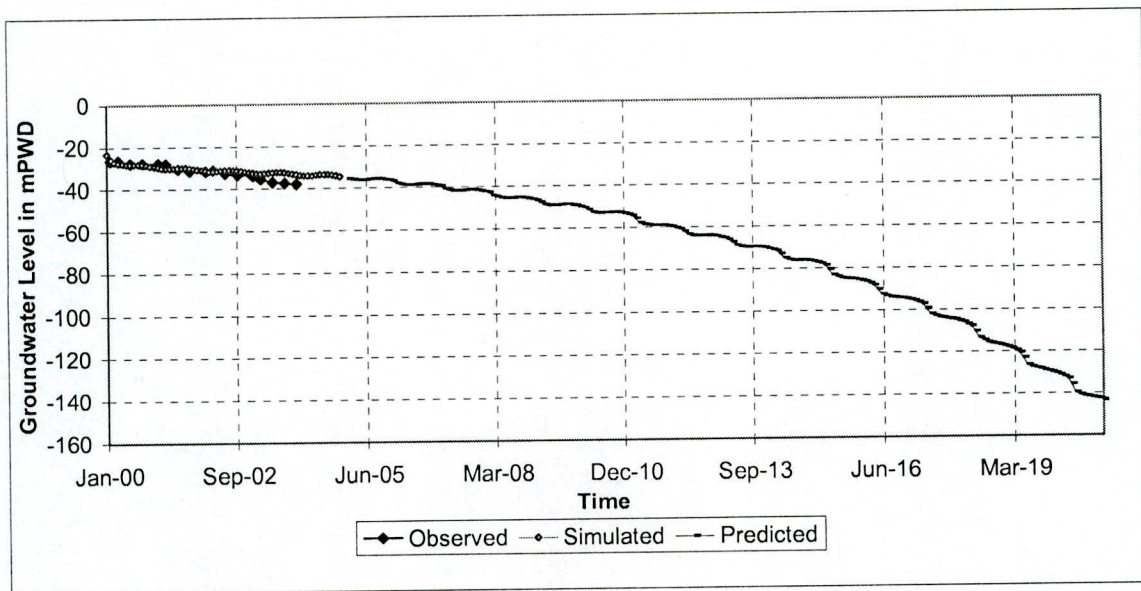


Figure 6.23 Predicted groundwater level at Lalbagh 1 for scenario 2

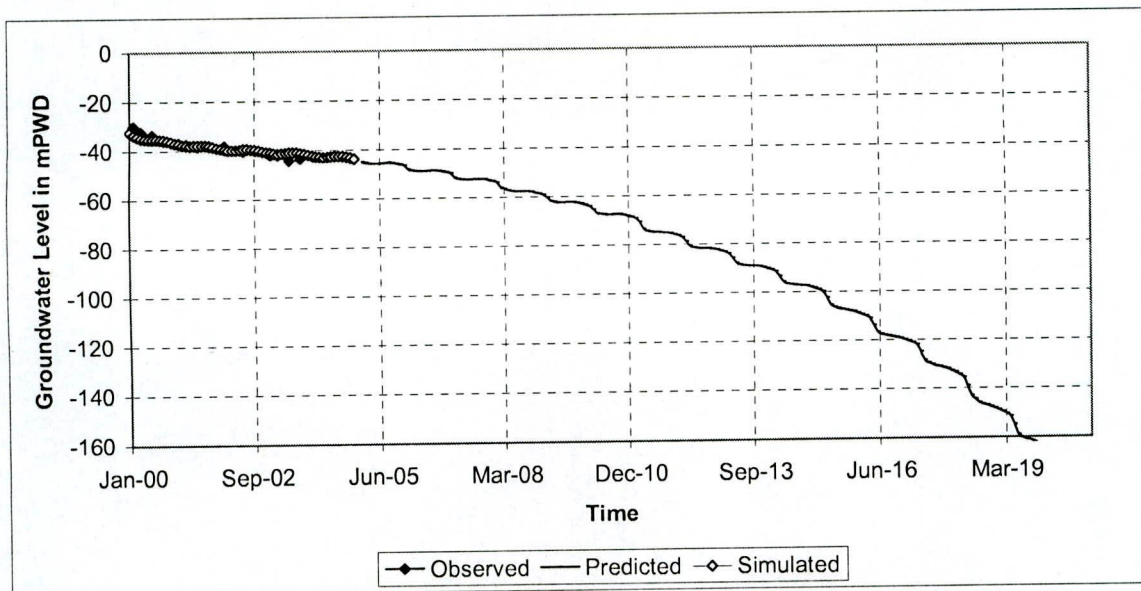


Figure 6.24 Predicted groundwater level at Gulshan for scenario 2

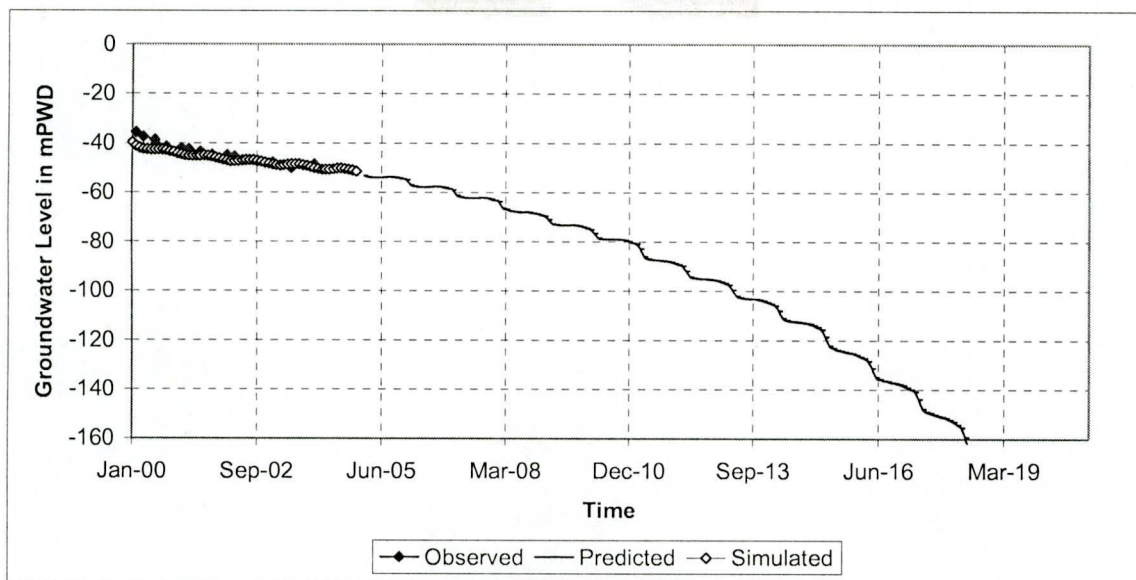


Figure 6.25 Predicted groundwater level at Motijheel for scenario 2

- **Scenario 3 Results: Continuation of 10% annual increase of private abstraction up to 2010 and then keeping it (abstraction rate of December 2010) fixed until 2020.**

This is a likely alternative situation for option 2. Result of this option (Figure 6.26 to Figure 6.28) shows that as the increase of abstraction is ceased GWL start to stabilize and the steady state condition is obtained by April 2011.

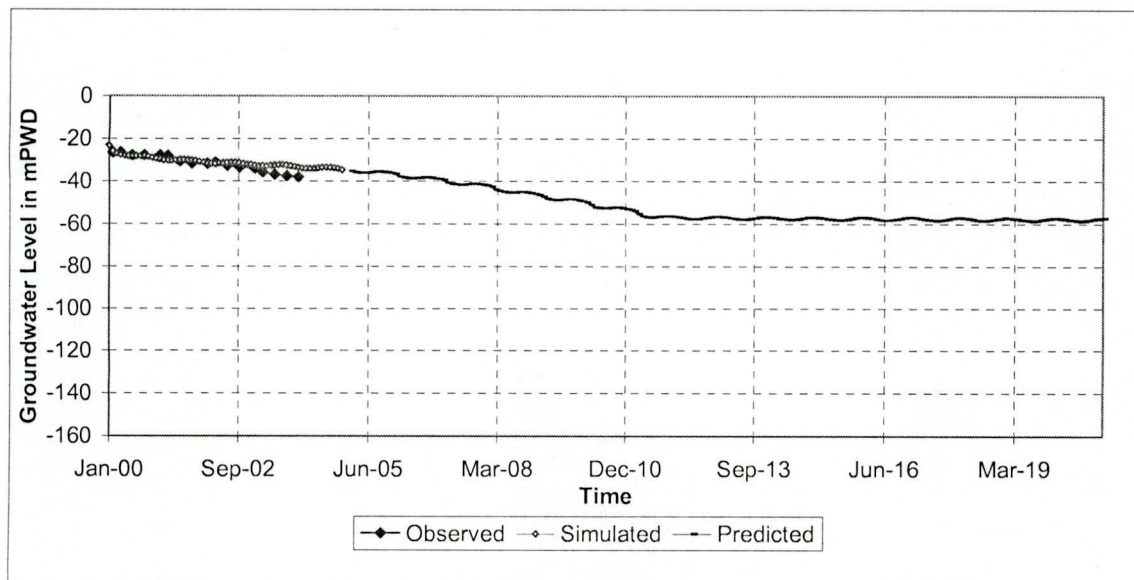


Figure 6.26 Predicted groundwater level at Lalbagh 1 for scenario 3

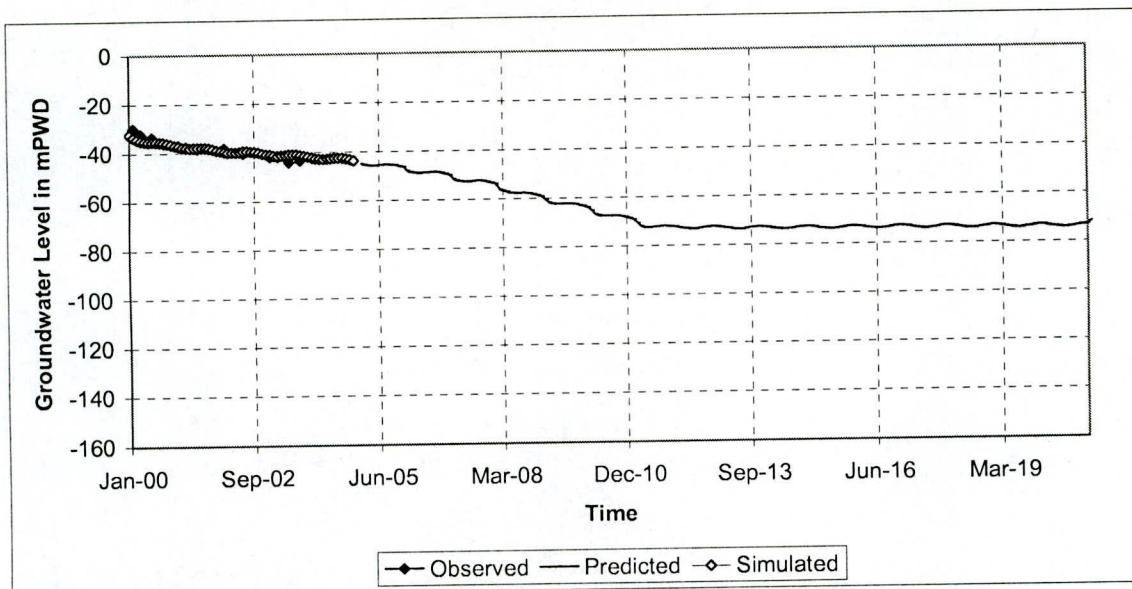


Figure 6.27 Predicted groundwater level at Gulshan for scenario 3

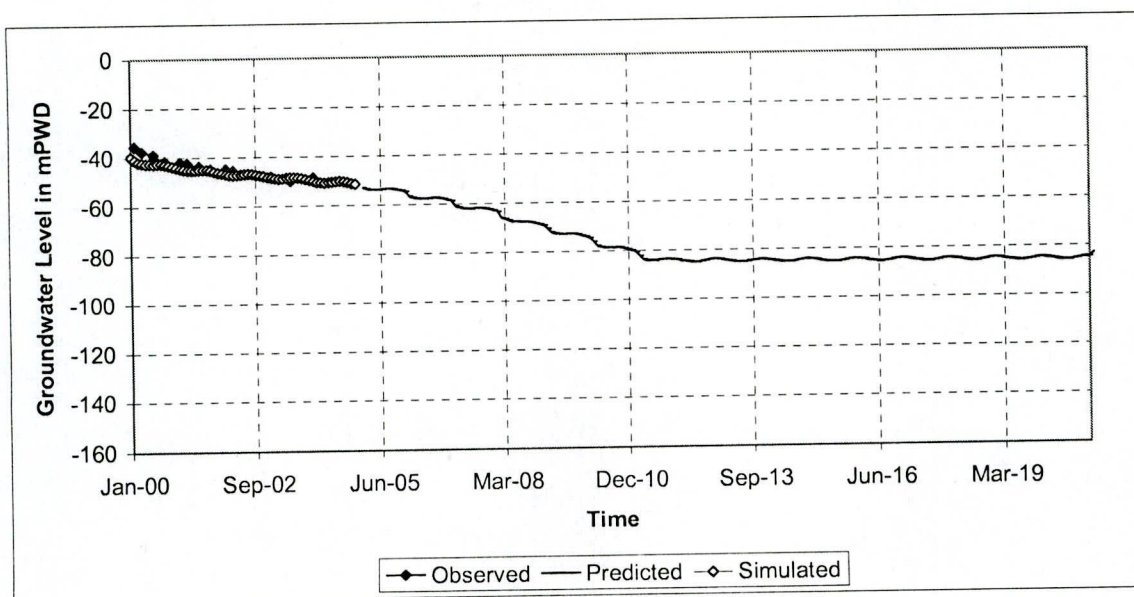


Figure 6.28 Predicted groundwater level at Motijheel for scenario 3

- **Scenario 4 Results: Increasing abstraction from deep aquifer with 94 wells from 2005 and continuing up to 2020.**

This development scenario is selected considering the rate of increase of wells in deep aquifer. During this run the abstraction from upper Dupi Tila aquifers was kept same as December 2004 up to 2020. The result (Figure 6.29) indicates that the GWL would continue to decline and the residual drawdown in the deep aquifer would be around 20 m in 2020 if this amount of water is abstracted each year from 2005.

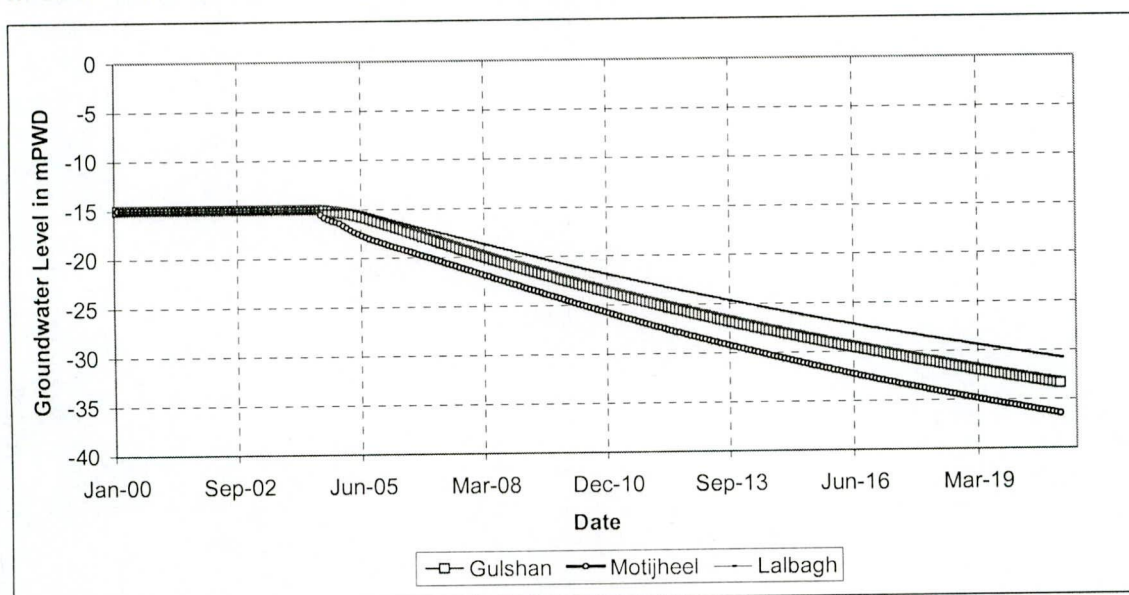


Figure 6.29 Predicted groundwater level of Dhaka deep aquifer at Gulshan, Motijheel and Lalbagh 1

6.6.2 Predicted land subsidence

Basing on the results obtained in the above scenarios the groundwater model was used to compute the possible future land subsidence. It was observed from the predicted GWL from various scenario runs that for some conditions the depletion would be sufficient to affect the storage of the confining units adjacent to the aquifers and thus cause some amount of subsidence. The results of predicted land subsidence at selected locations (Figure 6.15) for the year 2010 and 2020 are summarized in Table 6.6 and Table 6.7 respectively. Figure 6.30 shows the future trend of land subsidence for all the

four scenarios that was depicted for the groundwater model. Contour maps of predicted model subsidence within Dhaka City area is furnished in Figures 6.31 to 6.35.

Table 6.6 Model predicted subsidence in Dec 2010 at selected locations of Figure 6.15

Sl	SCU	Easting	Northing	Predicted Subsidence (m) in Dec 2010			
				Scenario 1	Scenario 2	Scenario 3	Scenario 4
1	1A	541000	631658	0.0421	0.0712	0.0570	0.0477
2	1B	536614	628405	0.0507	0.0780	0.0656	0.0545
3	1C	542357	622671	0.0412	0.0662	0.0561	0.0449
4	1D	538374	625760	0.0551	0.0840	0.0699	0.0585
5	1E	542559	625842	0.0536	0.0867	0.0684	0.0580
6	1F	541981	631921	0.0371	0.0653	0.0520	0.0433
7	1G	542645	637294	0.0043	0.0189	0.0187	0.0107
8	1H	543598	621964	0.0335	0.0553	0.0483	0.0376
9	2	530269	630861	0.0001	0.0052	0.0048	0.0025
10	3	542587	641434	0.0037	0.0057	0.0089	0.0058
11	4	549311	635963	0.0015	0.0040	0.0037	0.0002
12	5A	550726	622835	0.0002	0.0041	0.0001	0.0026
13	5B	548879	614028	0.0003	0.0003	0.0001	0.0041
14	6	540654	621176	0.0236	0.0430	0.0386	0.0265

Note: SCU – Subsidence Computation Unit

Table 6.7 Model predicted subsidence in Dec 2020 at selected locations of Figure 6.15

Sl	SCU	Easting	Northing	Predicted Subsidence in (m) Dec 2020			
				Scenario 1	Scenario 2	Scenario 3	Scenario 4
1	1A	541000	631658	0.0426	0.0794	0.0576	0.0522
2	1B	536614	628405	0.0510	0.0854	0.0660	0.0584
3	1C	542357	622671	0.0416	0.0735	0.0565	0.0489
4	1D	538374	625760	0.0554	0.0917	0.0703	0.0625
5	1E	542559	625842	0.0540	0.0953	0.0689	0.0626
6	1F	541981	631921	0.0376	0.0735	0.0526	0.0478
7	1G	542645	637294	0.0047	0.0253	0.0194	0.0142
8	1H	543598	621964	0.0340	0.0624	0.0489	0.0418
9	2	530269	630861	0.0001	0.0072	0.0049	0.0030
10	3	542587	641434	0.0040	0.0080	0.0095	0.0065
11	4	549311	635963	0.0022	0.0043	0.0050	0.0001
12	5A	550726	622835	0.0002	0.0072	0.0001	0.0042
13	5B	548879	614028	0.0003	0.0004	0.0001	0.0042
14	6	540654	621176	0.0240	0.0492	0.0390	0.0299

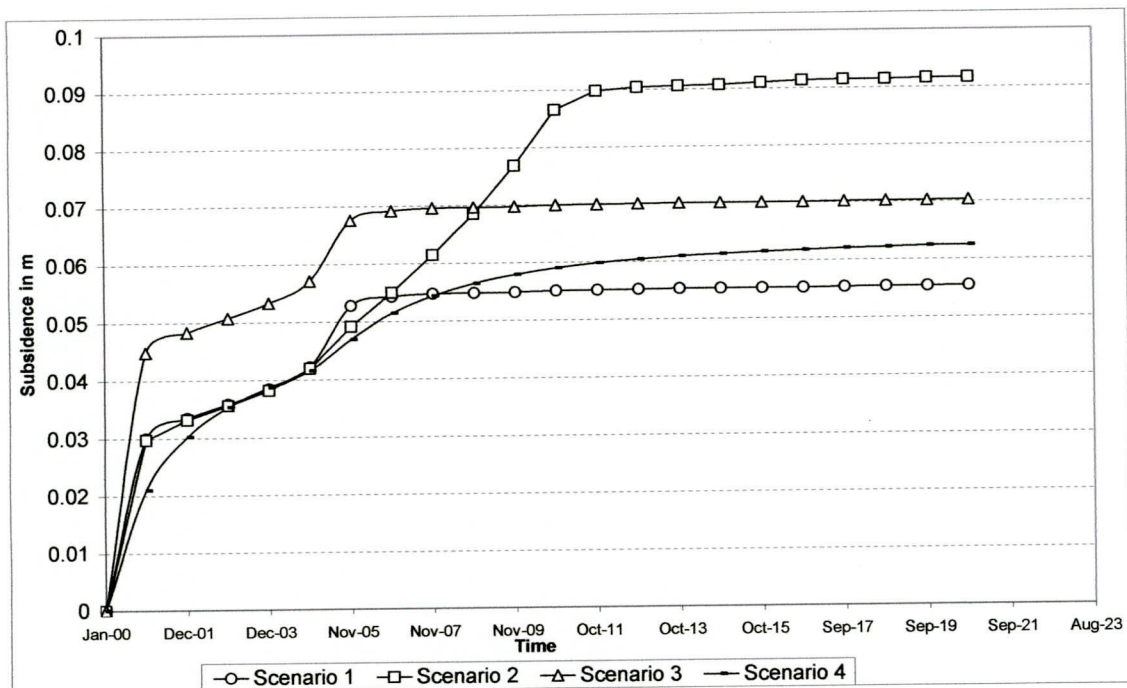


Figure 6.30 Model computed subsidence (m) with time at the selected point (SCU 1D in Table 6.24) of maximum subsidence for all the scenarios.

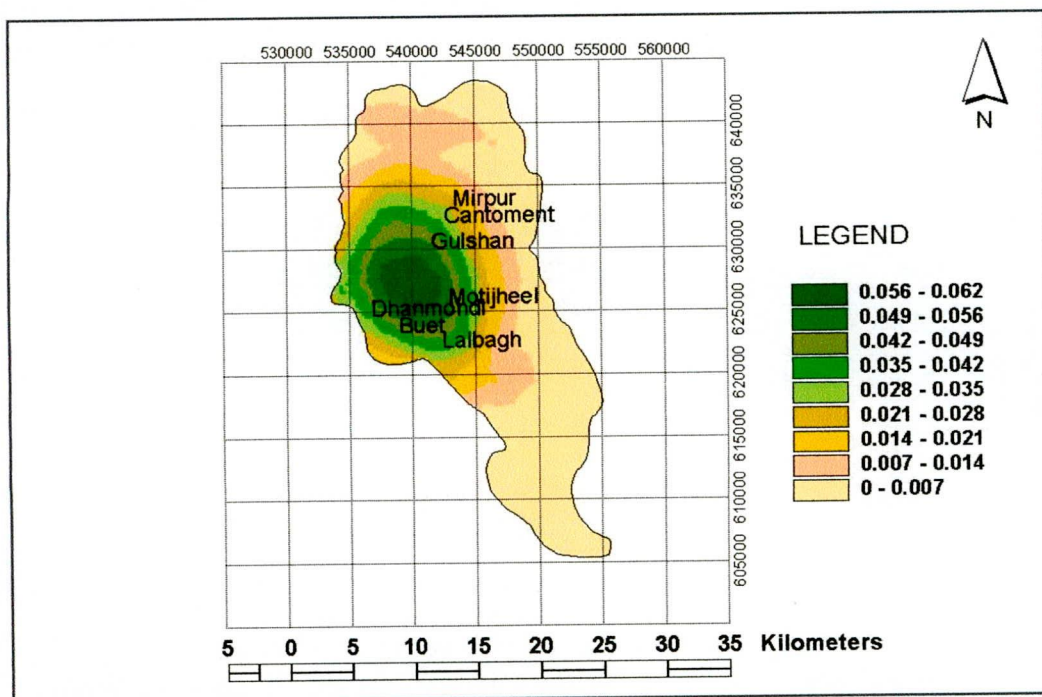


Figure 6.31 Predicted land subsidence (m) in December 2020 based on scenario 1

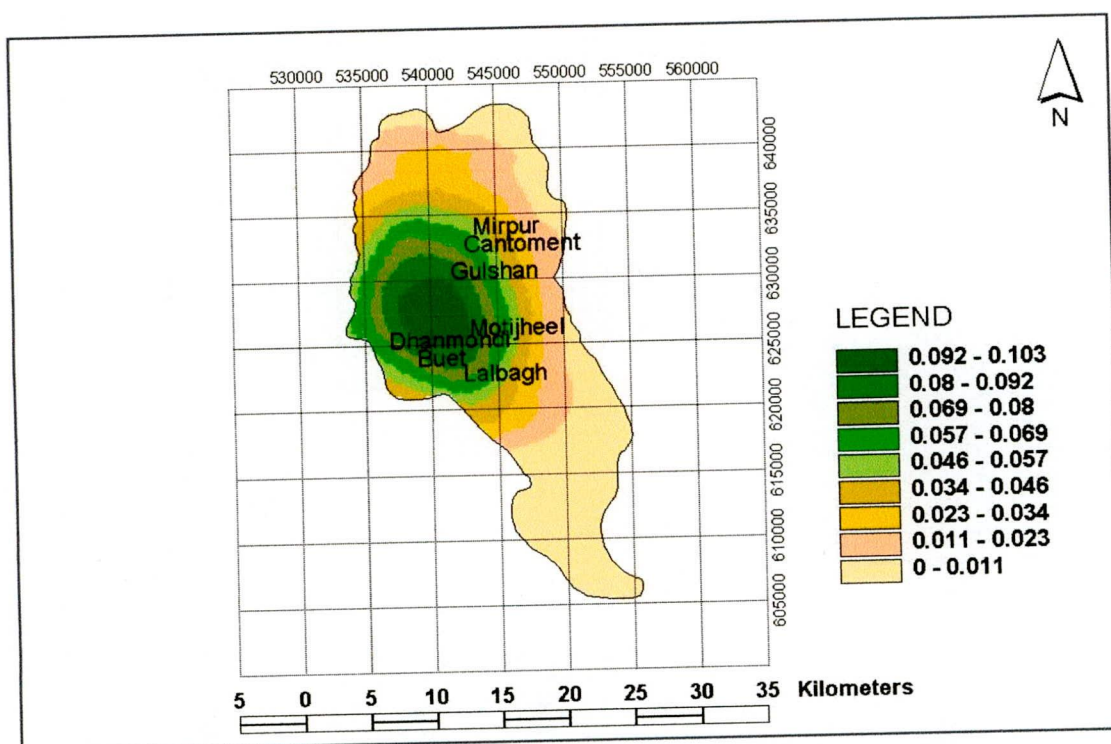


Figure 6.32 Predicted land subsidence (m) in December 2020 based on scenario 2

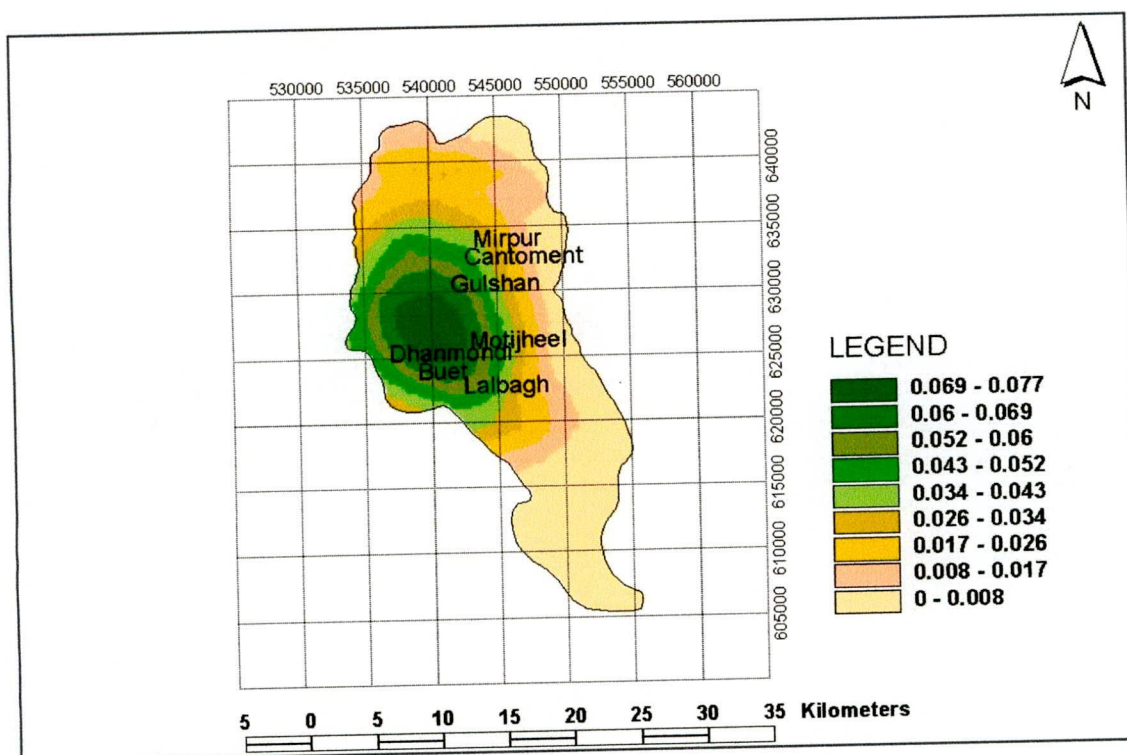


Figure 6.33 Predicted land subsidence (m) in December 2020 based on scenario 3

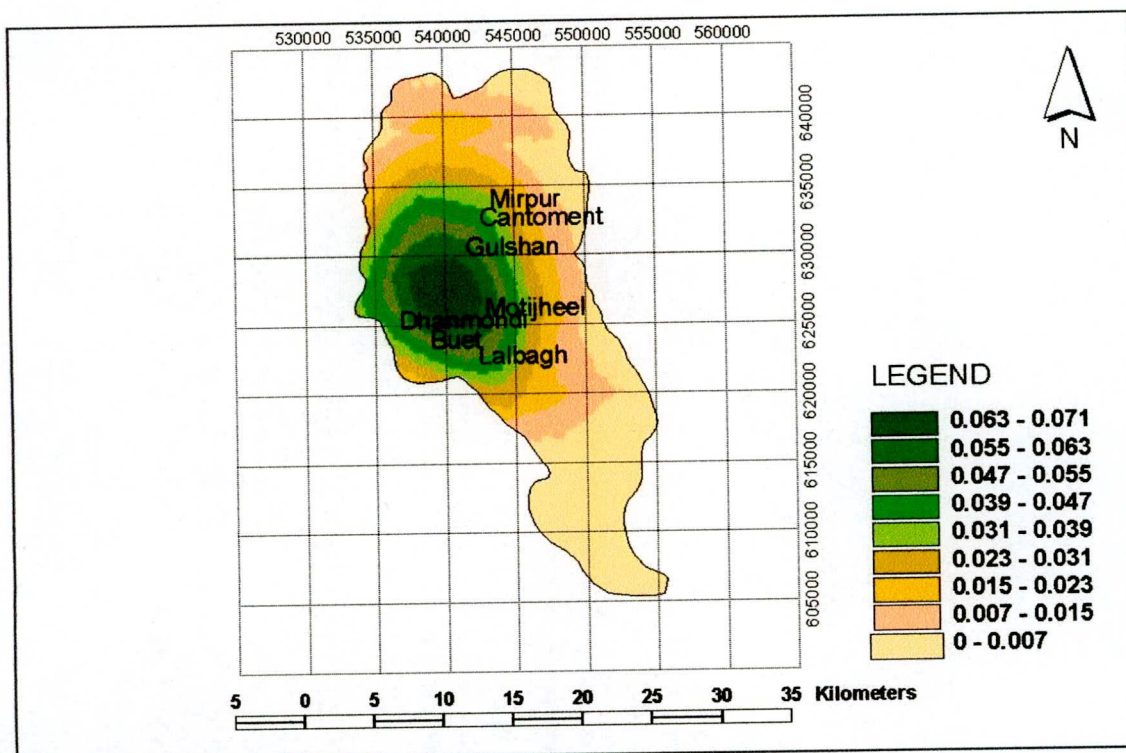


Figure 6.34 Predicted land subsidence (m) in December 2020 based on Scenario 4

Chapter 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 General

This study has been conducted to investigate and simulate the groundwater depletion and associated land subsidence using MODFLOW-2000. The subsidence module simulates the elastic and inelastic compaction of compressible fine-grained sediments within the aquifers. The model simulated results closely match with the observed groundwater levels as shown in Figures 6.3 to 6.13. The calibrated model was then used to estimate land subsidence in important places of Dhaka City area. The main limitation in the study has been the paucity of reliable observed data regarding abstraction, observation well and land subsidence. Still the study was demanding in the sense that it investigated into the most important source of water in the capital city and its possible impact on the environment. The conclusions and recommendations can be summarized in the succeeding paragraphs as they came out from the study.

7.2 Conclusions

- (a) The simulated piezometric level outside Dhaka City and up to the boundary of the study area is much higher than that of Dhaka City (Figure 6.1). Piezometric level within Dhaka varies because of varying degree of abstraction and different hydro-geological conditions.
- (b) In Dhaka City, the groundwater is depleting at a rate that contribution from peripheral rivers and surface recharge is not sufficient to change the situation. Currently annual depleting rate is 1.5 m over the city on an average. It indicates that the present rate of groundwater abstraction is not sustainable.
- (c) Due to continuous lowering of water table the resulting maximum land subsidence in Dhaka City during 2000-2004 as estimated by the model is 4.9

cm (Figure 6.14). The location and magnitude of land subsidence is quite analogous to the concentration pattern of DTWs (Figures 5.14 and 6.14) and hence to the declining piezometric levels (Figure 6.2) over Dhaka City.

- (d) From the increasing trend of and unplanned urbanizations, it is anticipated that more wells would be installed by the private users. This would further decline the piezometric level in the upper aquifers.
- (e) Scenario 1 results show that if no increase in abstraction is allowed after 2004 then an equilibrium condition would be reached by April 2006 (Figures 6.20 to 6.22). The resulting maximum subsidence in 2020 for this scenario is 6.2 cm (Figure 6.31). It can be noted that subsidence almost ceases (subsidence versus time curve of scenario 1 in Figure 6.26) after water level reaches a steady state condition. So it is apparent that subsidence is directly linked to the depletion of groundwater table.
- (f) A 10% incremental rate only in private abstraction up to 2020 would cause continuous declination of water table in Dhaka City area (Figures 6.23 to 6.25). The simulation shows that the water table has not stabilized for those incremental abstractions. So this future prediction confirms that the groundwater resources inside the model area are not adequate to meet the growing demand of the city population. The resulting maximum land subsidence for this possible future condition is 10.3 cm (Figure 6.32).
- (g) The future simulation for 10% incremental abstraction every year by private wells up to 2010 and then keeping withdrawal rate constant until 2020, shows that the water level goes down to a minimum level of -85.7, -74.3 and -58.6 mPWD in area Motijheel, Gulshan and Lalbagh respectively. Groundwater level in these locations stabilizes by April 2011 (Figures 6.22 to 6.24). The maximum subsidence in Dhaka City computed by the model for this scenario is 7.7 cm (Figure 6.33).

- (h) Scenario 4 results show that the water level in deep aquifer would be lowered around 20 m (Figure 6.29) over the period from 2005 to 2020 without reaching any steady state condition. To substantiate this figures, further investigation covering a complete hydrological cycle would be required including data on groundwater level, abstraction, isotopic analysis (for age determination of groundwater in deep aquifer to ascertain recharge mechanism), lithology and aquifer test from deep aquifer.
- (j) The resulting subsidence for scenario 4 (maximum 7.1 cm as shown in Figure 6.34) is not much as compared to scenario 2 and 3. This indicates that the incremental abstraction from deep aquifer is not likely to cause relative increase in land subsidence. This may be due to the stress history of the overlying confining unit which is likely to be over-consolidated and less susceptible to subsidence for an optimum level of declination. Also the condition for is scenario is planned keeping in mind that the lowest piezometric level of deep aquifer would remain at a safe level from the upper surface of the confining unit (deep aquitard) overlying the deep aquifer.
- (k) After calibration of the model, water balance of Dhaka City for the year of 2004 shows that the total abstraction (731 Mm^3 as shown in Figure 6.19) is higher than the total contribution from rivers, precipitation and return flows. There is a deficit of 134 Mm^3 which is coming from the storage of the aquifer system for that period and causing the water table lowering.
- (l) Results of sensitivity analysis (Table 6.5) shows that the most responsive hydraulic parameter is the horizontal hydraulic conductivity of the aquifer followed by vertical hydraulic conductivity of the overlying aquitard. Specific storage values have minimum influence on the model result.

- (m) The results of scenario runs show that a future water supply based only on the groundwater is not feasible. If no other alternative could be arranged in the near future, a large number of production wells in Dhaka City will be inoperative.

7.3 Recommendations

The recommendations for future investigation and study can be as follows:

- (a) A precision topographic survey should be carried out (by SOB and other concerned organizations) to determine possible land subsidence by re-surveying the old BMs in and around Dhaka City in relation to those BMs situated outside the city and unaffected by heavy construction and groundwater abstraction. This could result in a suitable monitoring system to detect and measure land subsidence in the form of a network of bench marks in areas which are most susceptible to land subsidence. Subsequently more sophisticated equipment may be procured and installed to measure land subsidence at selected places basing on the results of investigations.
- (b) Application of groundwater model to study and investigate land subsidence is very new in Bangladesh. For more realistic investigation to land subsidence the physical investigation must be carried out alongside modeling. Again the modeling result would be more precise when an accurate groundwater model will be used to estimate land subsidence.
- (c) The database for a groundwater model must be preserved and updated continuously to improve the quality of the model.
- (d) Water production data in respective MOD zones must be recorded and maintained correctly by DWASA to assist proper investigation. Private abstraction is nearly equal to DWASA abstraction and correct data regarding well location, number, water production, operating hours, specification etc. must be made available for future study on groundwater modeling and planning purposes.

- (e) Installation of new DTWs in upper and intermediate aquifer of Dhaka City by DWASA and private users should not be allowed any more. A comprehensive Water Law by the concerned ministry should be formulated to control the use of groundwater by all agencies including private users. This will help reach a steady state condition in the aquifers and avoid any adverse environmental impact like land subsidence.
- (f) The water demand of Dhaka City can not be met by only groundwater at present. A rational combination of surface and groundwater may be only the way to meet the required demand.
- (g) A separate study may be conducted for correct estimation of recharge component due to urban and irrigation return flow. This can enhance the accuracy of the regional groundwater model to a great extent. An accurate assessment of leakage from water distribution and sewerage system should also be done in future.
- (h) A network of observation wells with auto recorders may be established under the responsibility of DWASA for continuous monitoring of groundwater level within and outside of Dhaka City. Accurate data on groundwater observation is most essential for proper groundwater modeling.

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APPENDIX - A

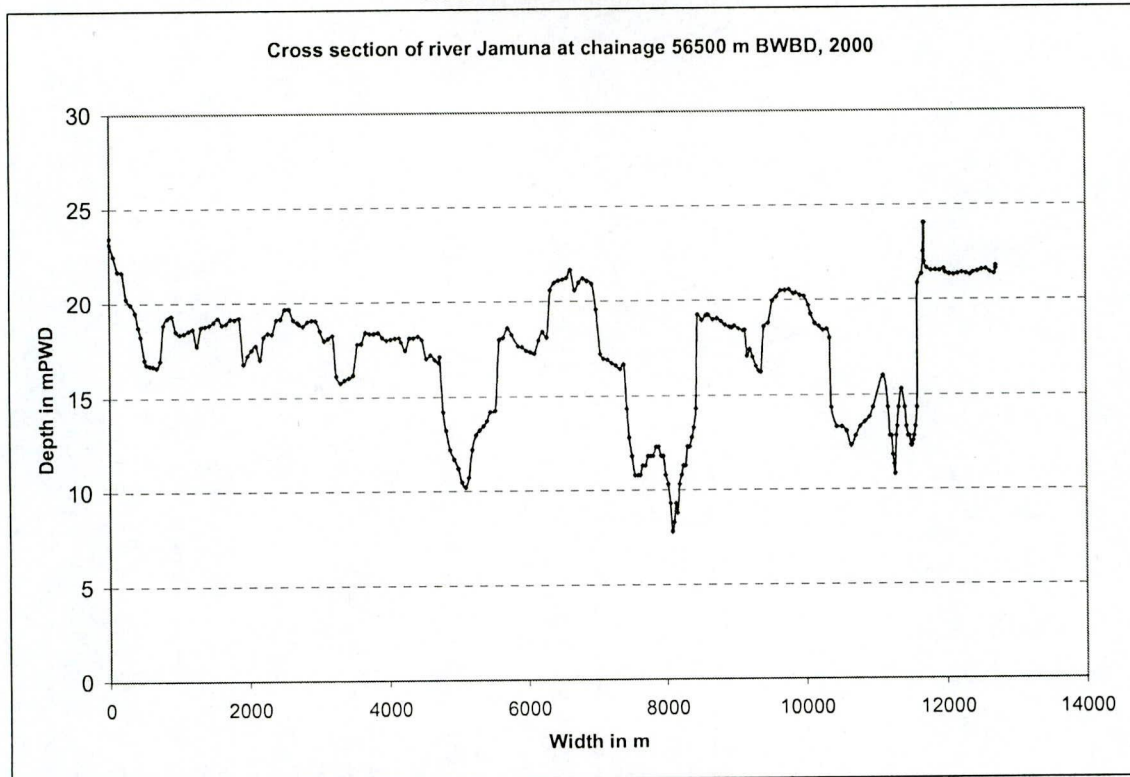


Figure A.1 Cross section of River Jamuna

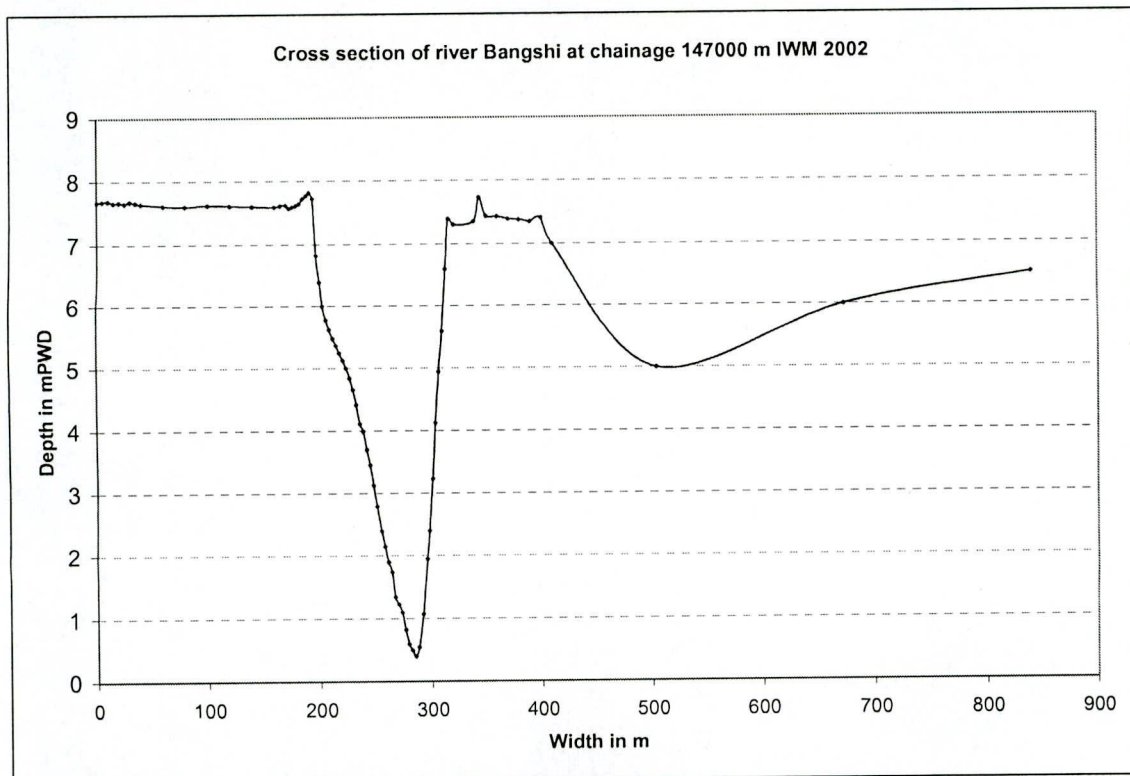


Figure A.2 Cross section of River Bangshi

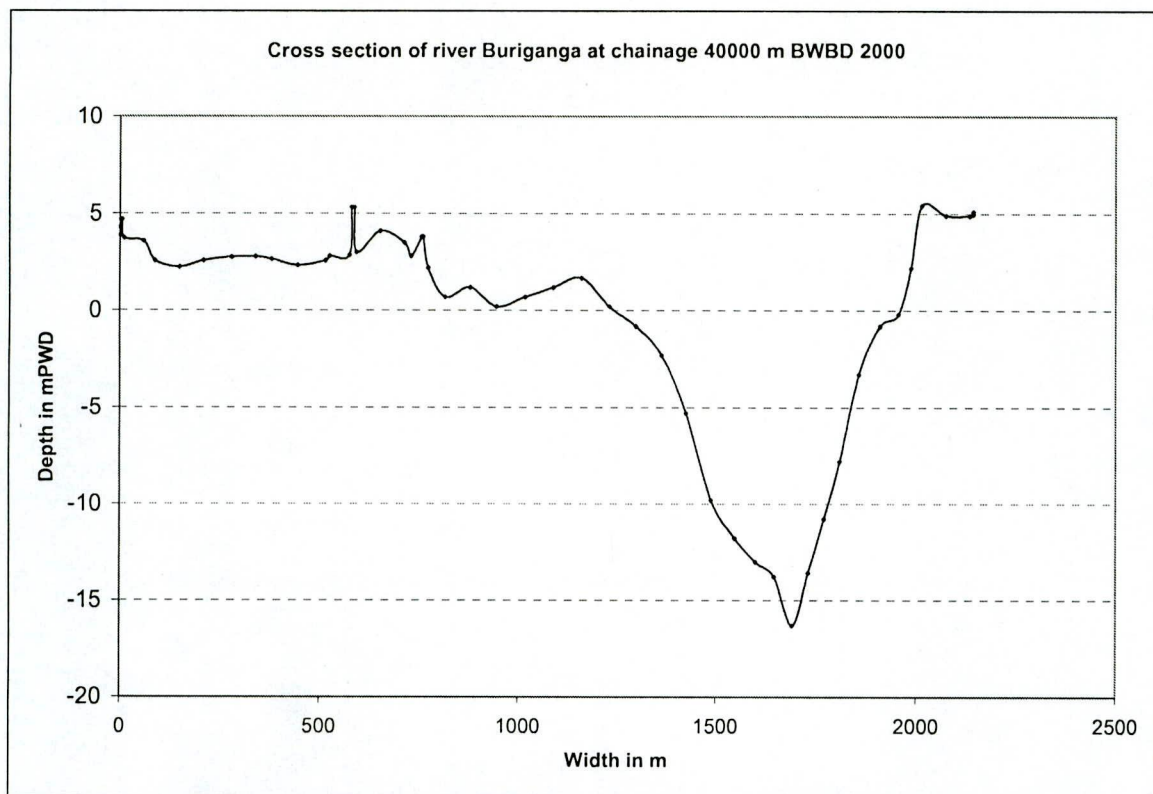


Figure A.3 Cross section of River Buriganga

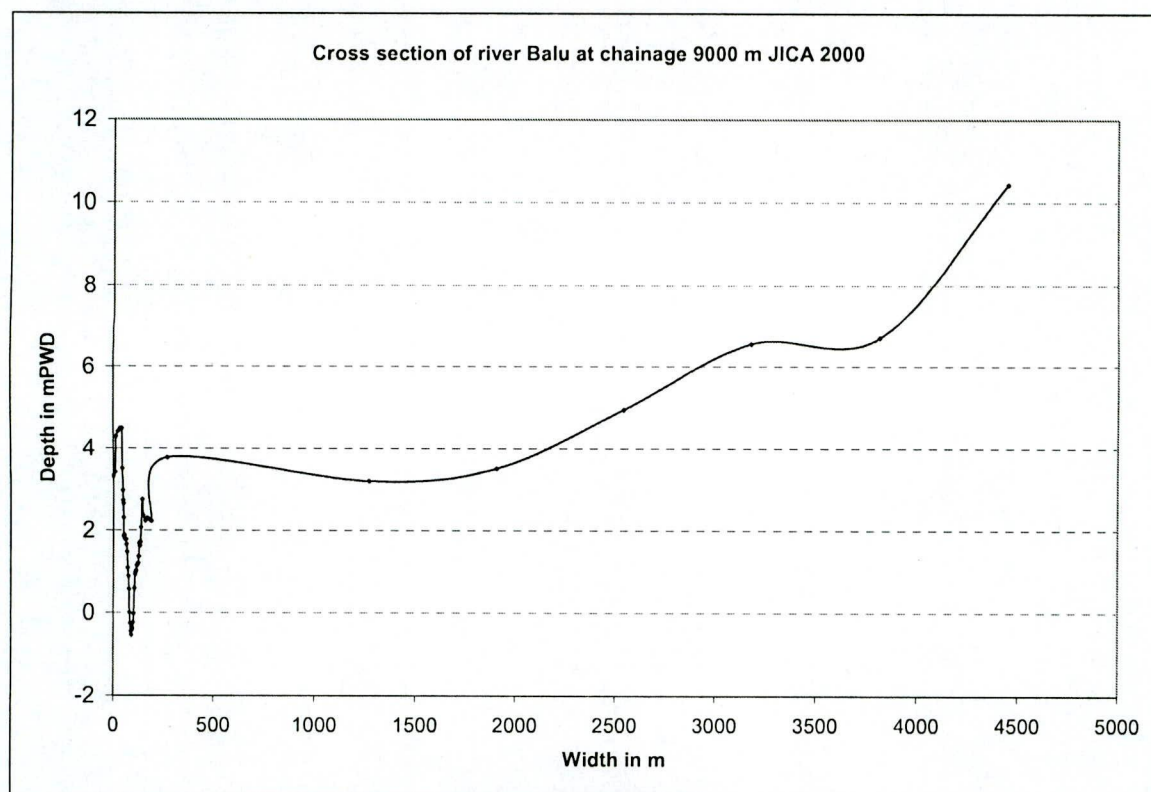


Figure A.4 Cross section of River Balu

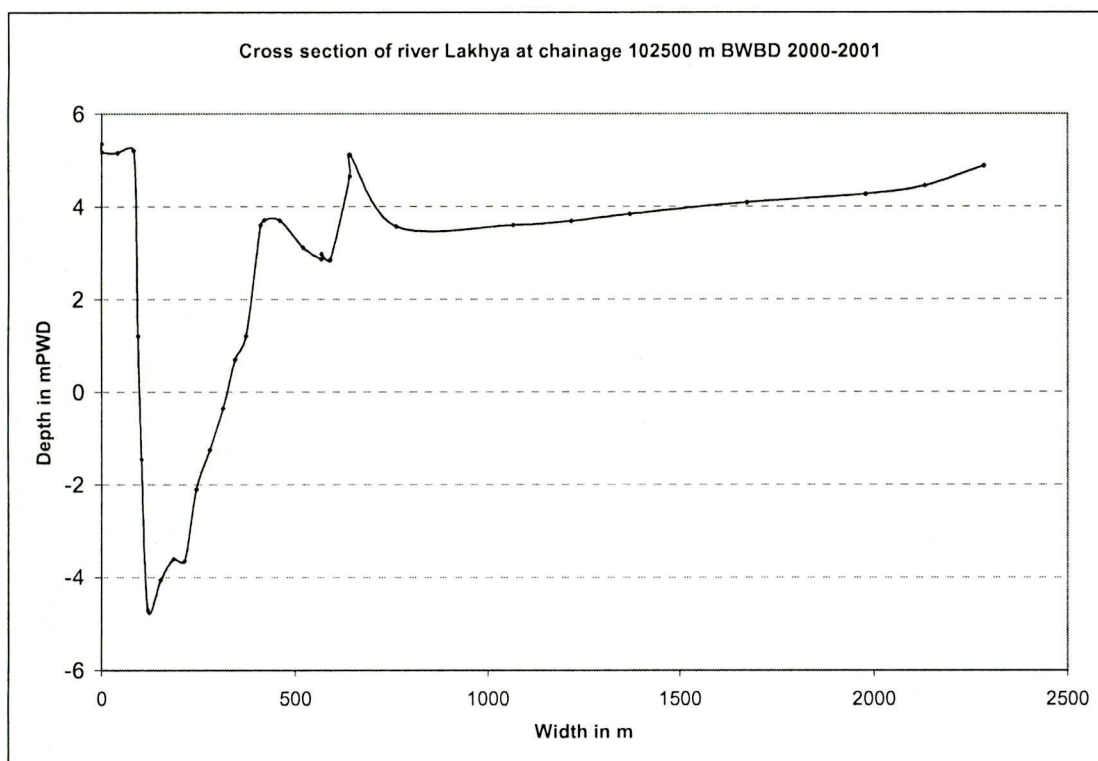


Figure A.5 Cross section of River Lakhya

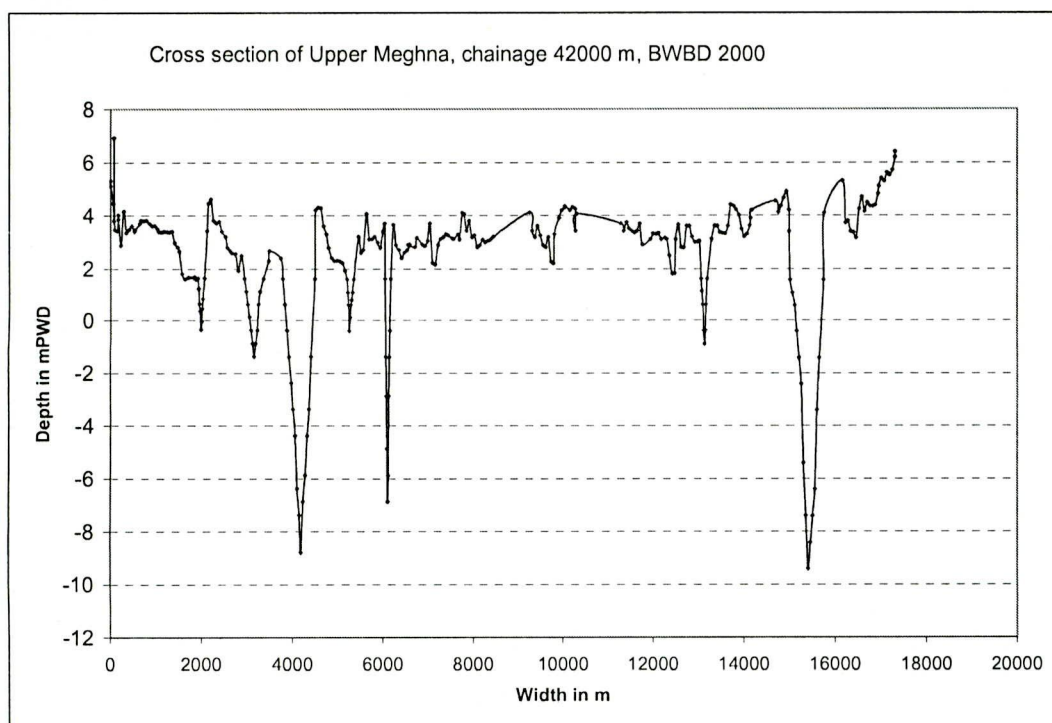


Figure A.6 Cross section of River Meghna

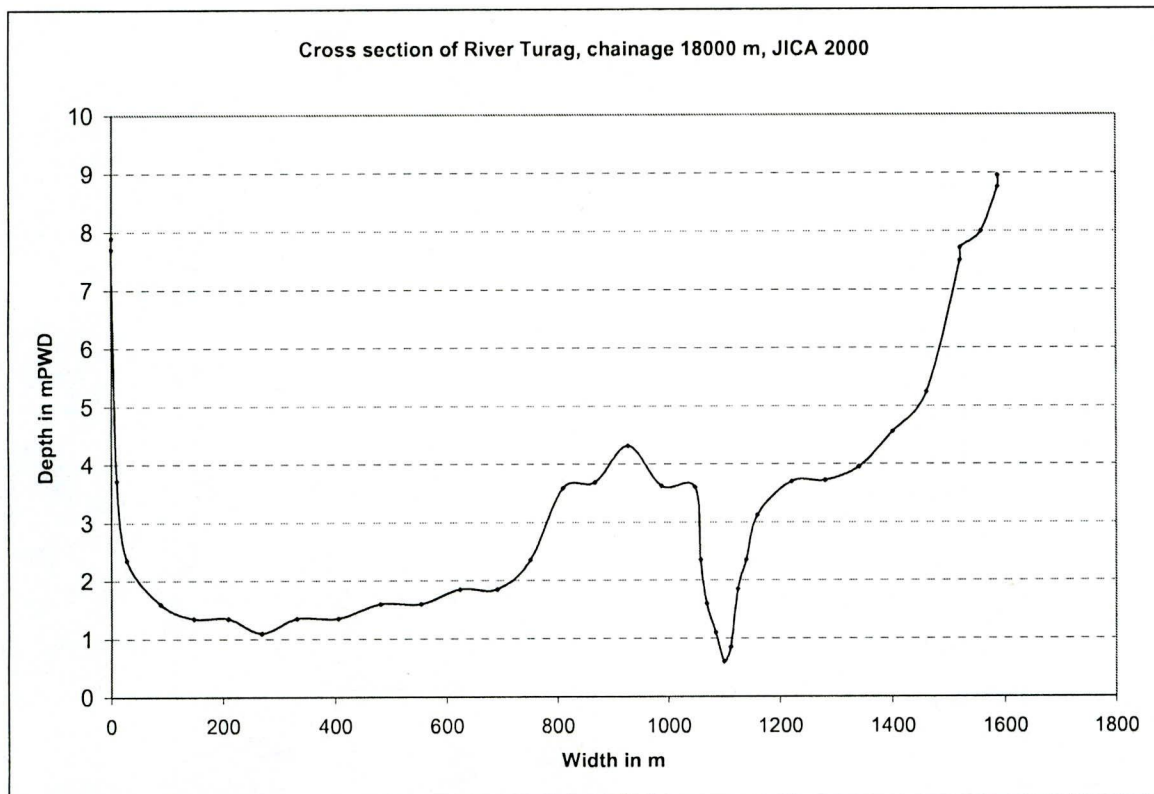


Figure A.7 Cross section of River Turag

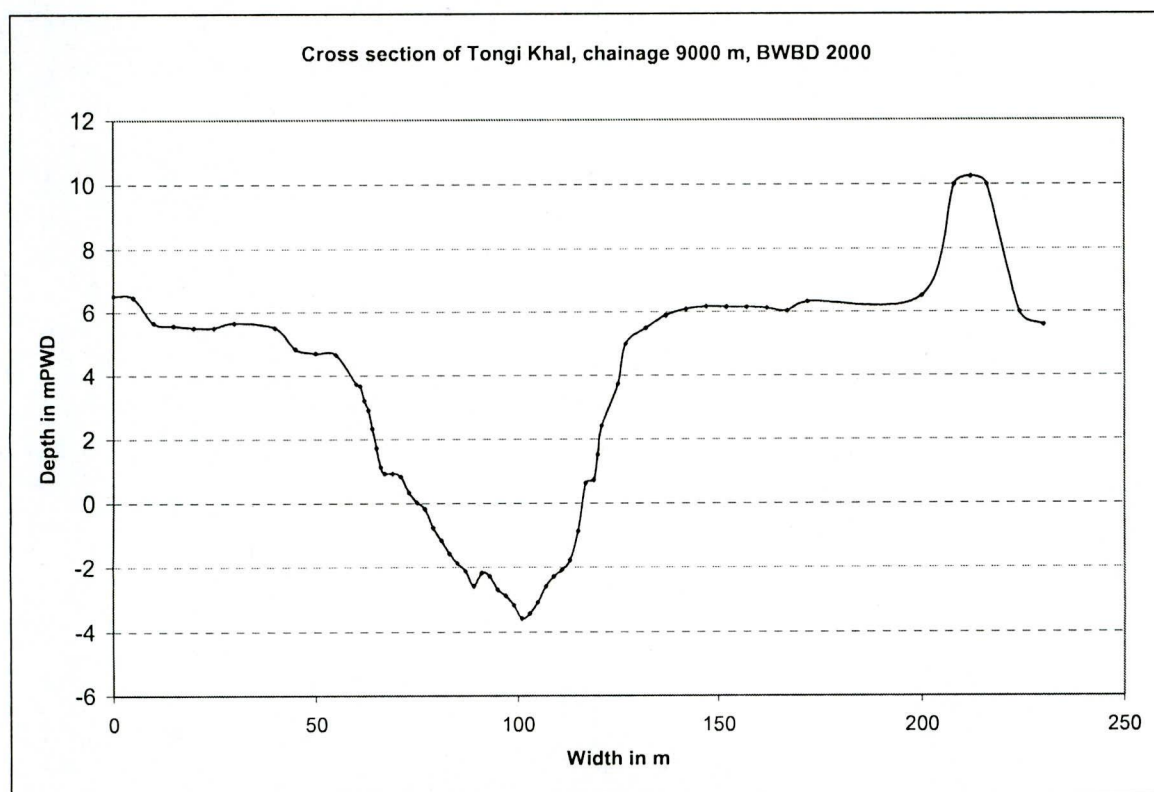


Figure A.8 Cross section of Tongi Khal

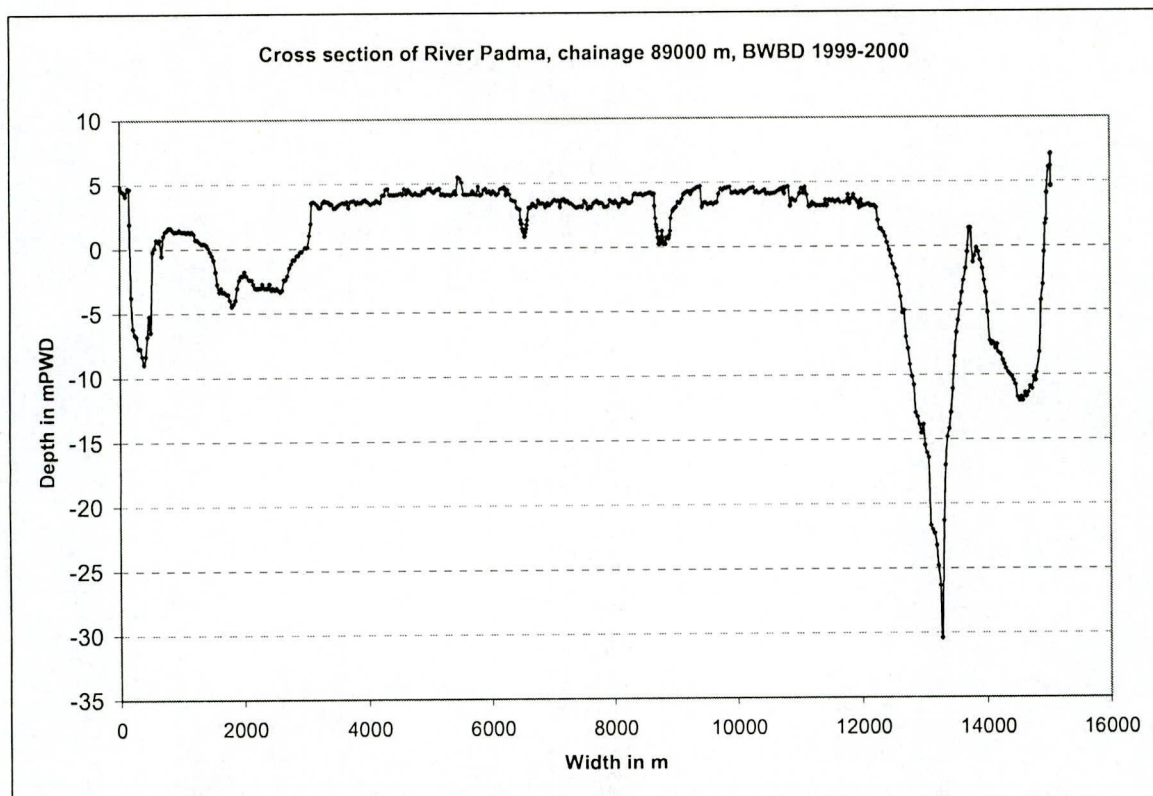


Figure A.9 Cross section of River Padma

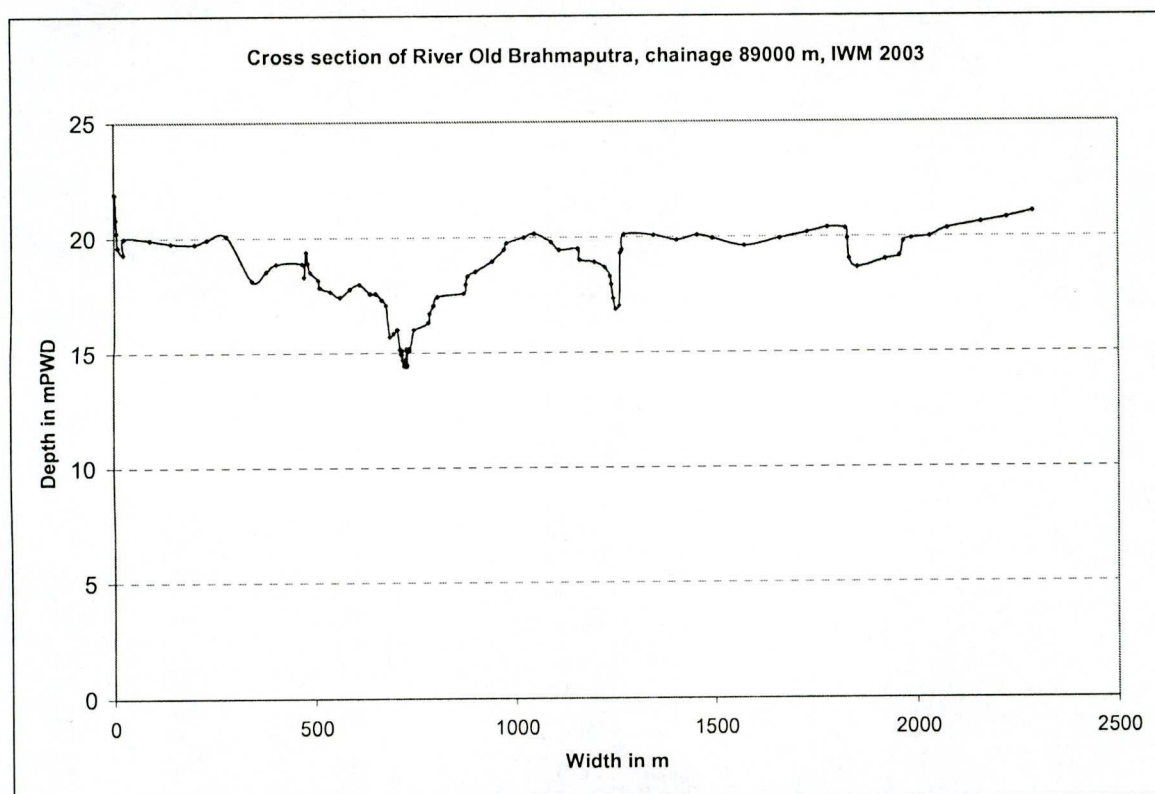


Figure A.10 Cross section of River Old Brahmaputra

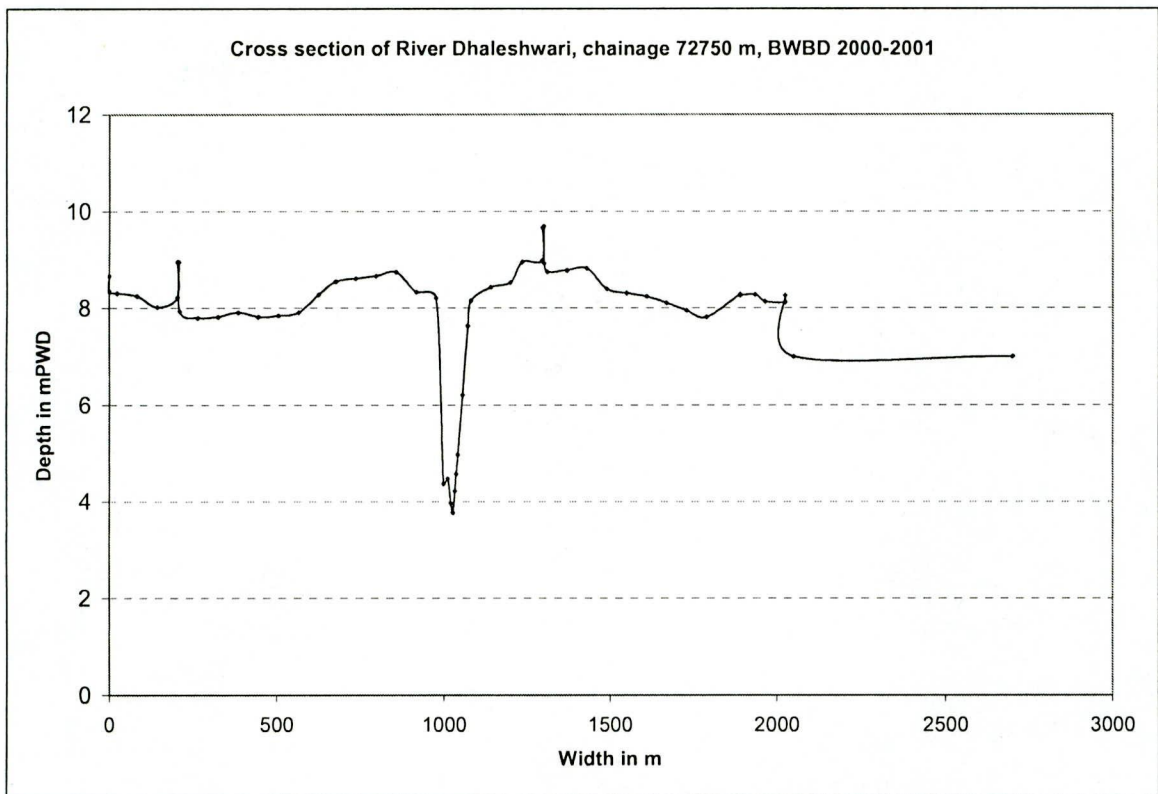


Figure A.11 Cross section of River Dhaleshwari

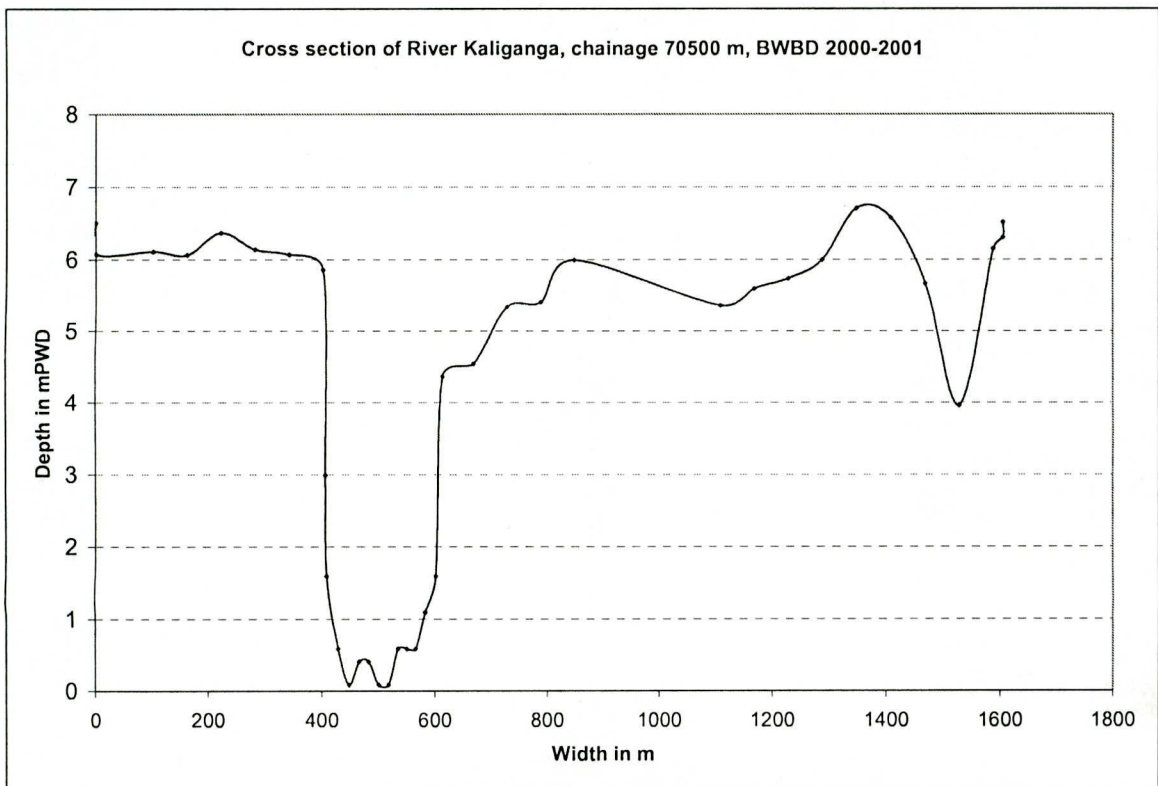


Figure A.12 Cross section of River Kaliganga

APPENDIX - B

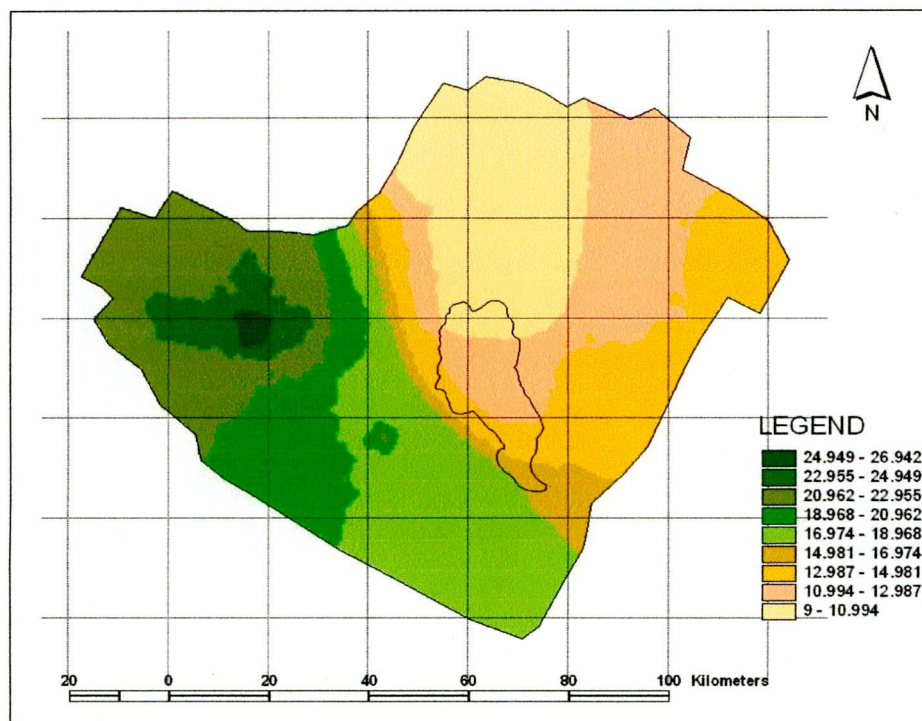


Figure B.1 Distribution of horizontal conductivity (m/day) in upper aquifer

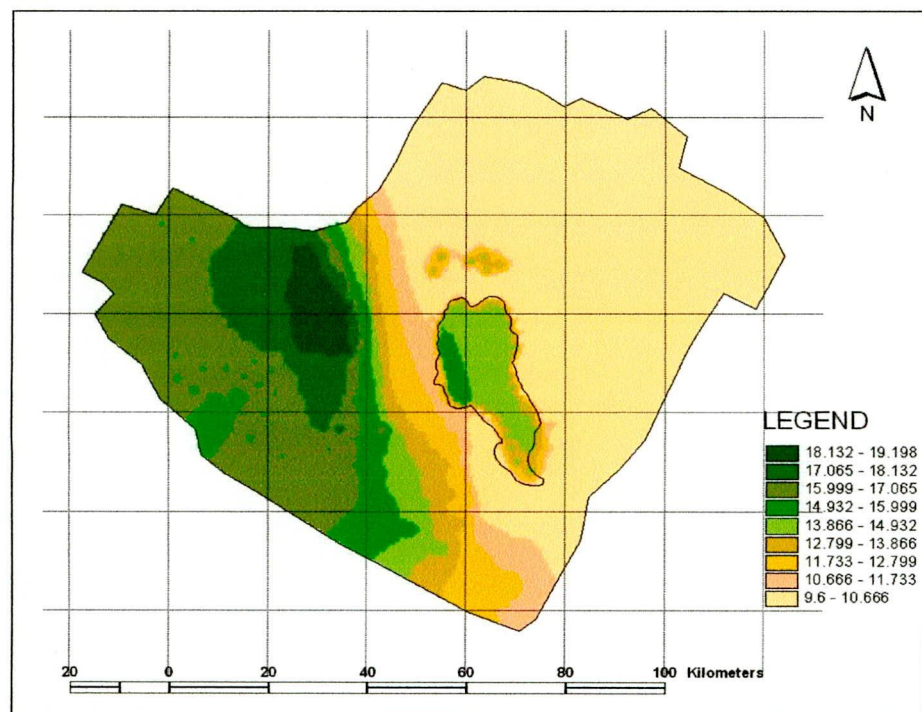


Figure B.2 Distribution of vertical conductivity(m/day) in upper aquifer

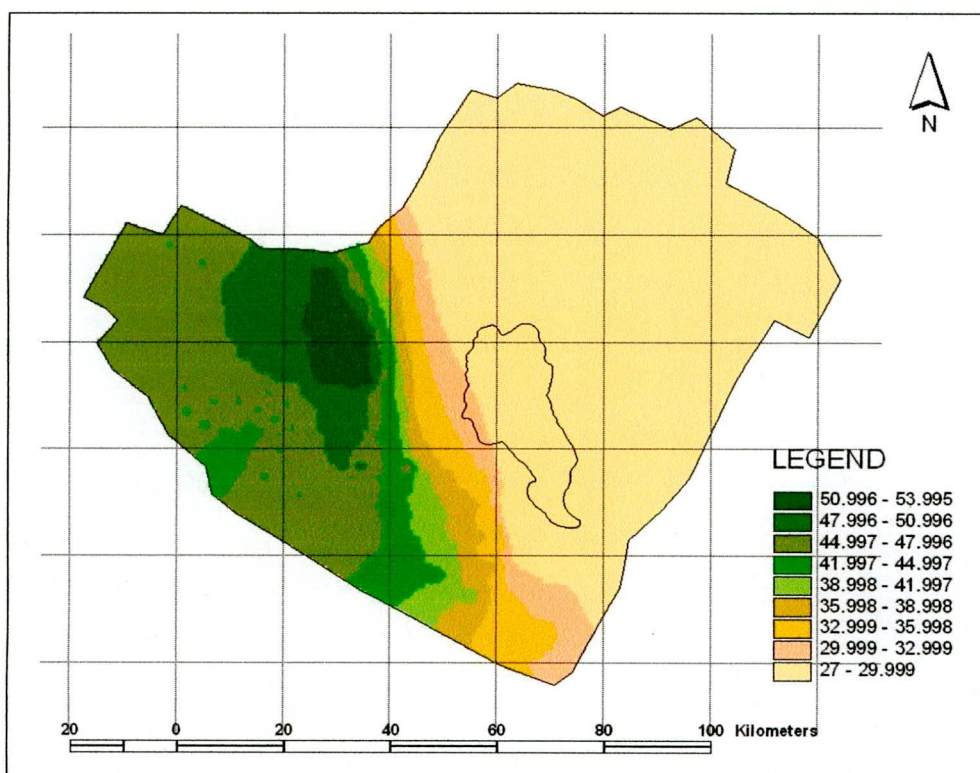


Figure B.3 Distribution of horizontal conductivity (m/day) in intermediate aquifer

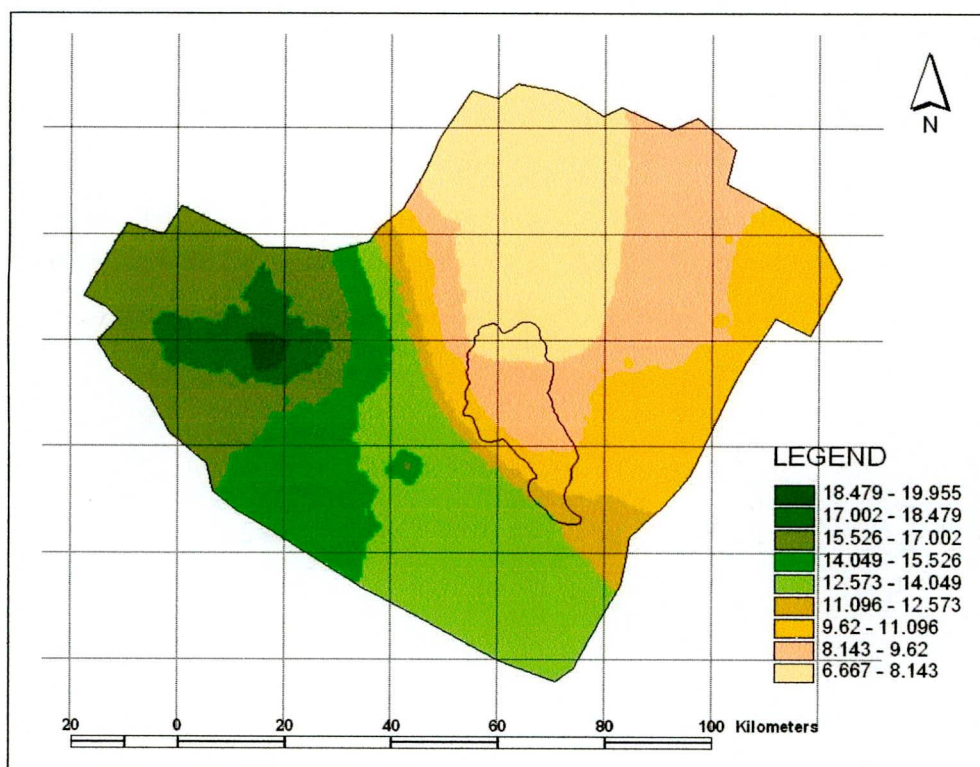


Figure B.4 Distribution of vertical conductivity (m/day) in intermediate aquifer

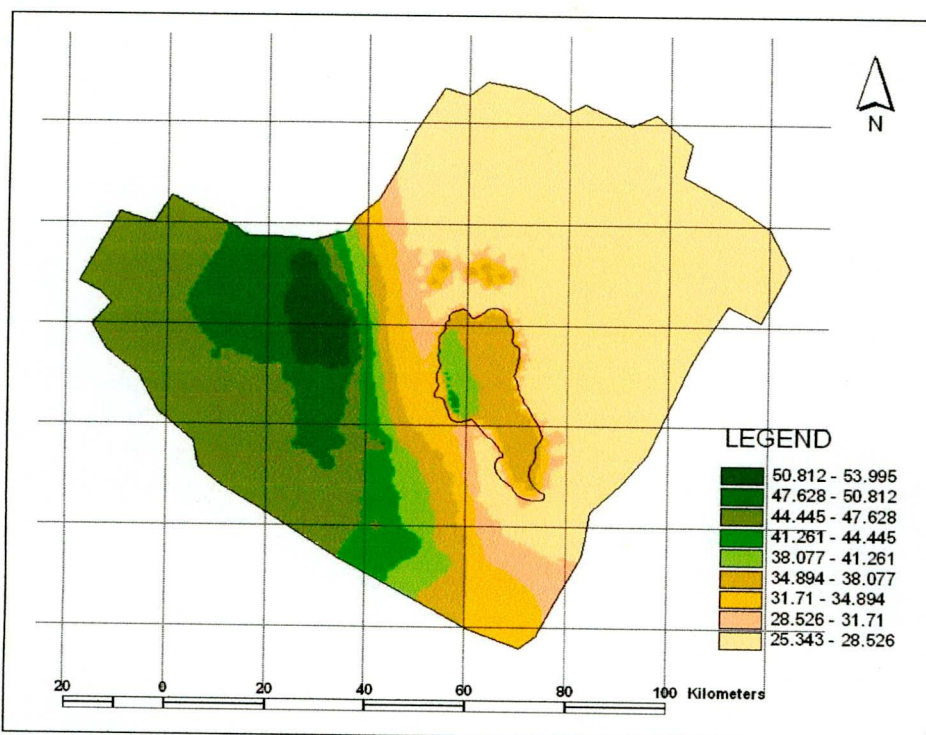


Figure B.5 Distribution of horizontal conductivity (m/day) in deep aquifer

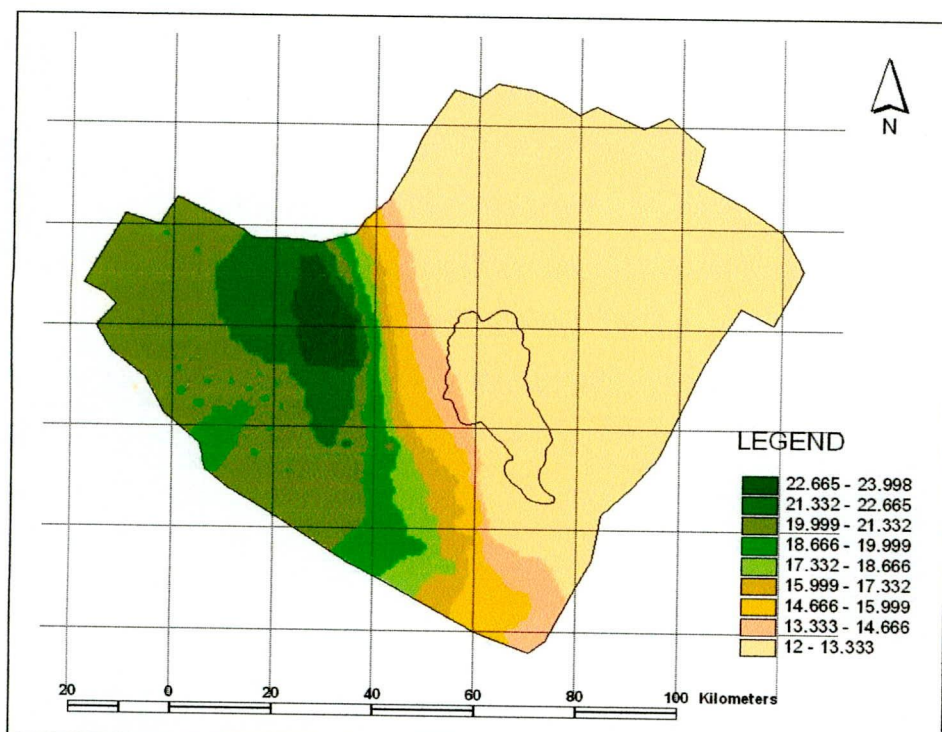


Figure B.6 Distribution of vertical conductivity (m/day) in deep aquifer

