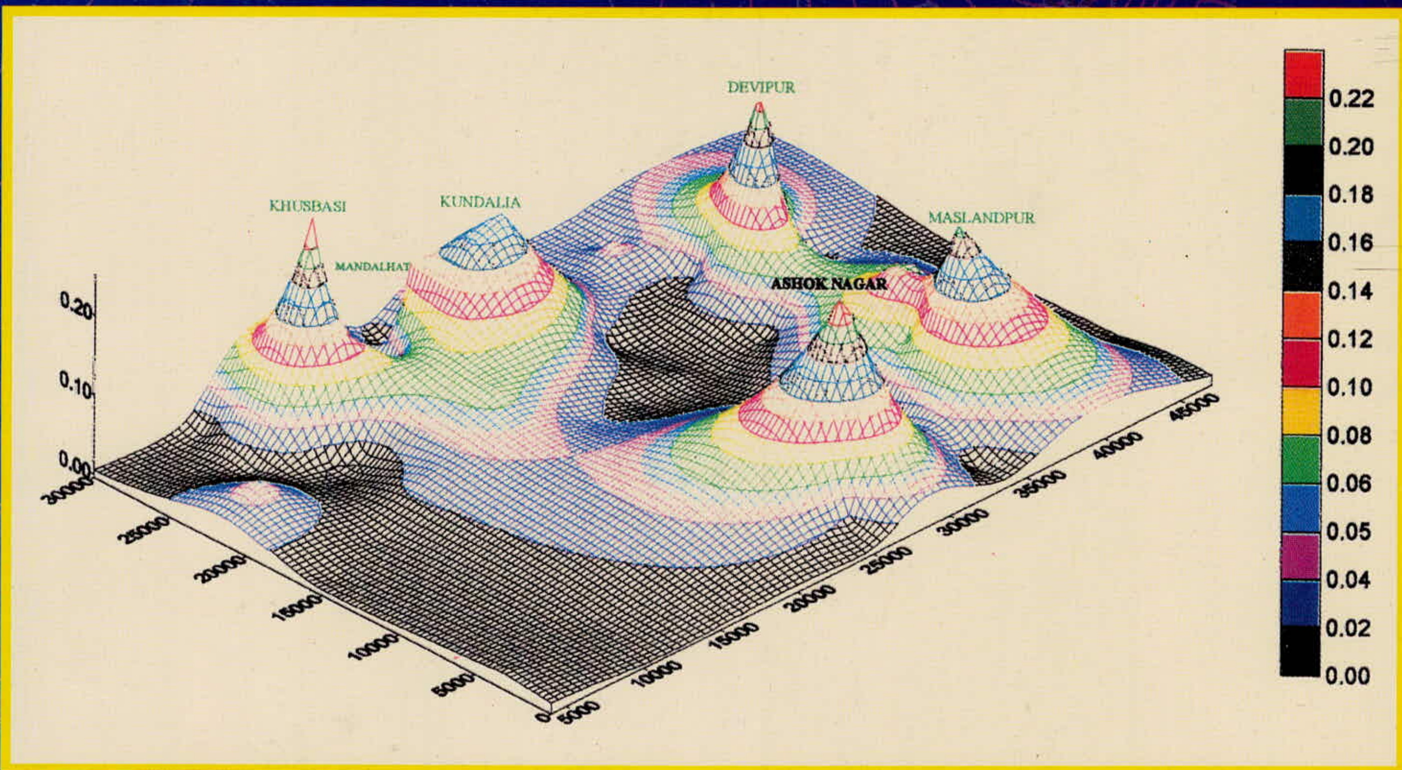
ARSENIC POLLUTION STUDY IN YAMUNA SUB-BASIN, NADIA AND NORTH 24-PARAGANAS DISTRICTS, WEST BENGAL



NATIONAL INSTITUTE OF HYDROLOGY, ROORKEE

AND

CENTRAL GROUND WATER BOARD
Eastern Region, KOLKATA

September, 2001

Report

on

ARSENIC POLLUTION STUDY IN YAMUNA SUB-BASIN, NADIA AND NORTH 24-PARAGANAS DISTRICTS, WEST BENGAL

by

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FOREWORD

Groundwater plays an important role in India's economy. According to World Bank study, the contribution of groundwater to India's GDP is estimated to be 9%. This resource has gained importance as a source of drinking water and food security. In the present scenario groundwater is contributing about 50% of irrigation water 80% of water for domestic use in rural areas and 50% of water for urban and industrial areas. Dependence on this resource has also increased due to its availability and less risk to pollution than the surface water.

The groundwater development has been intensive in alluvial areas of Indo Gangetic plains. This intensive development in many areas has given rise to a number of problems including social and public health. One such grave problem is Arsenic menace in groundwater of Gangetic plains in West Bengal. As many as 8 districts covering an area of 37,493 sq.km. with a total population of 4.5 million have been exposed to the menace of Arsenic pollution. The Arsenic pollution in West Bengal has been described as world's biggest calamity. The source of Arsenic has been suspected to be geologic in origin. The activation of Arsenic in groundwater has been debated by many experts is due to overexploitation of groundwater. The spreading of Arsenic in groundwater is suspected to be due to hydrologic and hydraulic conditions of the movement of groundwater in the aquifer. Since the extent of spreading has increased over time, doubt persists in many corners whether the occurrence of Arsenic in new pockets of the basin has any bearing with the transport of Arsenic from other sources.

To assess the spatial and temporal variation of Arsenic contaminated water and to understand the migration behaviour of Arsenic in groundwater, the **National Institute of Hydrology, Roorkee and the Central Groundwater Board, Eastern Region, Kolkata** have envisaged a joint collaborative study towards development of groundwater flow and Arsenic transport models. The groundwater domain of Yamuna sub-basin covering areas of North 24-Paraganas and Nadia Districts of West Bengal has been chosen as the study area.

The results presented in the report entitled "**Arsenic Pollution Study in Yamuna Sub-basin, Nadia and North 24-Paraganas Districts, West Bengal**" through the modeling studies are credible work and clarify many doubts, and provide an insight to mobilization of Arsenic in the groundwater flow domain. The efforts made by Scientists and staff of both the Organizations for carrying out the study and coming out with useful findings deserve appreciation.

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FINDINGS

Following are the main findings and contributions in the study:

1. Groundwater flow model of Yamuna sub-basin in Nadia and North 24-Parganas districts of West Bengal has been developed. Zones of equal hydraulic conductivity and specific storage have been demarcated. The calibrated and validated model can be used to find the response of flow domain for any stress conditions including remedial measures.

2. Prevailing scenario of recharge and withdrawal rate of the study area have been assessed.

3. A transport model considering the combined effect of advection and dispersion has been developed. The model requires verification of its performance after incorporating chemical reaction components, such as; adsorption, retardation and decay which are crucial for contaminant like Arsenic.

4. Analysis of transport processes clearly indicates that presence of Arsenic concentration in the flow domain of the Yamuna sub-basin has no bearing on the influence of contaminants from external boundary sources or from other domain. Even occurrence of Arsenic in different pockets of this domain is also not due to the transport of Arsenic from one place to another, but this is due to the activation and spreading of in-situ source(s).

5. Activation and de-activation processes of Arsenic in the flow domain, which perhaps represent the oxidation and reduction processes of Arsenic introduction in the groundwater system, have been established.

6. From the analysis of Arsenic concentration data and studying the transport phenomena, it is expected that Ashoknagar, Khusbasi, Mandalhat, Kundalia , Devipur and Maslandpur may have the localised in-situ source(s) material of Arsenic in and around and not necessarily at the places where measurements were taken.

7. The spreading in the localised area is due to the transport of contaminants from the nearby in-situ source point(s).

8. The cause of activation of Arsenic in the groundwater is preaumed to be due to the oxidation of source material because of falling water table and dissolution/ reduction during rising water table. This explanation needs validation by further geo-chemical analysis of the localised pockets.

9. It is also found that the points of maximum concentration of Arsenic and the contour of minimum value of transmissivity coincide. The minimum transmissivity occurs

where clay pockets exist. Eventually this signifies that clay pockets/lenses have the tendency to entrap the Arsenic. In these pockets further geological investigations need to be carried out to identify the source of Arsenic.

10. From the analysis of hydrograph data (1987-1996) of some observation stations it is revealed that water table in the study domain has declined to its minimum level (3 to 4 metre below average) during the months of April-May in 1993 and 1995. Linking the processes of oxidation-reduction of Arsenic with the fluctuation of water table, three cases; i) defuncting withdrawal from the Arsenic affected area, ii) creating hydraulic barriers (in the form of battery of injection wells) around the Arsenic spreaded area, and iii) reducing withdrawal pattern from the study domain, have been analysed as remedial measures to arrest spreading.

11. Analysis of remedial measures indicate that arrest of lowering of water table particularly during peak withdrawal months (November to April) below certain level would minimize the oxidation/reduction processes of Arsenic in the flow domain. For the Yamuna sub-basin, in general, the water table of November 1997 was found to be the safe level of groundwater. The safe groundwater table for six localized pockets are found to be: 6.00 m for Mandalhat (Chakdah block), 6.25 m for Khusbasi (Chakdah block), 5.50 m for Kundalia (Chakdah block), 4.25 m for Devipur (Gaighata block), 4.00 m for Maslandpur (Swarupnagar), and 3.60 m for Ashoknagar (Habra I block) above MSL. To arrest the spreading of contaminated groundwater, creation of artificial hydraulic barrier by injection of recharge wells seemed to be a reliable option.

12. It was felt that detailed investigations on a micro level can give better understanding of Arsenic movilization including understanding of geo-chemical processes in the flow domain rather than analysis and investigation in a large domain.

ABSTRACT

Occurrence of Arsenic in groundwater and their areal spreading in a linear track of 470 Km in the Ganga-Brahmaputra delta covering 8 districts in West Bengal are serious concern among users and beneficiaries, groundwater managers, and also to the researchers. Earlier investigations and available literature indicate different opinions on sources of Arsenic but show a common argument about its activation, which is suspected to be due to the excessive exploitation of groundwater environment. Many researchers have explained the sources are of geologic origin, however, their geo-chemical processes of activation are yet to be established.

The study of "Arsenic Pollution in the Yamuna sub-basin, West Bengal" presented in this report is a joint effort of the National Institute of Hydrology and the Central Ground Water Board, Eastern Region, Calcutta. The objectives of the study which were conceived as: i) understanding and prediction of contaminants transport in the saturation zone, and ii) quantification of remedial measures to arrest spreading. These objectives have been addressed through development of a groundwater flow model, and a transport model for the study area. The USGS 3-dimensional finite difference model, MODFLOW and MT3D compatible with MODFLOW have been used as tools for flow and transport modelling. The flow modelling has been carried out considering unsteady state of model boundaries and variable external stresses and so is the case for transport modelling. A 3-dimensional groundwater flow and contaminants transport model has been developed considering semi-confined unconfined aquifer system.

From the analysis of flow phenomena, the model parameters such as; hydraulic conductivity and specific storage values have been established and the existing recharge and discharge pattern of the area have been re-defined. From the analysis of transport phenomena, the activation and de-activation processes of Arsenic in the flow domain which in physical sense has been defined as the oxidation and reduction processes of Arsenic, have been established. It is also found that occurrence of Arsenic at a place has no bearing on transport from other external sources but it is due to the activation of entrap in-situ localised source(s).

As remedial measures to arrest spreading and to control the process of oxidation of Arsenic, a number of remedial options such as; i) defuncting withdrawal from the Arsenic spreaded area, ii) creating hydraulic barriers (in the form of battery of injection wells) around the Arsenic spreaded area, and iii) stepwise reducing the withdrawal from the study domain, have been analysed and presented in the report.

LIMITATIONS OF THE STUDY

The study has following limitations:

- Vertical conductivity has been considered uniform over depth and assumed 10% of location specific horizontal hydraulic conductivity,
- Rainfall recharge and recharge due to irrigation return flow have been considered to have uniform influence over the whole domain,
- Actual withdrawal pattern and number of wells operating in the study area including their tapping depth were not exactly known and therefore a quantitative estimate was made on pro-rata basis,
- Prediction of heads beyond May 1998 are based on the scenario prevailing in year 1997-'98, i.e., based on one year data,
- Transport phenomena has been studied considering the advection and dispersion phenomena. Geo-chemical analysis of the area is necessary to quantify the effect of adsorption and disorption and other chemical processes,
- The value of longitudinal dispersivity is assumed to be one half of the shorter gridal mesh size, i.e., $\alpha = \Delta x/2$, and the transverse and vertical dispersivities are considered respectively as 10% and 1% of longitudinal dispersivity. Further investigations to collect time-concentration data are necessary to validate these values,
- Six localized points shown in the analysis are not the representation of location of sources but these are the places where maximum value of Arsenic concentration were observed, however, these high magnitude can only be observed when sources are in and around those places, and
- One cycle of flow and transport run for three years of transient data with 100 x 100 gridal meshes requires a CPU time of about six and half hours excluding input and output data analysis and a hard-disk memory of about 500 MB.

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PART - I

BACKGROUND INFORMATION AND MODELLING TOOLS

1.0 INTRODUCTION

From the epidemiological studies during the year 1980, contamination of groundwater by Arsenic content above the permissible limit of 0.05 mg/l in some localised pockets in some districts of West Bengal was first detected. Later, during the years 1983 - 1993, a linear track extending NNW-SSE from Malda district to south 24 Paraganas district in the eastern bank of the river Bhagirathi and along a few localities in the western bank of Hoogly river has also been reported under the severe threat of arsenic pollution. The river Bhagirathi and Hoogly are same tributaries known by two names at upstream and downstream and is a diversion river of the river the Ganga. As on year 1998, as many as 57 blocks and 830 villages covering areas in the order of 37,493 sq.km in eight districts, namely; Malda, Murshidabad, Nadia, South and North 24-Paraganas, Burdaman, Hugli, Parts of Calcutta in the same basin have been reported to be contaminated by Arsenic. As such, no definite evidences are available about the cause of Arsenic activation at such a larger scale in the groundwater. There are number of opinions, however, the common suspicion is the presence of Arseno pyrite (FeAsS) in the unconfined shallow zone of groundwater, and their geo-chemical transformation due to the over exploitation of groundwater may be the probable cause of Arsenic activation. The spreading of Arsenic in the groundwater is speculated to be due to the hydrological and hydraulic behaviour of the groundwater. Since the extent of spreading has increased over time, doubt persists in many corners whether the occurrence of arsenic in new pockets of the basin has any bearing with the transport of contaminants from other sources. The main concern has been to arrest the spreading of Arsenic in groundwater.

To quantify the spatial and temporal variation of Arsenic contaminated water in the groundwater for different hydrologic and hydraulic settings, and to suggest possible means of arresting spreading, the National Institute of Hydrology (NIH) and Central Ground Water Board, (CGWB) Eastern Region, Kolkata have envisaged a study towards development of a transport model for a specific area under the threat of Arsenic pollution. The groundwater domain of Yamuna Sub-basin covering areas of north 24-Parganas and Nadia districts of West Bengal has thus been chosen as the study area. In the study, the CGWB was entrusted with the field investigation activities while the NIH was given the responsibility of analysis of the field data and modelling exercises.

The contaminant transport in a groundwater domain depends on the overall effect of the sub-surface flow, mixing mechanisms, and the physical, chemical and biological processes of the system. The pumping from groundwater reservoirs, recharge or leakage to/from the groundwater system, and other hydraulic and hydrogeologic settings influence the contaminant's propagation appreciably. For studying the contaminant transport phenomena in a groundwater system, estimation of flow fields and the behaviour of the flow domain for different hydrologic and hydraulic conditions of the groundwater are pre-requisites. Development of flow model in order to definite the flow fields of contaminants transport is thus the first task of transport modelling, and hence forms first part of the study.

The report presented here describes an analysis of the groundwater flow system, and analysis of different aspects of Arsenic contaminated zones of the Yamuna sub-basin and the evaluation of some remedial options. The flow domain for the prevailing boundary and different input conditions has been solved, and modelled considering a three dimensional system of semi-confined aquifer, using the USGS 3-dimensional finite difference flow model, **MODFLOW** (Mc Donald and Harbough, 1988). Movement of contaminants in the generated flow domain has been studied using 3-dimensional advection-dispersion and chemical reactions modular transport model, **MT3D** (Zheng, 1992).

From the analyses of flow domain, range of model parameters such as; hydraulic conductivity and specific storage have been determined. Discharge and recharge pattern of the study domain have been re-assessed. The validated flow model has been used for studying the contaminant transport in a unsteady state of flow domain. Responses of the flow and transport models for different hydrologic settings have been analysed. The processes of activation and de-activation phenomena of Arsenic have been established and simulated. Responses of different conceived remedial options have also been analysed.

The report presented here consists of four parts. The first part provides the background information and conceptualisation details about the modelling, while the second part deals with analysis of flow domain and flow modelling. The third part describes the analyses of various aspects of contaminant transport, and modelling, where as the fourth part describes the analysis of different remedial options.

1.1 OBJECTIVES OF THE STUDY

The objectives of the study are:

i. To develop a groundwater flow model to suggest the well field, and to quantify the groundwater flow parameters,

ii. Development of a transport model to quantify the spatial and temporal variation of Arsenic mobilisation,

iii. Quantification of hydrological barrier to arrest the movements of contaminant plume.

1.2 MODELLING APPROACH

Based on the intended objectives and nature of the study, different concepts can be applied to formulate a model particularly for solving the real-life situations confronted with a number of options. The effectiveness of the outputs of the model depends on how accurately one conceptualises the problem, and strength of the input database. In case of groundwater flow modelling, selection of the flow domain and its initial and boundary conditions, besides the system parameters, such as; transmissivity and storativity values, are important. In transport modelling, questions those need to be answered first are; i) what is the flow field? ii) What are the responses of flow domain for different initial and boundary conditions, and also for different stress conditions? Answers of all these questions are considered as inputs to the transport modelling. Figure 1.1 depicts the linkages between the solution strategy for coupled set of flow conceptualisations and the transport modelling.

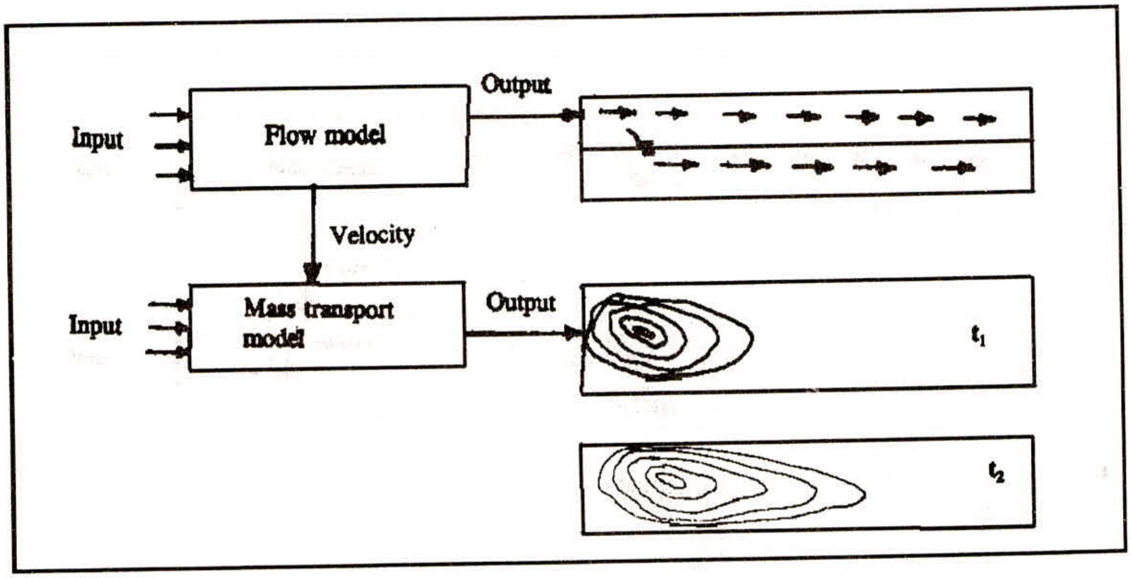


Figure 1.1: Linkages between the solution strategy for coupled set of flow conceptualizations and transport modelling.

For a one-dimensional straightforward simple boundary condition problem, an analytical model can give solutions. However, for problems of complex boundaries and varying hydrological conditions, which is usually observed in most of the real-life situations, analytical solutions of the equation of flow and contaminant transport are not available. The method suitable for solving a real-life flow and transport problem is the numerical modelling due to its capability in solving large and complex groundwater problems having spatial heterogeneity and anisotropy.

The approaches followed to study the flow scenario and the movement of contaminant transport in the flow domain are:

i. Conceptualisation of the flow domain,
ii. Evaluation of groundwater flow paths and groundwater velocities for different stress conditions considering a 3-dimensional flow domain,
iii. Calibration and validation of the model parameters through simulated runs of the model,
iv. Study of movement of Arsenic contaminated water in the flow domain considering following as the source of Arsenic propagation in the flow domain:

    (a) Maximum observed values of Arsenic concentration as source of Arsenic propagation,
    (b) River Baghirathi as the source,
    (c) Open boundaries as the source of Arsenic propagation.

The above issues are addressed through application of USGS 3-dimensional **finite difference** model, **MODFLOW** (Mc Donald and Harbough, 1988) for flow modelling, and **MT3D** (Zheng, 1992) compatible with outputs of MODFLOW capable of simulating advection, dispersion and chemical reactions in dissolved phase in groundwater system for transport modelling.

1.3 MODELLING TOOLS

1.3.1 Flow Model - MODFLOW

The model, MODFLOW, has the capabilities to simulate flow in three Cartesian co-ordinates for varying aquifer parameters, boundary and stress conditions. The program uses modular structures of different hydraulic and hydrologic variables usually encountered in solving the groundwater flow. The model can be set for one/two/three dimensional cases depending on one's interest.

MODFLOW programme has a main program and a series of independent subroutines called modules. The modules, in turn, have been grouped into 'packages'. A package is a group of modules that deals with a single aspect of the simulation. For example, the option `Well package' simulates the effect of wells, the `River package' simulates the effect of river etc.

MODFLOW discretizes the model domain with a mesh of blocks called cells, the location of which are described in terms of rows, columns, and layers.

The period of simulation is divided into a series of 'stress period' within which stress parameters are constant. Each stress period, in turn, is divided into a series of time steps. The user specifies the length of the stress period, the number of time steps at each stress period, and the time step multiplier. Using these terms, the program calculates the length of each time step in the stress period. Thus, within a simulation, there are three nested loops: a stress-period loop, within which there is a time-step loop, which in turn contains an iteration loop.

Discretization of a system describing by a partial differential equation in space and time, forms a number of simultaneous linear algebraic equations. MODFLOW has the option of a number of iterative methods, such as; **Strongly Implicit Procedure (SIP), Slice Over Relaxation (SSOR) Method and Pre Conjugate Gradient Method (PCG)** to obtain the solution of the linear algebraic equations.

1.3.1.1 Mathematical background of MODFLOW

The three dimensional movement of groundwater of constant density through porous earth material under equilibrium conditions in a heterogenous anisotropic medium is described by the following partial differential equation:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-q_s=S_s\frac{\partial h}{\partial t} \qquad (1)$$

where,

K_{xx},K_{yy}, K_{zz}	:	hydraulic conductivies along major axes, $[LT^{-1}]$;
h	:	potentiometric head, [L];
q_s	:	volumetric flux per unit volume and represents sources and sinks, $[T^{-1}]$;
S_s	:	specific storage of the aquifer, $[L^{-1}]$;
t	:	time, [T].

In general, S_s, K_{xx}, K_{yy}, and K_{zz} are functions of space and are the aquifer parameters, whereas h and q_s are functions of space and time and are variables. This equation for ***flow conditions at the boundaries*** of an aquifer system and specification of ***initial head conditions*** constitutes a mathematical model of the groundwater flow.

1.3.2 Transport Model - MT3D

The mass transport model referred as **MT3D,** is a 3-dimensional computer model, which can be used to simulate changes in concentration of *single species* miscible contaminants in groundwater considering advection, dispersion and some *simple chemical reactions* with various types of boundary conditions and external sources or sinks. It uses modular structure similar to that of MODFLOW. The modular structure of the MT3D transport model makes it possible to simulate advection, dispersion, source/sink mixing, and chemical reactions independently. After a flow model is developed and calibrated, the information needed by the transport model is saved in files, which are then retrieved by the transport model.

Available version 1.5 of MT3D accommodates the following spatial discretization capabilities and transport boundary conditions: i) confined, unconfined or semi-confined aquifer layers; ii) inclined model layers and variable cell thickness within the same layer; iii) specified concentration or mass flux boundaries; and iv) effects of external sources and sinks such as wells, drains, areal recharge and evapotranspiration.

1.3.2.1 Mathematical background of MT3D

The partial differential equation describing three-dimensional transport of contaminants in groundwater can be written as follows:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C}{\partial x_j}\right) - \frac{\partial}{\partial x_i}(v_i C) + \frac{q_s}{n}C_s + \sum_{k=1}^{N} R_k \quad (2)$$

Where

C	is the concentration of contaminants dissolved in groundwater, $[ML^{-3}]$;
t	is time, $[T]$;
x_i	is the distance along the respective Cartesian coordinate axis, $[L]$;
D_{ij}	is the hydrodynamic dispersion coefficient, $[L^2T^{-1}]$;
v_i	is the seepage or linear pore water velocity, $[LT^{-1}]$;
q_s	is the volumetric flux of water per unit volume of aquifer representing sources (positive) and sinks (negative), $[T^{-1}]$;
C_s	is the concentration of sources or sinks, $[ML^{-3}]$;
n	is the porosity of the porous medium,
$\sum_{k=1}^{N} R_k$	is the chemical reaction term, $[ML^{-3}T^{-1}]$.

The transport equation is linked to the flow equation through the relationship:

$$v_{ii} = -\frac{K_{ii}}{n}\frac{\partial h}{\partial x_i} \tag{3}$$

where

K_{ii} : is the principal component of the hydraulic conductivity tensor, $[LT^{-1}]$;

h : is hydraulic head, [L];

The hydraulic head is obtained from the solution of the three-dimensional groundwater flow equation:

$$\frac{\partial}{\partial x_i}\left(K_{ii}\frac{\partial h}{\partial x_j}\right) + q_s = S_s\frac{\partial h}{\partial t} \tag{4}$$

where, S_s is the specific storage of the porous materials, $[L^{-1}]$.

The advective velocity in Eq. 2 of the flow fields in 3-Cartesian co-ordinates used by MT3D is obtained from the simulated run of the MODFLOW.

1.4 DESCRIPTION OF THE STUDY AREA

Based on the surface network system, the area is described as the Yamuna sub-basin, but as far as, the geological formation and groundwater flow domain are concerned, the area is a part of the upper Ganga-Brahmaputra Delta, and the river Yamuna forms a surface water drainage channel of this domain. The Yamuna sub-basin is measured between the latitudes of 22°49′ and 23°03′ N and longitudes of 88°24′ and 88°51′ E. The basin area is estimated to be about 650 sq.km. which covers, 2-blocks of Nadia district and 7 blocks of north 24-parganas district. However, for the purpose of analysis and modelling, the study domain is chosen as 1500 sq.km with a linear length of 50 km. in east-west direction, and width of 30 km. in north-south direction. The river Bhagirathi (also known as Hoogly at the downstream) forms the western boundary whereas the river Ichamati forms the east side boundary of the study domain, and river Yamuna routed through north-west to south-east direction of the basin not exactly joining the river Bhagirathi at the upstream. Figures 1.2 and 1.3 represent location map of the study domain. The surface topography of the area (Figure 1.4) does not show any marked topographic features and can be described as flat country. The slope of the surface, estimated to be in the order of 1:25000, is generally from North-West to South-East direction. Land surfaces at some places exhibit minor undulation and formation of ditches, which usually remain ponded, or under sub-surface drainage congestion over the year.

With regard to the land-use pattern, the area has more agricultural activities, and cultivation of paddy (2-3 croprs in a year) is the main crop in the area. Use of fertilisers, pesticides and insecticides on the agricultural lands is very common. Around 12-15 % of the area is under habitation with number of thickly populated sub-divisional and district townships and thinly populated pockets of village habitation. As such, there are no major industrial activities in the area, except 2/3 industries around the study domain. Ichapur Gun factory, and Bandel thermal power plant on the other bank of Hoogly, are notable major industries. There may be a number of small-scale industries in the urban areas. Groundwater is the main source of water to meet the demand of irrigation, domestic, municipal and also for industrial activities in the area.

Within the catchment area of 650 sq.km of Yamuna sub-basin., 63 wells were identified as observation wells for monthly water table data collection, and for analysis of Arsenic concentration in groundwater. Pumping tests were carried out at 21 locations to determine the aquifer parameters. Litholog of 23 locations helped in knowing roughly the sub-surface strata. The river flow, cross-sections, stage and the geometry for Bhagirathi, Ichamati and Yamuna were partly collected from field surveys and partly obtained from other agencies.

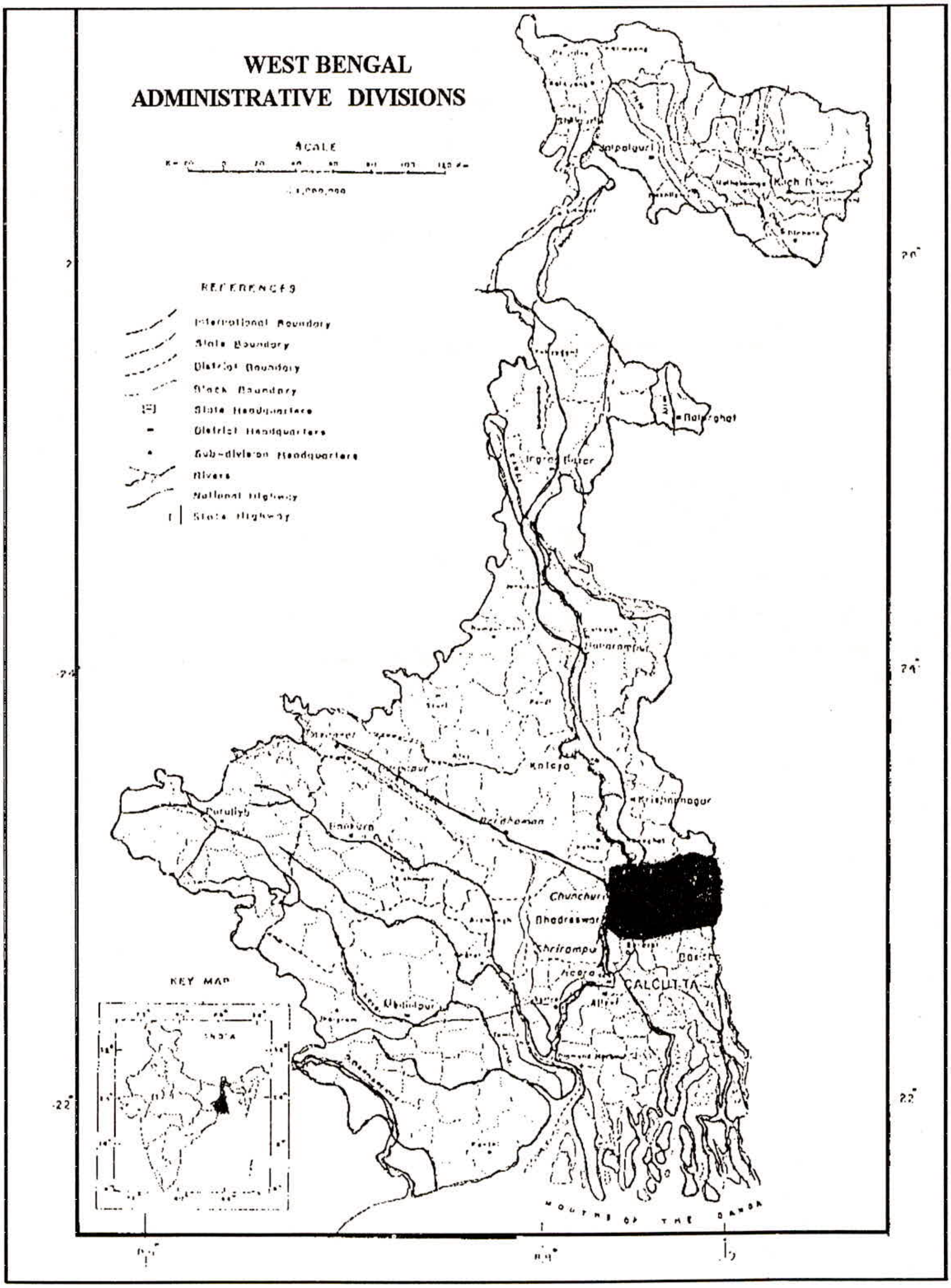


Figure 1.2 : Location map of the study domain.

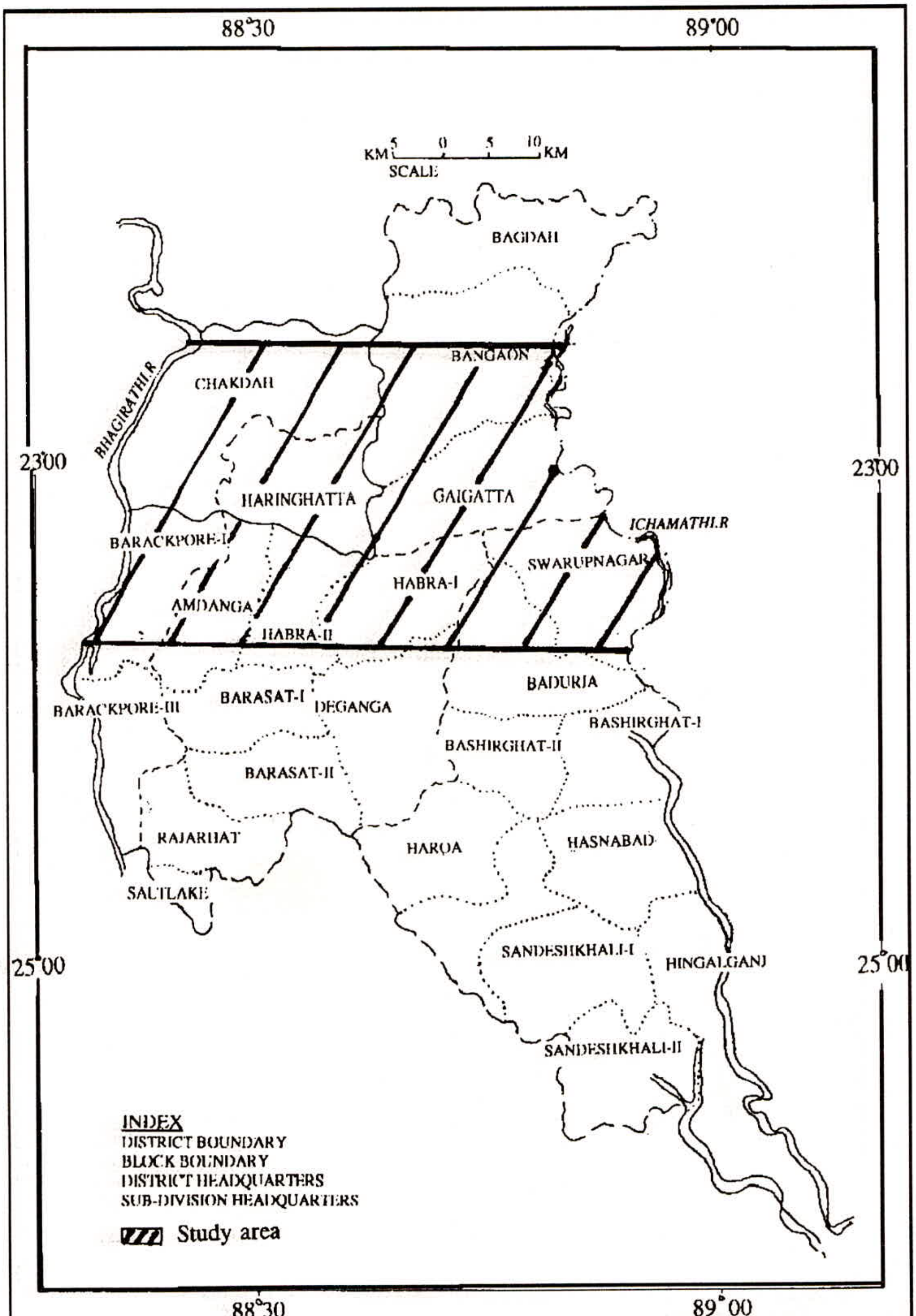
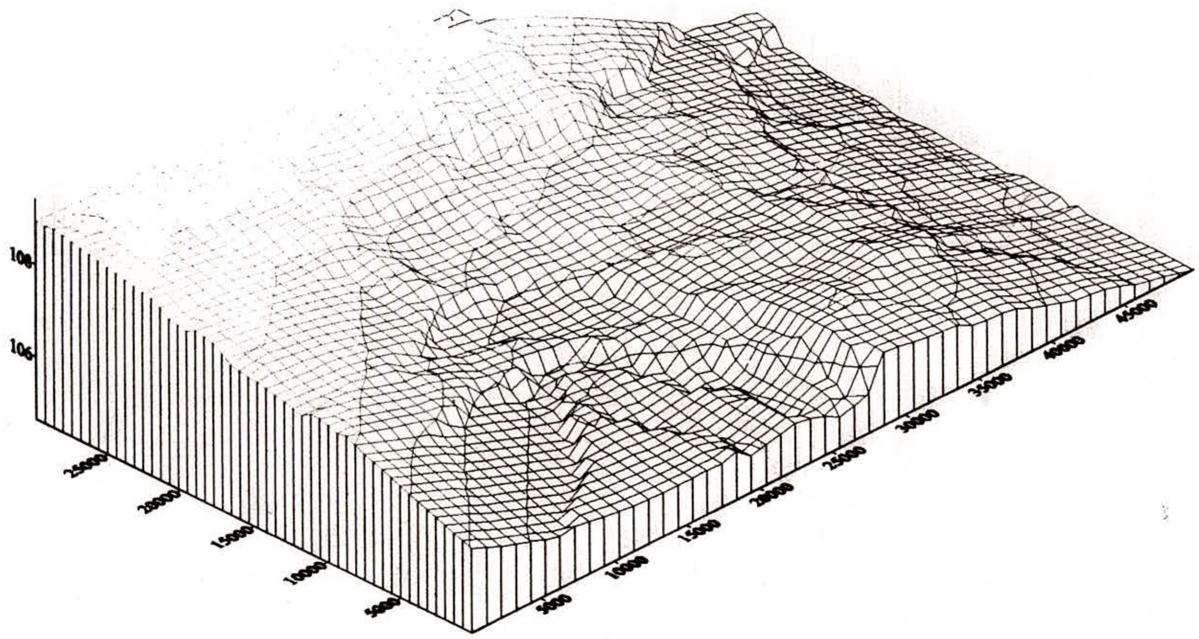


Figure - 1.3 : Location map showing blocks covered under the study area.



* 100 refers to the arbitrary datum above MSL

Figure -1.4: Topographical features of the study domain

1.4.1 Surface Water Hydrology

Being near to the Bay of Bengal, the area mostly experiences hot and humid type of climate. Variation of maximum temperature has been reported to be between 27.9°C to 37.5°C while the minimum temperature ranges from 12.4°C to 20.3°C. Relative humidity, on the other side, has the maximum and minimum variation of 93% (Sept. to Dec.) to 35% (March) respectively. The area receives good amount of rainfall, to the tune of 1850 mm/year, mostly from the south-west monsoon, which occurs during months from May to September. About 80% of the annual rainfall is received during the monsoon months with peaks during the month of June and July. The distribution of yearly rainfall pattern is given in Table-1.1.

Table-1.1: Distribution of rainfall in different seasons

Avg. annual rainfall(mm)	Winter(%) (Jan- March)	Hot weather(%) (March-May)	South West monsoon(%) (May-Sept)	Post monsoon(%) (Sept-Jan)
1850	2.50 - 3.00	10.50 - 11.50	78 - 82	5.5 - 6.5

The evaporation and evapotranspiration from the area have been estimated to be 500-600 mm/year and 1000-1200 mm/year per unit area respectively. The average evapotranspiration is considered to be 3.0136 mm/day per unit area.

The rivers Bhagirathi and Ichamati are perennial in nature, and carry considerable water throughout the year. Contour plots of water level apparently shows that Ichamati is an effluent river and the river Bhagirathi mostly an influent river in the study domain. The river stages data of the Baghirathi measured near Jalangi (about 30 Km. upstream of the study domain) show that during monsoon months water levels at the top of the study domain go as high as 9.5 metre (above MSL) against the yearly average of 7.0 metre (above MSL), and go down to 5.5 metre (above MSL) during the lean period (April/May). In case of Ichamati, monsoon water levels rise to 7.5 metre (above MSL) against the yearly average of 5.5 metre (above MSL) and go down to 3.5 metre (above MSL) during lean period. The bed slopes and the cross-sectional average velocities measured during Novemver'98 works out to be; 1:15,000 and 0.5 m/sec for Bhagirathi, 1:20,000 and 0.30 m/sec for Ichamati. The width of the river Baghirathi and Ichamati varies from section to section due to meandering of the rivers. The variation of width of the river Bhagirathi is measured between 400-650 m giving an average of 500 m. While the width of Ichamati varies between 300 - 550 m giving an average of 400 m. Both the rivers experience the back-flow due to the tide from Bay of Bengal, which comes twice in a day and water level of the river Baghirathi and Ichamati at the top of the boundary increases by about 0.20 m and 0.75 m respectively than the normal water level. The rivers bed materials are sand deposits.

The river Yamuna flows from north-west to south-east direction not exactly joining the river Bhagirathi, has the outfall at the river Ichamati. The river has a very flat slope with bed material consisting of mud, local soils etc. The river Yamuna has, in fact, no flow, particularly in the upstream half, except ponding in some places while at the lower stretches water flows with very less velocity. Demarcation of river width particularly at the upper stretches is difficult but width of the river at lower stretches varies between 75 - 150 m. The effect of back water flow due to the tide is more pronounced than the normal flow in the Yamuna.

1.4.2 Groundwater Hydrology

Groundwater is available in water table conditions. The depth to water table in the study area ranges between 2.5-3.0 metre (pre-monsoon) and 0.5-2.5 metre (monsoon) below ground level. Water table declines to its minimum level, usually during the month of April-May and rises to its maximum level during the month of August. Observed hydrographs of water table (1987-1996) indicate that variation of water levels in the study area is governed by the withdrawal of water and it varies from place to place. Hydraulic gradient is steeper (about 1:333) in the northern part and gentle in the central and southern part (about 1:1666). The gradient is in general southerly to south-easterly.

It was difficult to ascertain number of wells in operation, and ascertaining their yield. However, based on the assessment report of the Central Ground Water Board (CGWB, 1991), a quantitative estimate was made on pro-rata basis, which indicates possibility of about 29,058 number of shallow tube wells and 197 numbers of heavy duty wells in existence in the study domain in year 1990. The shallow tubewells operate mostly for irrigation purposes having tapping zones between 18-50 m. below ground level with discharge rate between 23-43 m^3/hour, and the deep tubewells operate to meet the demand of domestic and municipal supplies having tapping zones between 60-150 m below ground level with discharge rate between 45-200 m^3/hour. Table-1.2 shows block-wise distribution of wells ascertained on pro-rata basic. Groundwater levels fluctuate according to the operation of wells. Since withdrawal of groundwater is largely dependent on agricultural need of the area, recharge and discharge pattern to/from the groundwater reservoir also varies both in time and space. Over the year, usually three crops are cultivated, namely, Kharif (June,15 - Oct.,15), Rabi (Oct.,16- Feb.,15), and Bado (Feb.,16-June,15). Water requirement of all these seasonal crops varies. Survey report indicates that, out of the yearly withdrawal of 307.264 MCM per year (conservative estimate), about 10% is withdrawn for Kharif, 30% for Rabi and 60% for Bado. Water table data show that the discharge from the groundwater system in the area occurs between August-May and recharge occurs from May-August.

Table 1.2: Block-wise distribution of wells (after CGWB, 1991)

Sl.	BLOCKS	AREA (Km^2)	SHALLOW WELLS (Nos)	DEEP WELLS (Nos)
1	CHAKDAH	265.28	3718	28
2	BANGAON	183.39	4292	23
3	HARINGHATA	170.13	2924	35
4	GAIGHATA	209.30	6352	19
5	BARRACKPORE-I	121.10	627	17
6	AMDANGA	83.05	1585	17
7	HABRA-I	134.95	2804	25
8	HABRA-II	80.74	1292	22
9	SWARUPNAGAR	164.94	3882	6
10	BHADURIA	53.63	1582	5
	TOTAL	1,465 (*)	29,058	197

(*) Remaining 35 km^2 falls beyond the other side of Bhagirathi and Ichamati river.

1.4.3 Sub-surface Geology

The top surface I s mostly patched with formation of clay and sandy clay locally, in some parts, these are as thick as 20-30m. Lithological information of 23 stations (Table-A.5 in appendix and their locations are shown in Figure A.4 in appendix) indicates a complex sub-surface geological formation of the area with varying soil formations. The formations, however, indicate presence of a thick Gangetic alluvium of quaternary age with succession of fluviatile sediments. The sediments consist of sands of various grades, silt, clay, gravels and their various admixtures deposited by the river Ganga.

Background information reveals that the sub-basin is characterised by a series of meander belts formed by rivers, one superimposed/cutting across the other. Most of the meander belts are not continuous stretches - but - are preserved as festoons with the successive belts eroding and in-setting into the older ones. Although sand, silt and clay make up the sedimentary fill in general, the older meander belts are sandier, and are underlain by gravel beds indicating the existence of high-energy streams during their formation.

A close look of lithologs of the area (Figure 1.5(a) and (b)), which is drawn after re-classifying the information of 23 borehole logs (given in Table-A.6 in appendix) depicts existence of a non-distinct aquifer system in the study area. The different layers are not continuous. The thickness of each lithological unit also changes abruptly.

So, a general trend is difficult to establish. However, the trend of the formation material is; top layer consisting of clay followed by fine sand, sand/coarse sand and again clay. Most of the wells are tapping within the sand zone. The study area thus is considered as **unconfined to semi-confined aquifer system.**

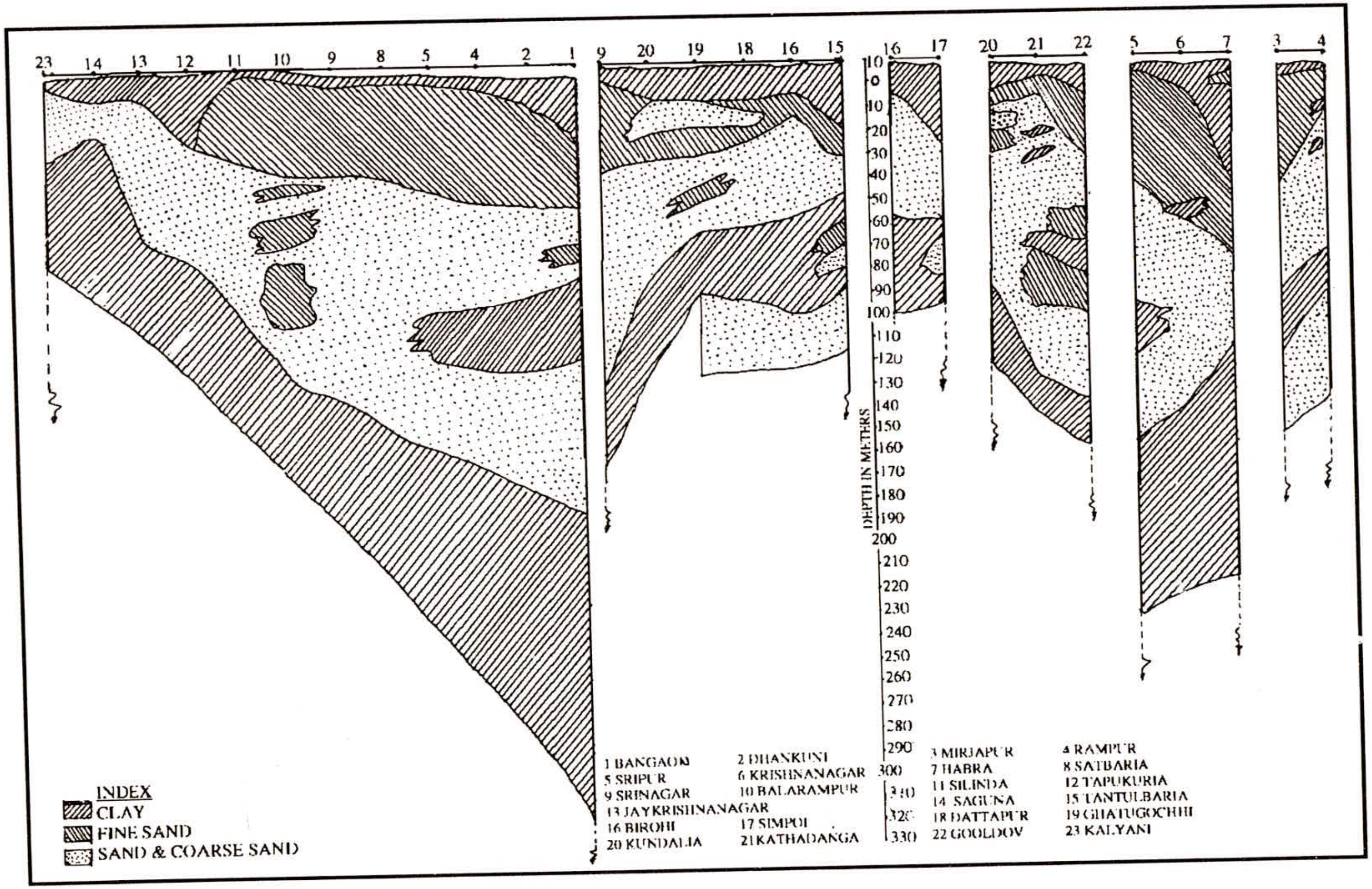


Figure 1.5(a) : Formations of sub-surface geology.

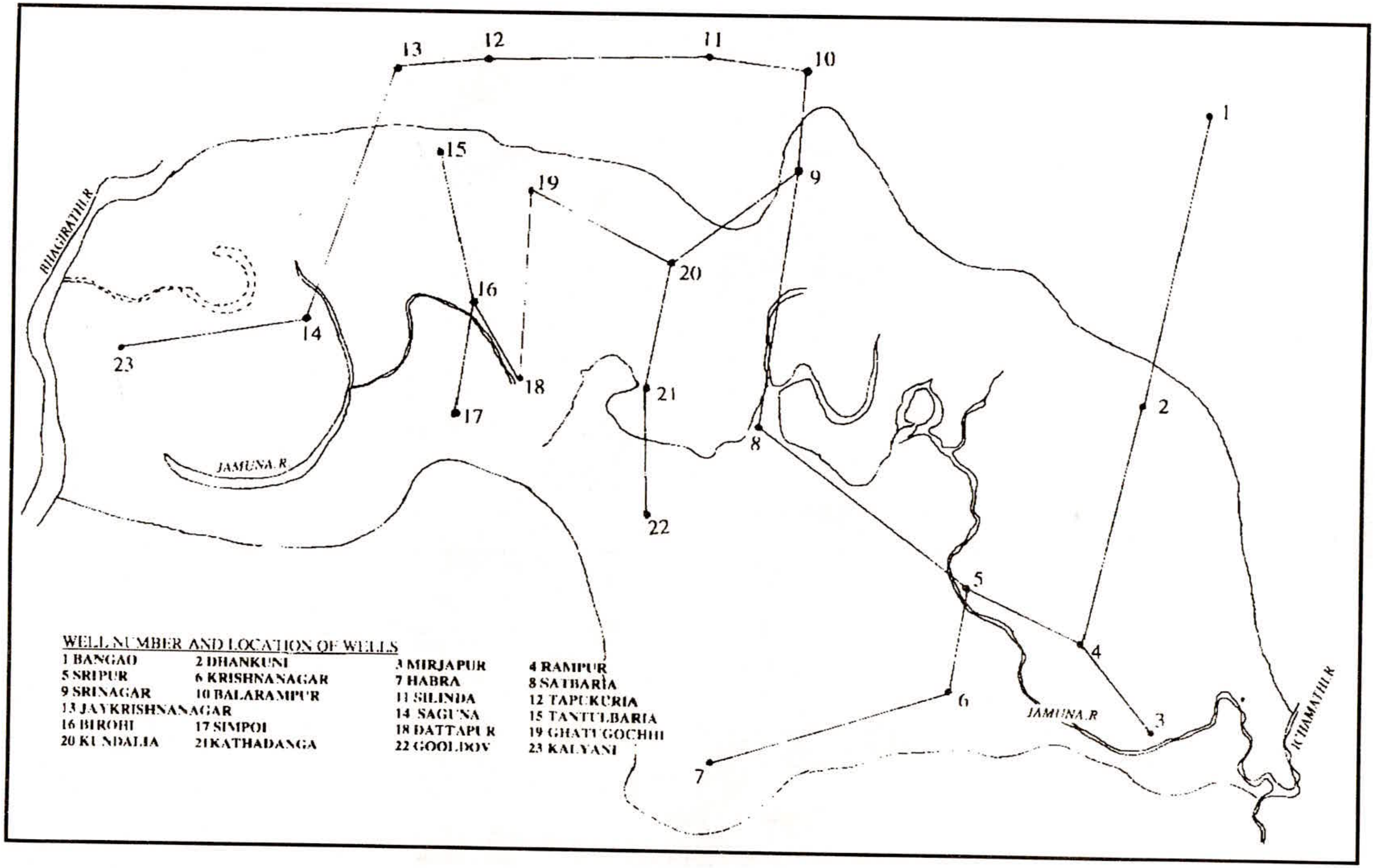


Figure 1.5(b) : Location of bore hole logs.

1.5 DISCRITIZATION OF THE STUDY AREA

The east and west boundaries of the study area are governed by the layout of rivers Ichamati and Bhagirathi respectively, with varying distances between them as they move from north to south. The layout of all rivers in the study area has been shown in Figure.1.6. Meandering of the rivers (Ichamati has more meandering than Bhagirathi) increases /decreases the horizontal length between the rivers. The distance between the extreme point of the river Bhagirathi in the West side, and the extreme point of the river Ichamati in the East side is measured to be 50 Km. While the north and south sides do not have any conventional boundaries. For simplification of analysis of data and output results, modelling area has been chosen as 50 km. in length in the east-west direction, and 30 km. in width in the north-south direction. The area outside the river boundaries is considered as free zone and beyond our interest.

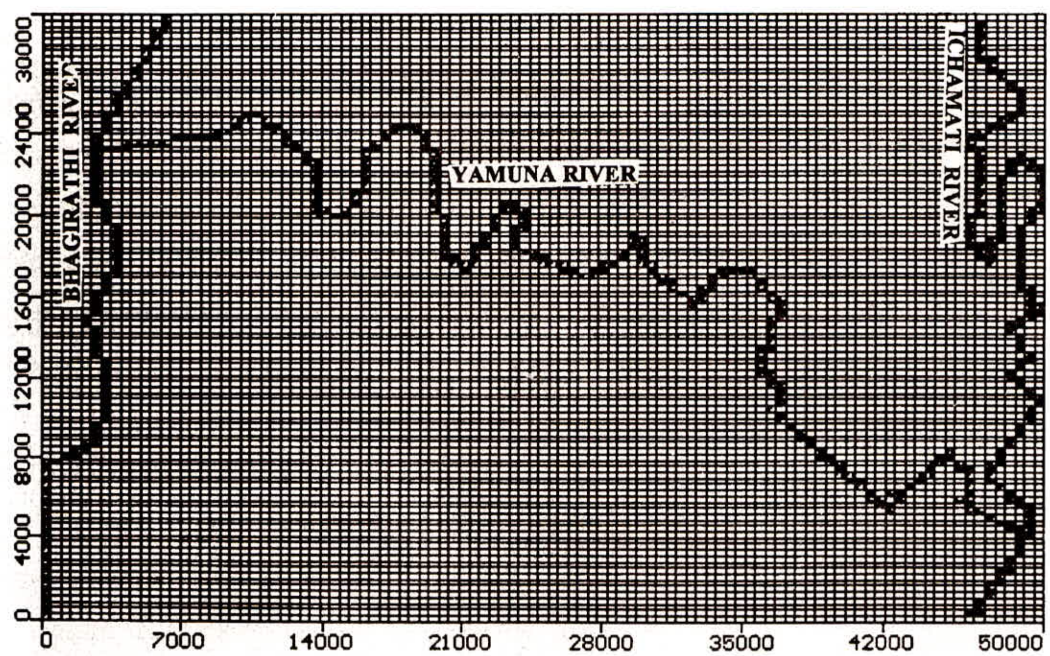


Figure 1.6 : Discretized map of the study domain showing network of rivers (NC=100, NR=100, NL=10)

There are no standard procedures for fixing the grid size. It is the modeller's prerogative to decide and select the grid size(s). Smaller the size of grid, more the number of gridal meshes/cells and larger the computational burden. Finer grids provide detailed scenarios in the local scale and preferred when representative database is available. Requirement of output results and the field conditions can be a guideline to select the grid size. It is not necessary that the grid size(s) throughout the domain should be of same size. Depending upon the interest, the grid size can be made larger or smaller at any specific location. The processor of MODFLOW (PM ver. 3.0) has all the options to do so. However, the model has limitation of maximum of 15,000 number of cells with maximum number of cells along column and rows to be 500. The study area of 50 km.X 30 km. has thus been divided into 100 X 100 equal sizes gridal network i.e 10,000 cells having a cell dimension of 500 m X 300 m. Width of the rivers, (Bhagirathi and Ichamati in the x-direction and the Yamuna in the Y-direction) is taken as the criterion to select the grid size. Figure 1.6 depicts the discretized map of the study area.

The water table fluctuations and lithologs do not indicate any multilayer aquifer system up to the depth of 150 metre. However, based on the water use system, these are termed as shallow (when tapping depth is within 15 metre), intermediate (for tapping depth ranges between 15 m to 40 m), and deep (for tapping depth between 40m - 80 m) aquifers. A single aquifer system of **unconfined to semi-confined in nature has been considered up to a depth of 80 metre.** In order to take the account of change of lithologs in local scales, the vertical depth of 80 m. has been divided into 10 equal layers of each 8 m thick having variable storativities and transmissivities in the horizontal scale but no change in the vertical scale. The another reason of dividing in slices in the vertical direction is to see the movement of particles in the vertical direction.

PART - II

FLOW MODELLING AND ANALYSIS OF FLOW DOMAIN

2.0 FLOW MODELLING

The main objective of the flow modelling is to estimate piezometric heads and the velocity vectors for different hydrologic conditions. This is possible when model parameters are known. The flow equation (1) clearly indicates that the hydraulic conductivity (K_{ii}) and the specific storage (S_s) are the parameters, which shape the flow equation. Recharge/discharge to/from the groundwater reservoir and initial and boundary conditions are the external forcing factors which are needed to compute the response of flow domain for any specific condition.

2.1 INPUT DATA PREPARATION

Data requirement for the flow model can be understood from Eq.(1). It basically requires initial and boundary conditions and the aquifer parameters (hydraulic conductivity and the storativity) besides the external stresses.

2.1.1 Hydraulic Properties

For a 3-dimensional groundwater flow model, hydraulic conductivity and the specific storage are the model parameters. These parameters are usually estimated from the pump test data. In the study domain, transmissivity and storativity were available at the 21 locations, which are shown in Figs. A.1, and A.2 in the appendix. The location/wells, where the pump tests were carried out, had different screen depths, which are at different lithological units. So, the estimated transmissivity and the storativity values represent the overall performance of that layer only. The pump test data represent that the transmissivity values varies from 530 to 4000 m^2/day and storativity between 0.33 $x10^{-5}$ to 1.3 x 10^{-2} in the study domain. Distributions of transmissivity and storativity values are given in Figs. 2.1 and 2.2 respectively.

Since the aquifer type is unconfined to semi-confined, it is required to calculate the hydraulic conductivity from the transmissivity values and specific storage from storativity values. These values were found by dividing the respective values by the corresponding aquifer thicknesses in the following way:

$K = T/b$, and $S_s = S/b$, where, T is the transmissivity $[L^2T^{-1}]$, S is the storativity and b is the layer thickness [L].

Since, the sub-surface lithologs vary vertically and layer thickness also vary, the values

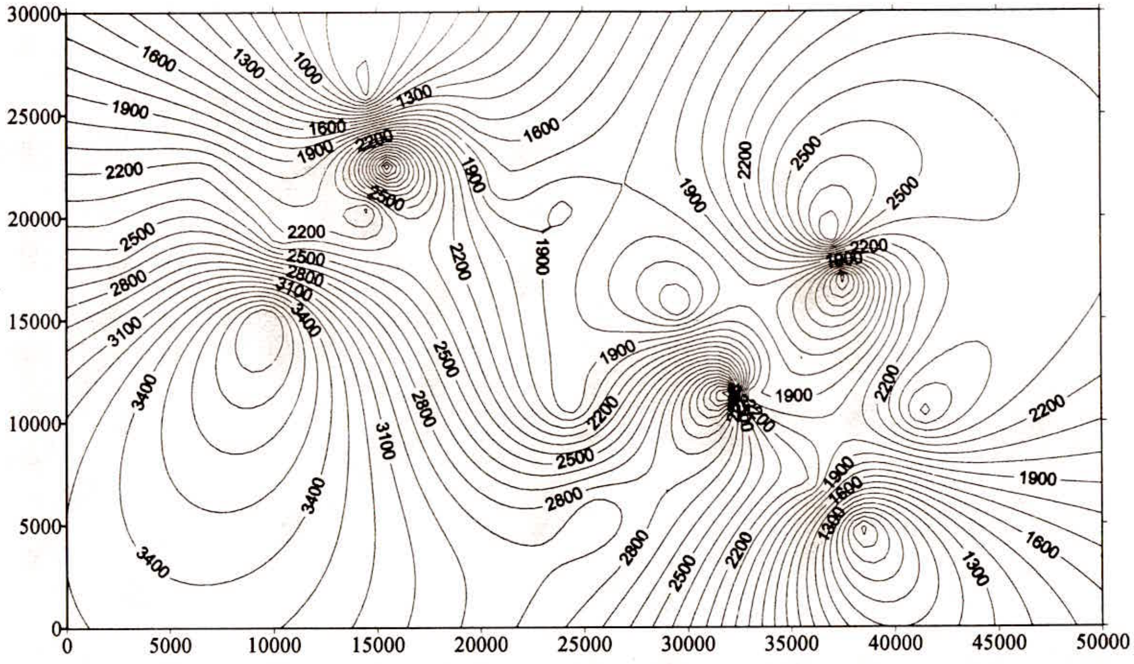


Figure-2.1 : Distribution of Transmissivity values (m 2/day) in the study domain (Yamuna sub-basin)

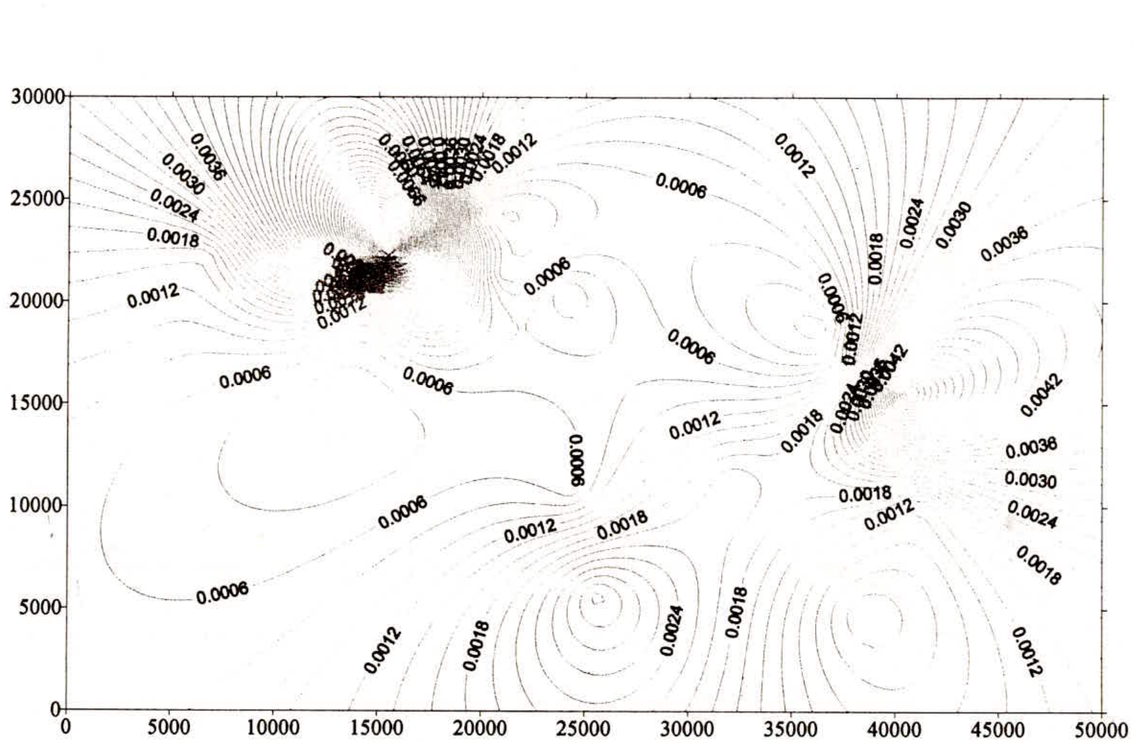


Figure - 2.2 : Distribution of Storativity values in the study domain (Yamuna sub-basin)

of `K' and `S_s' estimated from the above expression also varies for the same `T' and `S' values in space. These values of `K' and `S_s' are assumed to be as initial guess for other places, which need to be calibrated through simulation of the flow model. The vertical hydraulic conductivity is assumed to be equal to 0.1 times of horizontal hydraulic conductivity.

2.1.2 Initial conditions

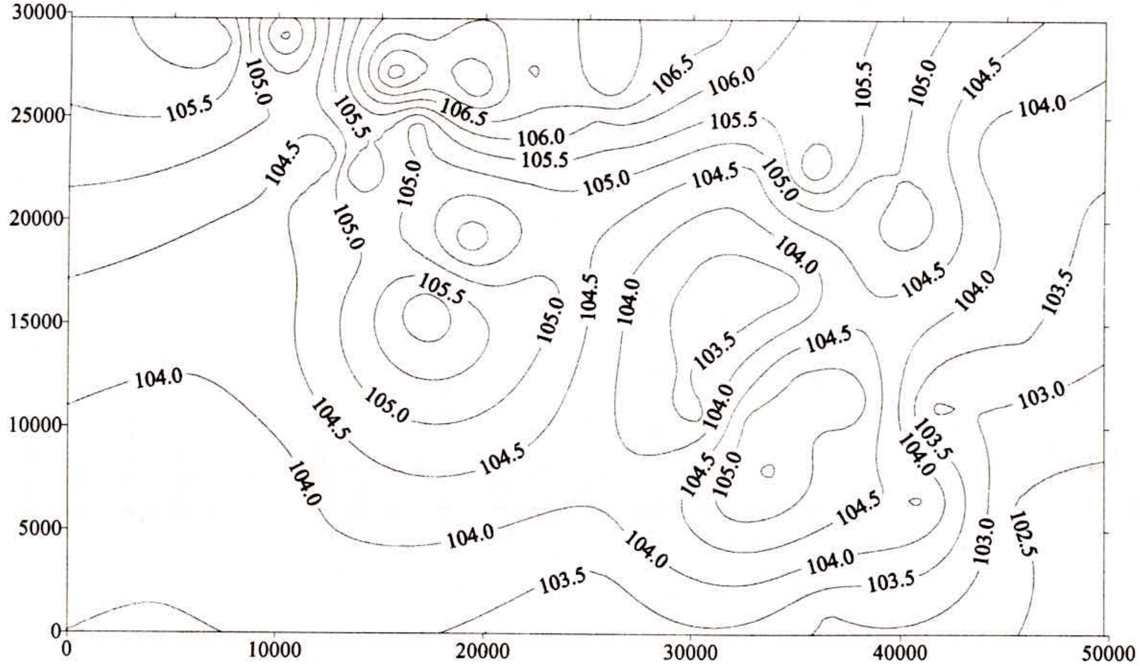
One year observed water level data for 58 locations were available, location of which is shown in Fig.A.3 in the appendix and the observed data of these locations are given in Table A.1 in the appendix. From the water level data, water table elevations were calculated. The water table elevations for different months are shown in Table A.2 in the appendix. Since most of the data were available for September'97, the water table data of September'97, which is shown in Fig. 2.3 was taken as the initial water table condition for simulation of the flow model. For the sake of avoiding negative values, all the water table data were transformed and elevated with respect to an arbitrary reference level of **100 m** above mean sea level.

2.1.3 Boundary conditions

Ideally - a groundwater basin boundary should form the boundary condition to solve the flow equation. In the absence of a natural hydrological (groundwater basin) boundaries, it is appropriate to select some surface water hydrological features like rivers as the boundary.

In Yamuna sub-basin, the east and west side of the study domain is bounded by the Ichamati, and the Bhagirathi flowing from north to south. So, the river boundary has been taken in the east and west side of the study domain. In the central part, Yamuna has also been taken as a river. Rivers contribute water to the groundwater system or drain water from the flow domain depending on the head gradient between the stream and the groundwater regime. The effect of river is taken care of by the `River package' in the MODFLOW, which simulates the flow between surface water features and groundwater systems. To simulate these effects, three data types are required for each river cell viz. hydraulic conductance of the river bed $[L^2T^{-1}]$, elevation of the river bed bottom [L] and the head in the river [L]. These data for different months used as input for different stress periods in the model are given in Table-A.3(a,b,c) (in appendix). The hydraulic conductance of the riverbed (CRIV) is estimated from the following formula:

$$CRIV = \frac{\beta . X . W}{M}$$



* 100 is the arbitrary datum above MSL

Figure -2.3: Contour plot of initial water table elevation (September '97)

where β = hydraulic conductivity of river bed [LT^{-1}], X = length of the reach contained in the river cell [L], M = thickness of the river bed material [L], and W = width of the river [L]. Considering, the river bed material is composed of coarse sand, the standard value of 0.04 m/day is assumed as the hydraulic conductivity of the river bed. Thickness of bed materials is considered to be 2m for all the rivers. Widths of the rivers at different sections have been calculated from the cross-section and the river hydraulic data made available from the field survey by NIH team. The cell length (X) for river Bhagirathi and Ichamati is 300 m while for river Yamuna it is 500m. The river details of other cells have been calculated by linear interpolation from the slope of the riverbeds.

North and south side of the study domain did not have any kind of conventional hydrological boundaries - but - water table data of some of the nearby observation wells were available. These two sides were therefore considered as general head boundaries or flux boundaries or open boundaries. The General Head Boundary (GHB) in the flow model simulates flow into or out of a cell from an external source. Two data types are required for each GHB cell namely: hydraulic conductance [L^2T^{-1}] of the interface between the aquifer cell and the boundary and the head on the boundary. The hydraulic conductance values of GHB's are calculated by multiplying the hydraulic conductivity and the layer thickness while heads on the boundaries are estimated from information of observation wells near the boundaries.

Since river stages vary from month to month, and so is the GHB, the set up of the model boundaries thus represents **unsteady condition.**

2.1.5 Estimation of Stresses

Stresses in a groundwater system are usually due to outflow from the aquifer or inflow into the aquifer. The components of outflow consist of pumpage from the aquifer, evapotranspiration, and the outflow through drains, rivers and boundaries. The inflow components consist of recharge through rainfall, irrigation return flow, and due to horizontal boundaries etc. The outflow from the aquifer is defined as discharge and the inflow is termed as recharge.

2.1.6 Estimation of Discharge

Withdrawal from the aquifer and the evapotranspiration have been considered as the discharge components. Evapotranspiration value is assumed to be 1000 mm/year from root zone depth of 2.0 metre, while withdrawals from the aquifer are estimated from the block-wise groundwater resources data of 1991 (CGWB). Table-2.1 represents a quantitative estimation of block-wise withdrawal pattern.

The outflow/inflow through boundaries (rivers or general head) are taken care of by the model automatically while simulating the flow depending on the river stages and the head on the boundaries.

2.1.7 Estimation of Recharge

Aerial recharge through rainfall and the irrigation return flow have been considered as the external recharge to the flow domain while, the recharge/inflow from rivers and the head dependent boundaries are taken care of by the model depending upon the heads in the boundaries.

Rainfall recharge is considered as 20% of the annual rainfall of 1850 mm distributed over the monsoon period (May to September). For other months no rainfall recharge is considered. The irrigation return flow has also been taken as 20% of the net draft in each block in the respective periods. The block-wise estimation of recharge pattern is shown in Table-2.2.

Table - 2.1 : Blockwise withdrawal pattern of groundwater (based on the net draft data of 1991)

Sl.	BLOCKS	Net Draft (m^3/year)x10^6	Draft (m^3/day) (A)			Draft (mm/day)		
			Feb-June	June-Oct	Oct-Feb	Feb-June	June-Oct	Oct-Feb
		(1)	60% * (1)	10% * (1)	30% * (1)	(A) ÷ Area	(A) ÷ Area	(A) ÷ Area
1	CHAKDAH	46.900	234500	39083	117250	0.882	0.147	0.441
2	BANGAON	45.490	227450	76991	113725	2.520	0.419	1.259
3	HARINGHATA	35.900	179500	29917	89750	1.055	0.176	0.527
4	GAIGHATA	65.000	325000	54167	162500	1.550	0.259	0.776
5	BARRACKPORE-I	5.437	27185	4531	13592	0.224	0.037	0.112
6	AMDANGA	18.140	90700	15117	45350	1.092	0.182	0.546
7	HABRA-I	31.140	155700	25950	77850	1.152	0.192	0.576
8	HABRA-II	16.130	80650	12442	40325	0.925	0.154	0.462
9	SWARUPNAGAR	38.940	194700	32450	97350	1.180	0.197	0.590
10	BHADURIA	4.187	20935	3489	10467	0.390	0.065	0.195

* Explanation of calculation in (A), i.e., Draft (m^3/day) = (Net draft x (% withdrawal))/120

Table 2.2: Blockwise Recharge pattern (Irrigation return flow is based on the data in Table-2.1)

Sl.	BLOCKS	Rainfall Recharge (mm/day) [20% of 1850 mm during May-Sept]	Irrigation Return Flow(IRF), (m^3/day) per block = [20% of Net Draft]			Total Recharge (mm/day)		
			Feb-May	May-Sept	Sept-Feb	Feb-May	May-Sept (Rain+IRF)	Sept-Feb
1	CHAKDAH	3.087	46900	7816	23450	0.1764	3.1200	0.0880
2	BANGAON	3.087	45490	15398	22745	0.5040	3.1220	0.2518
3	HARINGHATA	3.087	35900	5983	17950	0.2110	3.1205	0.1054
4	GAIGHATA	3.087	65000	10833	32500	0.3100	3.1421	0.1552
5	BARRACKPORE-I	3.087	5437	906	2718	0.0448	3.0977	0.0224
6	AMDANGA	3.087	18140	3023	9070	0.2184	3.1267	0.1092
7	HABRA-I	3.087	31140	5190	15570	0.2304	3.1287	0.1152
8	HABRA-II	3.087	16130	2488	8065	0.1850	3.1211	0.0924
9	SWARUPNAGAR	3.087	38940	6490	19470	0.2360	3.1297	0.1180
10	BHADURIA	3.087	4187	698	2093	0.0780	3.1033	0.0390

2.2 CALIBRATION OF THE MODEL

For a system with reliable input parameters and stresses, the response of the model generally comes in close agreement with the observed field data. Disagreement in the model outputs with the observed values would reflect unreliable input data with respect to either the stresses or the system parameters. Such kind of disagreement was experienced in the initial phases of the present modelling exercise. This eventually seeks the requirement to calibrate the model parameters, and to look into the uncertainty part of input stresses. For example, stresses to the flow domain as given in Table-2.1 and 2.2 have been estimated based on some distribution factor on the net draft of groundwater assessed in the year 1991. On the other hand, the hydraulic conductivity and specific storage values have been estimated based on the pumping test data of 21 locations (Figure A.1 and A.2 in appendix) which were not uniformly distributed over the whole domain. Moreover, screen depths of the pumping test data varies from location to location. Calibration of the model parameters and reliable estimation of the magnitude of stresses are thus necessary.

In order to calibrate the model parameters a steady state condition of flow domain with a hydrostatic head at the highest altitude of the model has been considered as initial piezometric head/water table elevation. Data of April'97 for all the three rivers namely Bhagirathi, Ichamati and Yamuna has been considered for calibration purpose. No other external stresses were considered. These boundaries/external factors and the assigned values of aquifer parameters would then govern the response of the flow domain. The condition of all three rivers for April'97 being fixed, the trend of computed output would depend on the assigned values of aquifer parameters only. So, if the aquifer parameters were correctly assigned, the trend of computed output would match with the trend of the observed one. Thus, calibration was carried out by adjusting the values of the hydraulic conductivity. Once a satisfactory computed trend was achieved, the water balance of that simulation was referred and the difference of water balance (IN-OUT) was adjusted through recharge in subsequent simulation to obtain the magnitudal match of April'97. The river details, the calibrated model parameters and the water balance corresponding to the calibrated parameters are given in Tables 2.3 and 2.4.

Table-2.3 : River stresses considered for calibration

Sl.	River Location	River Stage* (m)	Bottom of River* (m)	Conductance (m^2/day)
1.	Bhagirathi (North End)	104.56	101.20	3870
2.	Bhagirathi (South End)	102.56	100.40	1457
3.	Ichamati (North End)	103.25	99.93	770
4.	Ichamati (South End)	103.05	100.31	960
5.	Yamuna (West End)	104.07	104.07	200
6.	Yamuna (East End)	103.10	101.78	200

(100 is added as arbitrary reference datum above MSL)

Table 2.4: Calibrated Model Parameters

Zone	K_x (m/day)	K_y (m/day)	K_z (m/day)	S_s (1/m)
1	15.0336	15.0336	1.50336	0.001087
2	18.3136	18.3136	1.83168	0.00326
3	21.6864	21.6864	2.16864	0.0042
4	11.6640	11.6640	1.16640	0.00867
5	8.2944	8.2944	0.82944	
6	4.8384	4.8384	0.48384	

The calibrated zones of hydraulic conductivity and specific storage values are shown in Figs. 2.4 and 2.5. Zones indicated in Table 2.4 could be read in accordance with the Figs. 2.4 and 2.5. A comparison of calibrated model parameters with that of the corresponding observed values of transmissivity and storativity is made in Table 2.5, which reveals that values corresponding to the calibrated model parameters are within the observed ranges. These calibrated values could be regarded as the model parameters for regional level modelling.

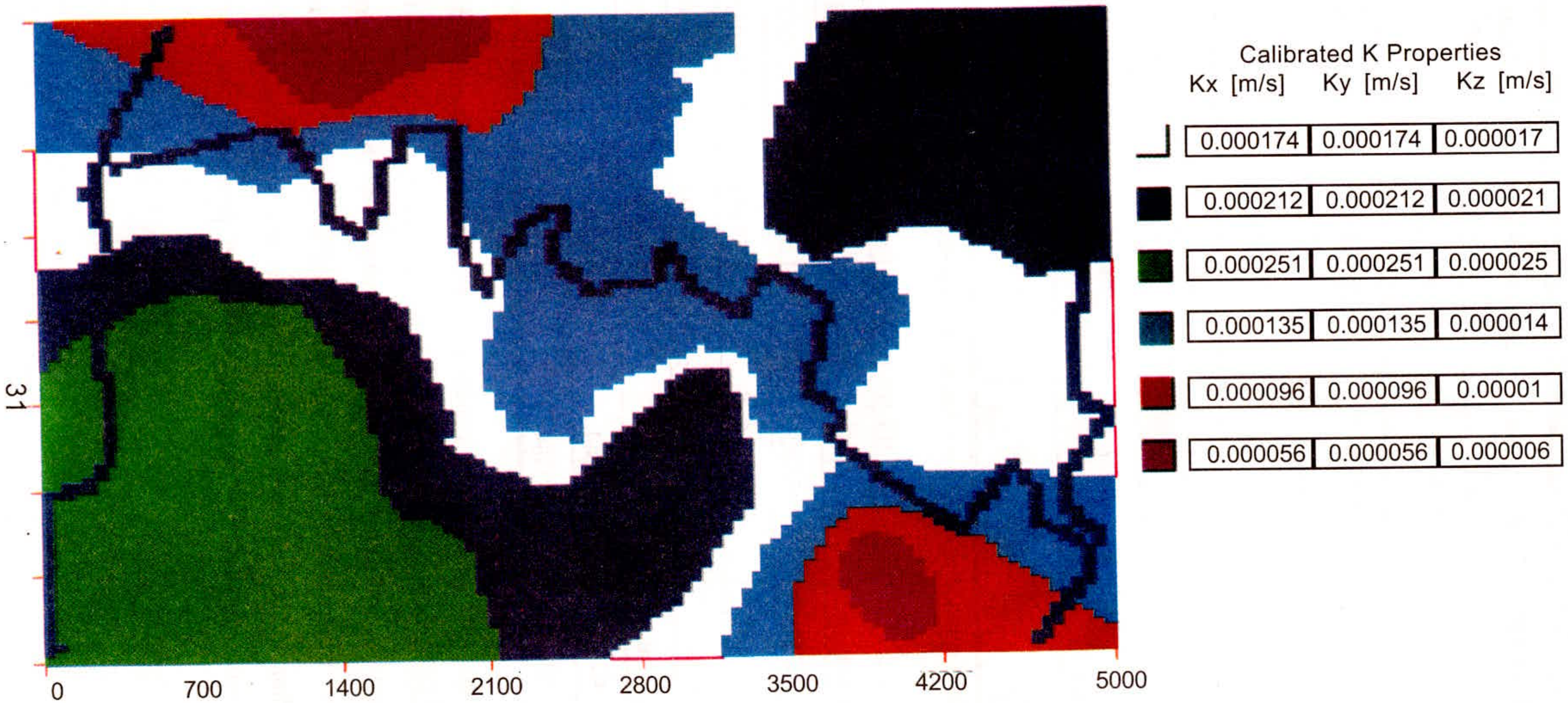


Figure 2.4 : Calibrated zones of equal Hydraulic Conductivities.

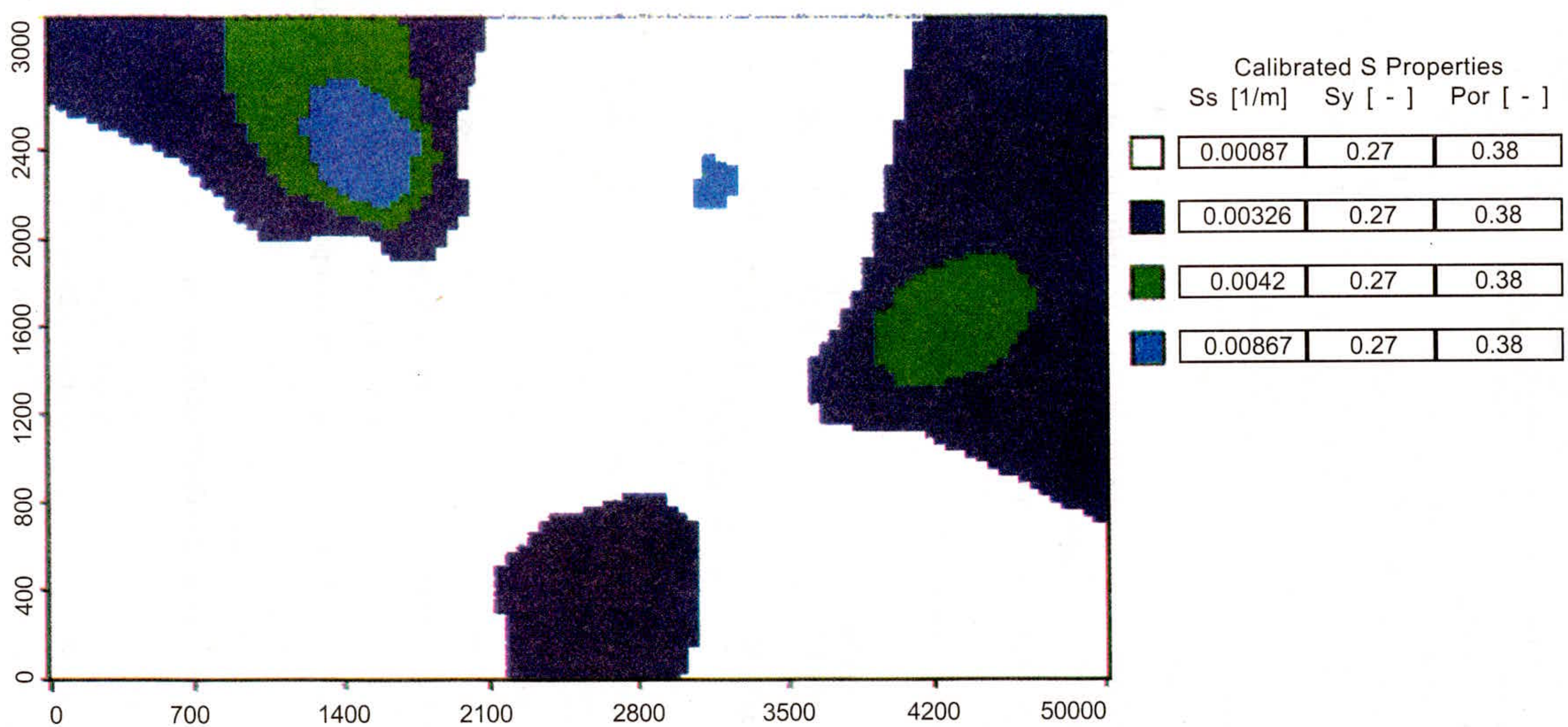


Figure 2.5 : Calibrated zones of equal Specific Storage values.

Table 2.5 : Comparison of calibrated model parameters with the observed values.

Zone no	Transmissivity values corresponding to Calibrated K_x and K_y (m^2/day)	Transmissivity values from pumping test analysis (m^2/day)	Zone no	Calibrated storativity values	Storativity values from pumping test analysis
1	2255.04	2000 - 2500	1	0.001087	0.0006 – 0.0012
2	2747.52	2500 - 3000	2	0.003260	0.0012 –0.0042
3	3252.96	3000 – 3500	3	0.004200	0.0042- 0.0070
4	1749.60	1500 – 2000	4	0.008670	0.0070 – 0.0090
5	1244.16	1000 – 1500			
6	725.76	650 - 1000			

The model output corresponding to the response of calibrated runs is shown in Fig. 2.6 for layer 4 (since abstraction from wells are taking place mostly from this layer). All other layers are also having the same potentiometric heads due to unilateral conditions. Water balance corresponding to this run is shown below:

	Inflow to the domain (in m^3)	**Outflow from the domain (in m^3)**
i.	Drains = 0.00	Drains = 0.00
ii.	Recharge = 357,640	Recharge = 0.00
iii.	River Leakage = 0.00	River Leakage = 324,380
	Total IN = 357,640	Total OUT = 324,380

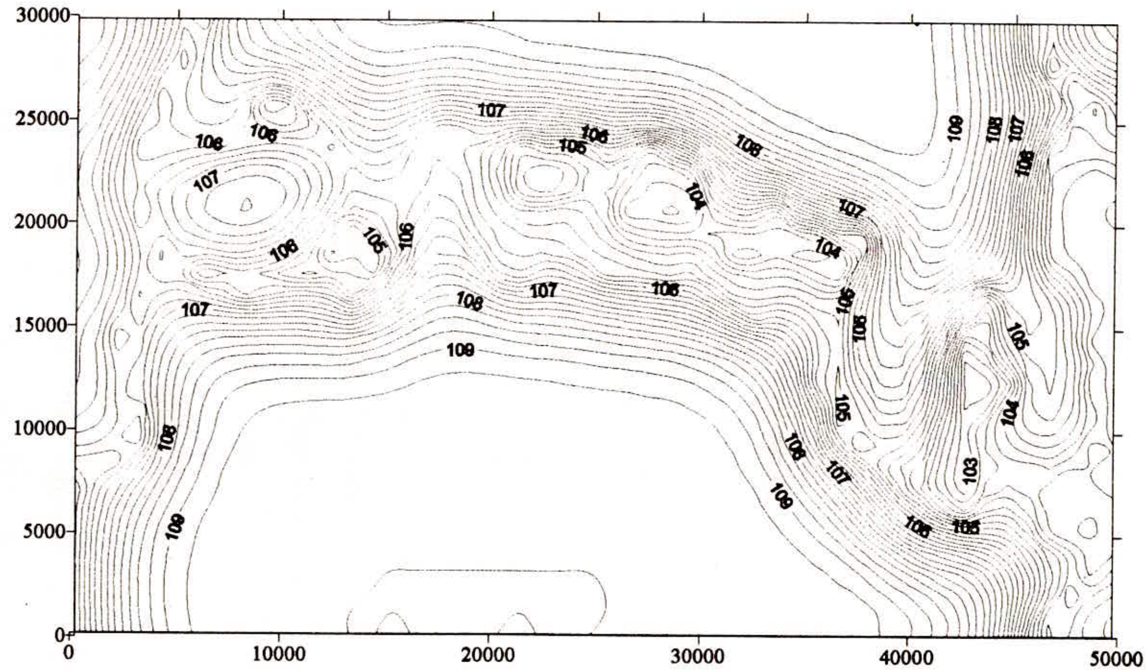
IN - OUT = 33,260 m^3
Percent Discrepancy = 9.75%

The water balance due to the calibrated run shows a percentage discrepancy of 9.75 %, which is very minor and could be accepted for transient run.

The calibrated model parameters have been validated for other boundary conditions viz. General Head Boundary and the recharge. From the analysis of observed water table data, the zone-wise distribution of recharge pattern was obtained and incorporated as input data. Zonewise recharge values and some of the general head boundary values at some key locations for the northern and southern boundaries incorporated in the validation run is stipulated below:

Recharge Values considered for validation of the model

Zone 1 = 25.0mm/year
Zone 2 = 15.0mm/year
Zone 3 = 5.0mm/year and
Zone 4 = 3.0mm/year
Zone 5 = 2.0mm/year
Zone 6 = 0.2mm/year.



* 100 refers to arbitrary datum above MSL

Figure 2.6 : Model computed head corresponding to calibrated model parameters

General Head Boundary Values considered for validation of the model

Cell	Genl. Head(m)	Cell	Genl. Head(m)	Cell	Genl. Head(m)
1,31	105.455	1,60	104.460	100,9	102.335
1,44	106.390	1,72	104.180	100,53	102.240
1,55	106.175	1,95	102.725	100,76	101.725

The conductance value in the General Head Boundary was taken as 150 m^2/day.

The percentage discrepancies in the water balance for both the calibrated and validated model is found to be minor, which may be due to the localised effects of stresses. The model parameters are then considered for transient simulation of the flow model.

The transient condition was considered month-wise for the period from September, '97 to August,'98. The initial condition of water table/piezometric head was assumed to be the observed data of September, 1997. The external stresses and the boundaries are considered *variable in each month*, which indicates an **unsteady state condition of the flow domain**. Following boundary conditions and stresses were considered for unsteady state simulation:

i. River stages in Bhagirathi, Ichamati and Yamuna,

ii. General Head Boundary in the northern and southern boundaries,

iii. Recharge due to rainfall and irrigation return flow,

iv. Discharge due to withdrawal, and evapotranspiration.

The observed water table data (Table A.2 in appendix) indicate that the period from August to May is the period when the water table declines and thus these months can be considered as the discharge months while the months May to August are the recharge months. Since the model did not respond satisfactorily with the estimated stresses as given in Table 2.1 and 2.2, the month-wise fluctuation of water table elevation was taken as a guiding factor for computation of recharge and discharge pattern in the flow domain and considered as input stresses for simulated run.

2.3 DISCUSSION AND ANALYSIS OF RESULTS

In the present problem, the inputs to the modelling exercise are; external stresses (recharge and discharge pattern), initial and boundary conditions of flow domain, and the values of the parameters characterising the system function. Neither of the above characteristic factors is accurately known from the available information. A scattered range of system's parameters, rough estimate of external stresses such as; recharge and discharge pattern, and more rough data towards river hydraulics are available. However, month-wise water level data of 58 observation wells (Figure A.3 in appendix) covering almost the whole Yamuna basin is available for one year. Considering the observed water levels data as the reference points to check the sensitivity of interpolated and extrapolated values, the ranges of input forcing factors can be reasonably approximated. These exercises, in fact, need trials for a number of combinations. For example, sensitivity of initial guesses of system parameters, viz: hydraulic conductivity and specific storage can be obtained from the trial combinations of i) influence of rivers without any external recharge/discharge, and ii) validation and further refinement of parameters through consideration of GHB and recharge.

In the first case, with the steady state flow condition, same highest water table elevation throughout the domain and the rivers acting as the only external stresses, the simulated head behaved in accordance with the external stress and the input parameters. For known external river stresses, the trend matching of the computed head with the observed head would depend on the correct assignment of the parameters. The model parameters are taken to be correctly assigned once the trend of the computed head and the observed head in the study domain is similar in nature. In the present study, trend matching is thus used to calibrate the aquifer flow parameters. The performance of the calibrated parameters is then examined for other boundary conditions for validation using the later case, and the values of the model parameters are established.

This exercise is definitely an over simplification of the approach for estimating the parameters under the assumption that hydraulic conductivities and specific storage have a linear relationship with fluctuation of water levels. Moreover, the vertical conductivity at every spatial co-ordinate is considered to be constant, and the influences of lithological changes are approximated by considering the value as one tenth of the horizontal hydraulic conductivity values. Over estimation or under estimation of K_{xx} and K_{yy} which can not be over ruled in the above exercises, would also effect the value of K_{zz}. The range of values of K_{xx}, K_{yy} and K_{zz} and specific storage (S) given in Table 2.4, can therefore, be considered as location specific values with variation on either side by 10-15%.

Once the system parameters are estimated, the problem then stands as detection of correct/nearer magnitude of input stresses. For estimation of draft/recharge (consisting of withdrawal, evapotranspiration, areal recharge, irrigation return flow etc.) the month-wise difference of water table elevation data was considered as the trial value of external draft/recharge. The difference of the water table elevation data gives the net effect of all the external stresses acting on the model domain. Further refinement of draft/recharge pattern was thus done after simulating the model with known boundary conditions and minimising the difference of observed and the computed head for different months. For example, to obtain the net effect of recharge and discharge for the month of October, level of September has been considered as initial condition. The river stages data and other external stresses for the month of October have been considered for boundary conditions. In similar way, month-wise net effects of recharge and discharge have been obtained for all the months in the simulation period. Though, 78 to 82% of the annual rainfall occurs during the month from May to September, but its effect on the groundwater is found to be during May to July. The net effect of rainfall recharge, which raises the groundwater level from its minimum to the maximum position during these months, is estimated to be in the order of 18-30% of the annual rainfall which is nearly in accordance with the value prescribed in the GEC'97 norms as rainfall recharge. The effect of irrigation return flow is found to be 30-45% of the draft of the respective months. From the above analysis, the month-wise discharge and recharge components have been re-assessed and given in Table 2.6(a), (b) and (c). Table 2.6(a) represents block wise discharge pattern, which includes pumpages and evapotranspiration. Table 2.6 (b) represents the block wise withdrawal after deducting the evapotranspiration component, which is 3.0137 mm/day. Table 2.6(c) represents block wise rainfall recharge and irrigation return flow. Comparison of Tables 2.1 and 2.2 with Table 2.6 (b) and (c) shows that the withdrawal from the flow domain has increased by about 42% to 199% (except Barrackpore- I, where it has increased by about 600%) than the magnitude assessed in year 1991. There is not much appreciation in the cumulative value of recharge (irrigation return flow + rainfall recharge), rather show a falling trend in overall ground water storage. For example, taking the case of HABRA-I - a Arsenic influence area - (Table-2.6(a)), converting the net withdrawal to depth of groundwater which works out to be 1.0787m/year, whereas the depth of water replenishes by the irrigation return flow and by rainfall recharge (Table 2.6(b)) is estimated to be in the order of 0.964 m/year. Comparing these two magnitudes, it indicates that water level has a net falling effect of 0.1147 m during year 1997-98. For other blocks, by and large, a similar trend prevails. A comparison of block wise groundwater withdrawal (after deducting the evapotranspiration) in the flow domain given as in Table-2.7, it is clear that there is an increase in the withdrawal in all blocks than that of the year 1991, and the rate of increase varies between 5 and 6 % per year except Chakdah, Barrackpore-I, Habra-I, and Bhaduria blocks. The estimation of block wise areal recharge and discharge is also given in Table 2.7. The table gives an indication of deficit of recharge over withdrawal. However, part of the deficit is compensated by the river aquifer interaction and by the flux boundary.

Making use of estimated recharge and discharge, the model has been run for transient condition to predict the heads for the given time step size. Month wise comparisons of heads computed by the model have been depicted in the form of error maps (Figures 2.7 to 2.17). The error is estimated from the difference of the absolute value of computed head and the observed head at that location. The error maps of June and August (Figures 2.15 and 2.16) represent comparison of computed head of current year with the observed head of previous year and hence depict higher degree of errors. For other months except minor errors in localized pockets, the overall performance of the model is satisfactory. Thus, **the model can be reliably used to predict the flow regime corresponding to any given hydraulic stress in the area**. The computed head at each gridal mesh of the transient model generates velocity vectors, which are used by the transport model (MT3D) in the form of advective velocity.

Table 2.6 (a): Re-assessed value of Block-wise discharge (withdrawal + evapotranspiration) pattern

BLOCK	Area (Km^2)	Withdrawal (m^3/day)				
		Sept	Oct-Jan	Feb	Mar-Apr	Aug
CHAKDAH	Upper zone (22.5km x 4.5km)=101.28 Lower zone = 164	6.0768E+05 [900] 9.4026E+05 [860]	5.4016E+05 [800] 6.10079E+05 [558]	5.8336E+05 [864] 9.4464E+05 [864]	5.8336E+05 [864] 6.2976E+05 [576]	1.3504E+05 [200] 2.1866E+05 [200]
BANGAON	183.39	1.0514E+06 [860]	6.822E+05 [558]	1.0563E+06 [864]	8.8027E+05 [576]	2.4452E+05 [200]
HARINGHATA	170.13	9.754E+05 [860]	6.3288E+05 [558]	9.7992E+05 [864]	6.5329E+05 [576]	2.2683E+05 [200]
GAIGHATA	eastern part (6.66km x 13.5 km) = 90 Rest = 119.3	5.94E+05 [990] 6.84E+05 [860]	4.68E+05 [780] 4.438E+05 [558]	5.1840E+05 [864] 6.871E+05 [864]	4.8384E+05 [806] 4.5811E+05 [576]	1.2000E+05 [200] 1.5907E+05 [200]
BARRACKPORE-I	121.10	6.943E+05 [860]	4.5049E+05 [558]	6.975E+05 [864]	4.6502E+05 [576]	1.6147E+05 [200]
AMDANGA	83.05	4.716E+05 [860]	3.0895E+05 [558]	4.7837E+05 [864]	3.1888E+05 [576]	1.1072E+05 [200]
HABRA-II	80.74	4.629E+05 [860]	3.0035E+05 [558]	4.6504E+05 [864]	3.1000E+05 [576]	1.0765E+05 [200]
HABRA-I	middle strip (5km x 7.5km) = 37.5 Rest = 97.45	2.150E+05 [860] 5.587E+05 [860]	1.750E+05 [700] 3.625E+05 [558]	2.1600E+05 [864] 5.6130E+05 [864]	2.016E+05 [806] 3.7416E+05 [576]	5.000E+05 [200] 1.2993E+05 [200]
SWARUPNAGAR	164.94	9.4565E+05 [860]	6.1357E+05 [558]	9.5008E+05 [864]	6.3336E+05 [576]	2.1992E+05 [200]
BHADURIA	53.63	3.0747E+05 [860]	1.995E+05 [558]	3.0891E+05 [864]	2.0379E+05 [576]	7.150E+04 [200]

*** Value in parentheses [*] is the discharge from each cell of size 500 m x 300 m.**

Table 2.6 (b): Re-assessed value of block-wise withdrawal pattern (after deducting the evapotranspiration, 3.0136 mm/day)

BLOCK	Area (Km^2)	Withdrawal (m^3/day)[a]				
		Sept	Oct-Jan	Feb	Mar-Apr	May-Aug
CHAKDAH	Upper zone (22.5km x 4.5km)=101.28 Lower zone = 164	3.3020E+05 [489] 4.9094E+05 [449]	2.6268E+05 [389] 1.60763E+05 [147]	3.0588E+05 [453] 4.9532E+05 [453]	3.0588E+05 [453] 1.8044E+05 [165]	0.0000 [0] 0.0000 [0]
BANGAON	183.39	5.4896E+05 [449]	1.79761E+05 [147]	5.5386E+05 [453]	3.3778E+05 [305]	0.0000 [0]
HARINGHATA	170.13	5.0929E+05 [449]	1.6677E+05 [147]	5.1381E+05 [453]	1.8718E+05 [165]	0.0000 [0]
GAIGHATA	eastern part (6.66km x 13.5 km) = 90 Rest = 119.3	3.4742E+05 [579] 3.24465E+05 [449]	2.21426E+05 [369] 1.1695E+05 [147]	2.7182E+05 [453] 3.6025E+05 [453]	2.3726E+05 [395] 1.3126E+05 [165]	0.0000 [0] 0.0000 [0]
BARRACKPORE-I	121.10	3.6252E+05 [440]	1.1871E+04 [147]	3.6572E+05 [453]	1.3324E+05 [165]	0.0000 [0]
AMDANGA	83.05	2.4406E+05 [440]	8.145E+04 [147]	2.50835E+05 [453]	9.1353E+04 [165]	0.0000 [0]
HABRA-II	80.74	2.41694E+05 [440]	7.9144E+04 [147]	2.4383E+05 [453]	8.8794E+05 [165]	0.0000 [0]
HABRA-I	middle strip (5km x 7.5km) = 37.5 Rest = 97.45	1.1226E+05 [440] 2.9171E+05 [440]	7.226E+04 [289] 9.5514E+04 [147]	1.1326E+05 [453] 2.9431E+05 [453]	9.886E+04 [395] 1.0717E+05 [165]	0.0000 [0] 0.0000 [0]
SWARUPNAGAR	164.94	4.9376E+05 [449]	1.6168E+05 [147]	4.9819E+05 [453]	1.8146E+05 [165]	0.0000 [0]
BHADURIA	53.63	1.60538E+05 [449]	5.2568E+04 [147]	1.61978E+05 [453]	5.6858E+04 [165]	0.000 [0]

a Value in parentheses [*] is the withdrawal from each cell of size 500 m x 300 m.

Table 2.6 (c):Re-assessed value of block-wise recharge pattern

BLOCK	Recharge during monsoon months (mm/day)			Irrigation return flow (mm/day)			
	May	June – July	August	Sept	Oct-Jan	Feb	Mar-Apr
CHAKDAH	i) 4.50 ii) 2.00	i) 4.200 ii) 7.40	i) 0.300 ii) 0.300	i) 1.000 ii) 0.960	i) 0.880 ii) 0.620	i) 1.200 ii) 1.200	i) 1.200 ii) 0.800
BANGAON	3.50	7.40	0.300	0.960	0.620	1.200	0.800
HARINGHATA	1.00	7.40	0.300	0.960	0.620	1.200	0.800
GAIGHATA	i) 1.00 ii) 1.00	i) 7.40 ii) 7.40	i) 0.300 ii) 0.300	i) 1.100 ii) 0.960	i) 0.867 ii) 0.620	i) 1.200 ii) 1.200	i) 1.120 ii) 0.800
BARRACKPORE-I	3.50	7.40	0.300	0.960	0.620	1.200	0.800
AMDANGA	2.50	7.40	0.300	0.960	0.620	1.200	0.800
HABRA-II	2.50	7.40	0.300	0.960	0.620	1.200	0.800
HABRA-I	i) 1.00 ii) 3.00	i) 11.00 ii) 7.40	i) 0.300 ii) 0.300	i) 0.960 ii) 0.960	i) 0.778 ii) 0.620	i) 1.200 ii) 1.200	i) 1.120 ii) 0.800
SWARUPNAGAR	1.00	7.40	0.300	0.960	0.620	1.200	0.800
BHADURIA	1.00	7.40	0.300	0.960	0.620	1.200	0.800

Table 2.7 : A comparison of block wise withdrawal and recharge.

BLOCK	Withdrawal of groundwater as in year 1991(m^3/year)x 10^6	Withdrawal of groundwater in year 1997-98(m^3/year)x 10^6	Percentage increase/ decrease	Areal discharge (m^3/year)x10^6	Areal recharge (m^3/year)x10^6	Deficit of areal recharge (%)
CHAKDAH	46.900	111.24	(+) 137.18	303.94	251.236	17.34
BANGAON	45.490	65.27	(+) 43.92	197.911	186.177	5.93
HARINGHATA	35.900	50.75	(+) 41.36	173.803	144.644	16.77
GAIGHATA	65.000	89.05	(+) 37.00	240.437	182.719	24.00
BARRACKPORE-I	5.437	36.10	(+)563.97	123.714	122.940	0.60
AMDANGA	18.140	24.77	(+)36.55	84.706	81.821	3.40
HABRA-II	31.140	60.08	(+) 92.93	82.480	79.545	3.50
HABRA-I	16.130	47.96	(+)199.00	145.575	130.112	10.62
SWARUPNAGAR	38.940	49.20	(+)26.37	168.502	140.231	16.77
BHADURIA	4.187	11.98	(+)186.12	54.658	45.596	16.58

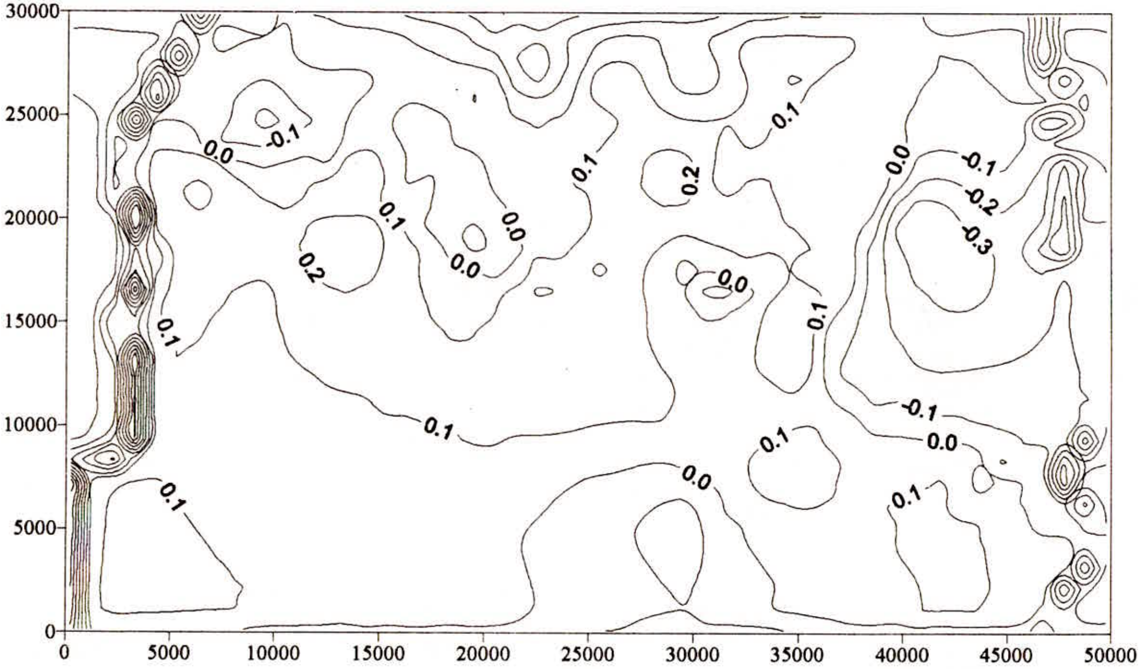


Figure 2.7: Error map of water table of October 1997.

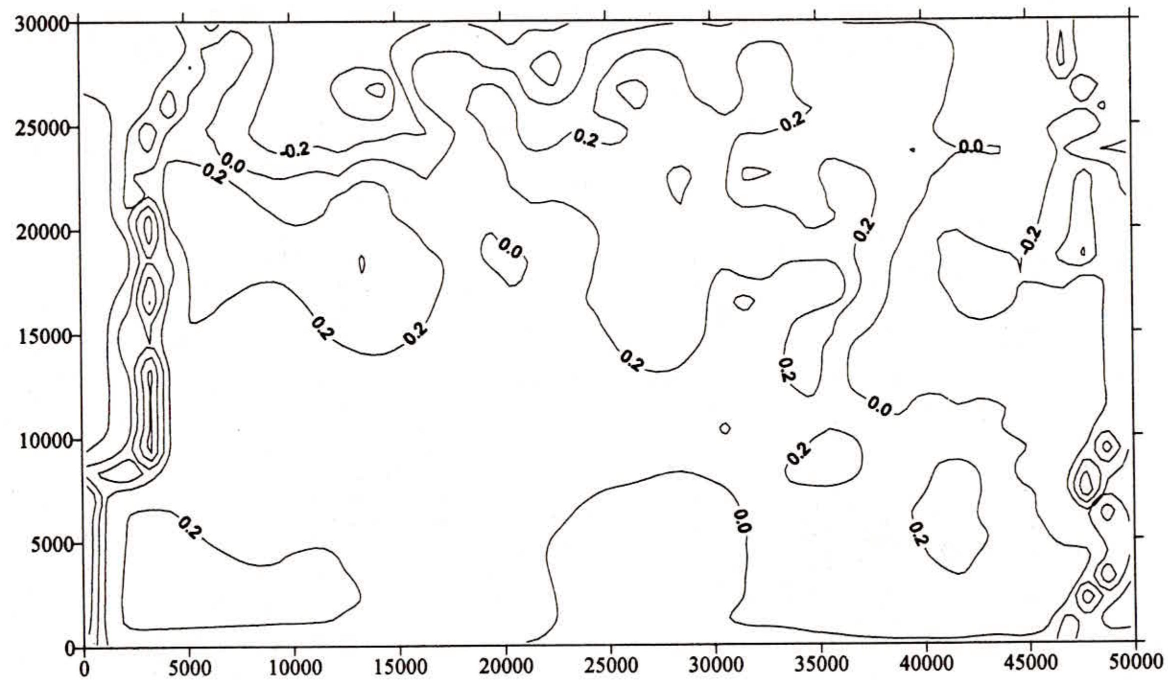


Figure 2.8 : Error map of water table of November 1997.

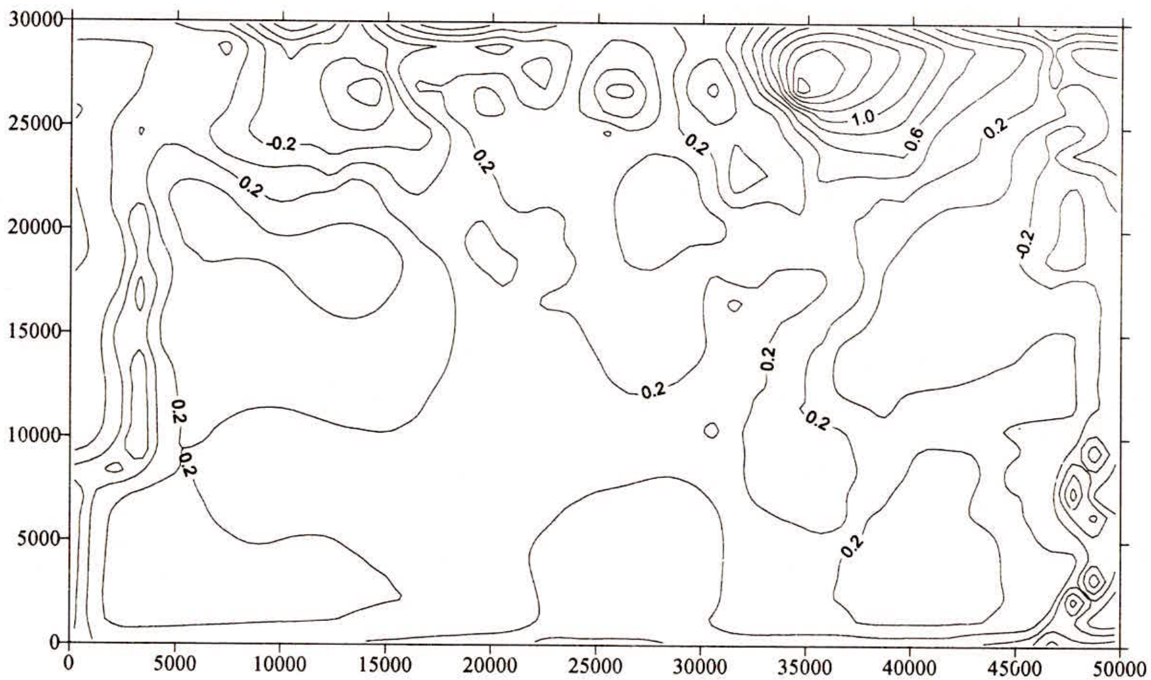


Figure 2.9 : Error map of water table of December 1997.

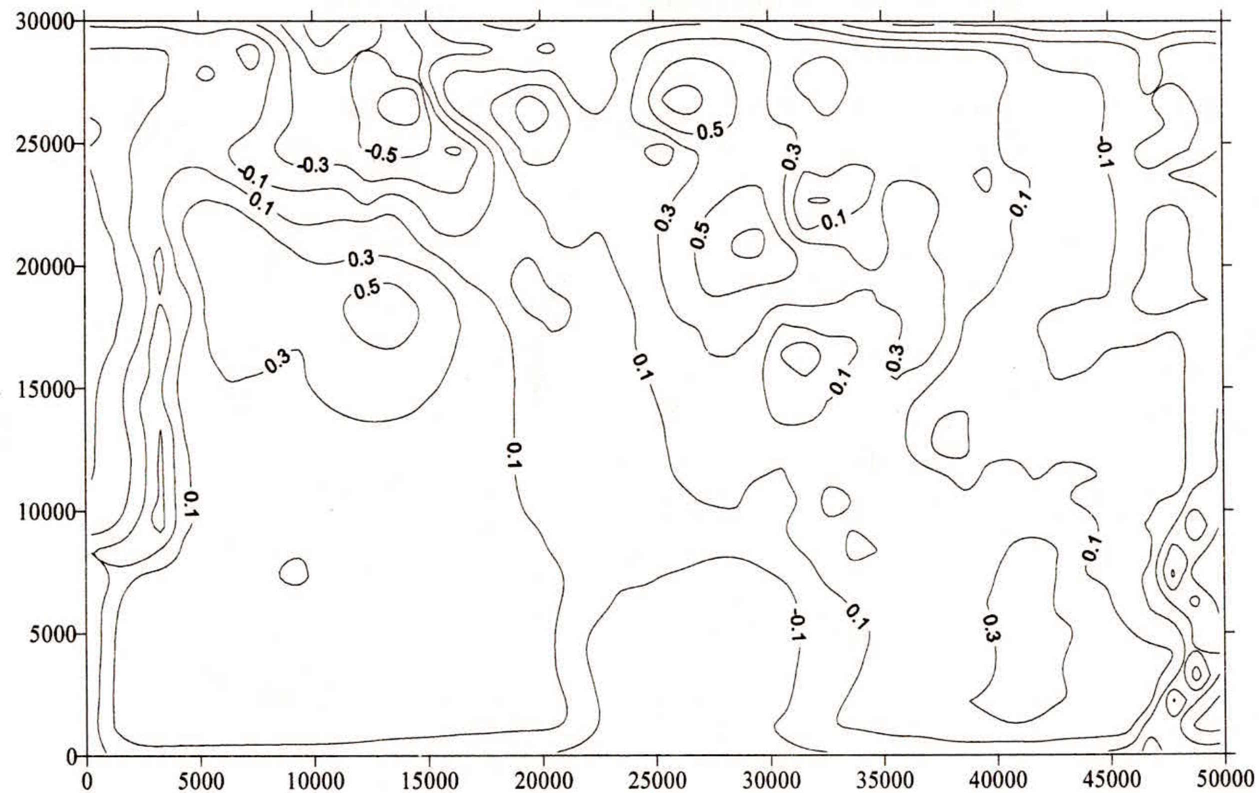


Figure 2.10 : Error map of water table of January 1998.

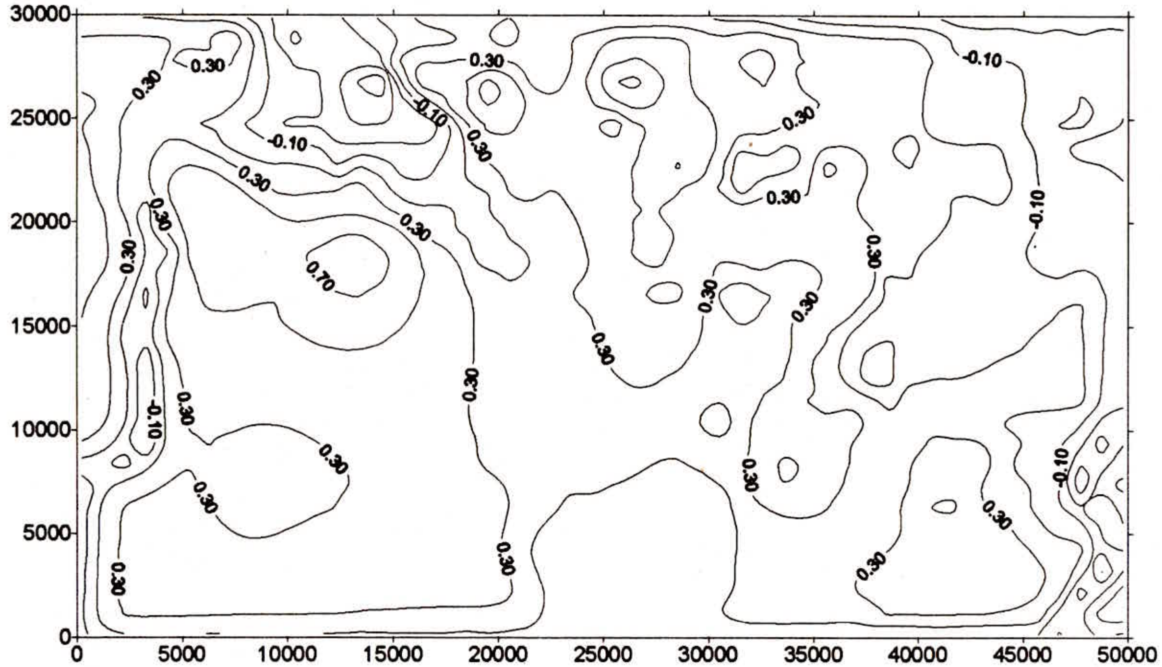


Figure 2.11 : Error map of water table of February 1998.

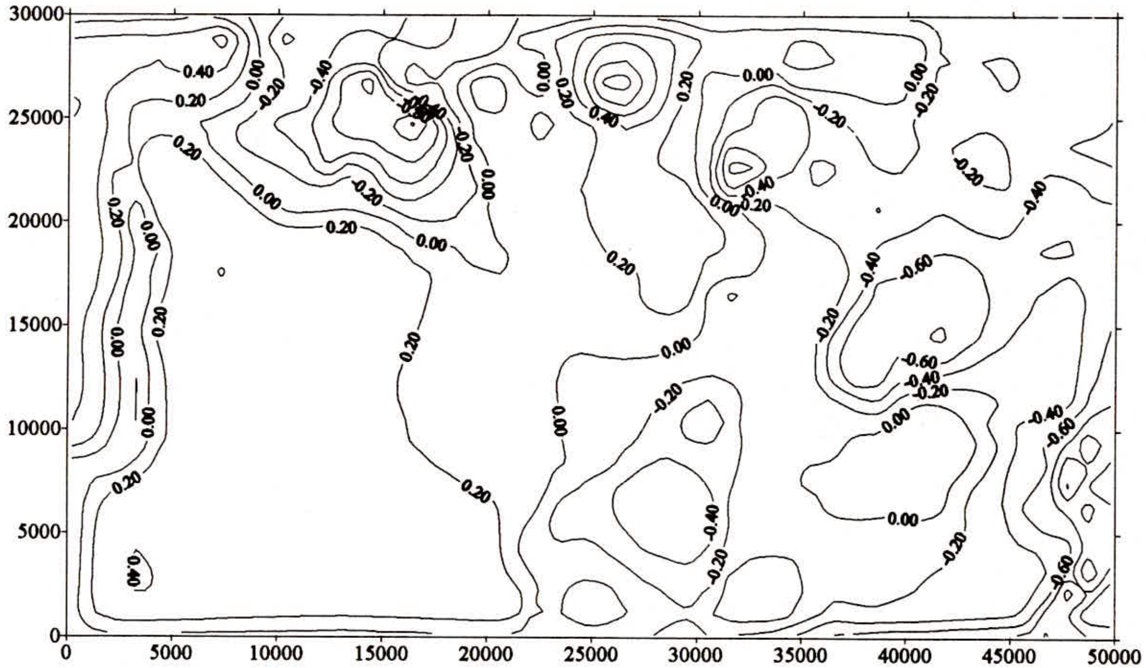


Figure 2.12 : Error map of water table March 1998.

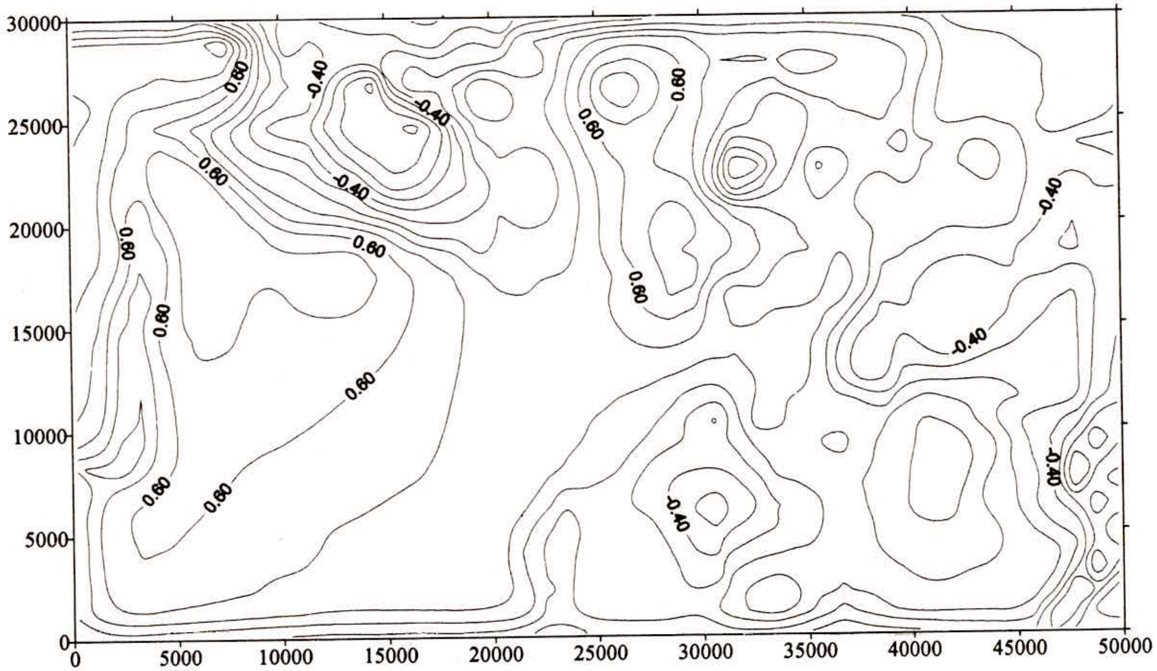


Figure 2.13 : Error map of water table of May 1998

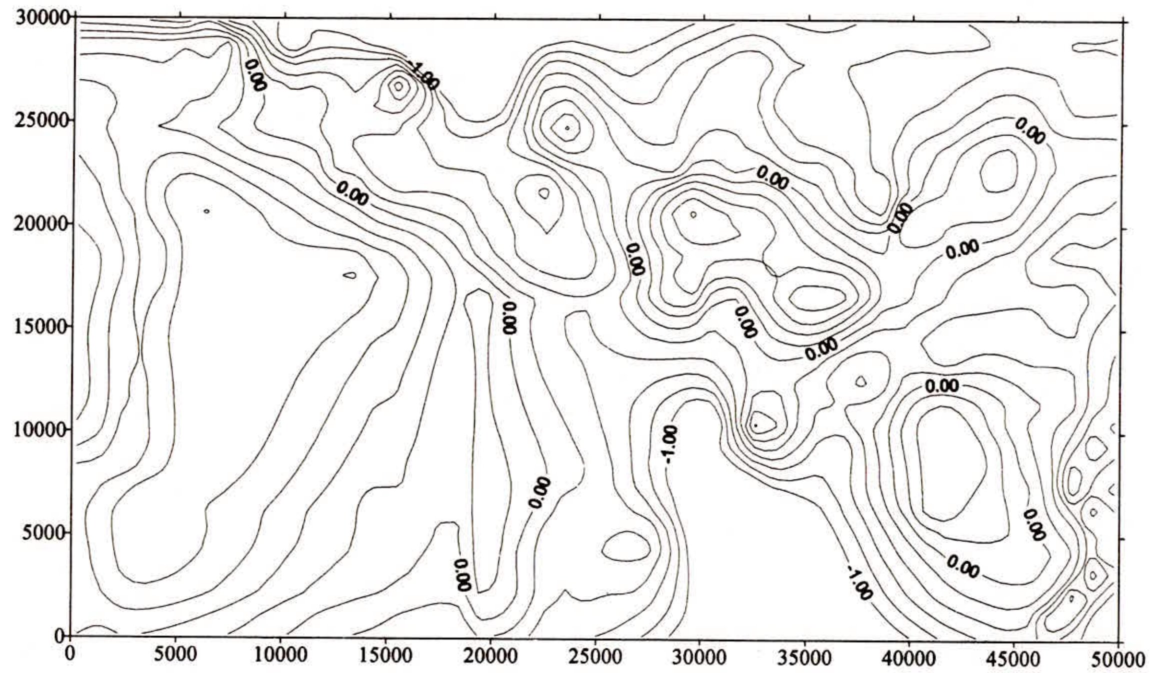


Figure 2.14 : Error map of water table of June 1998

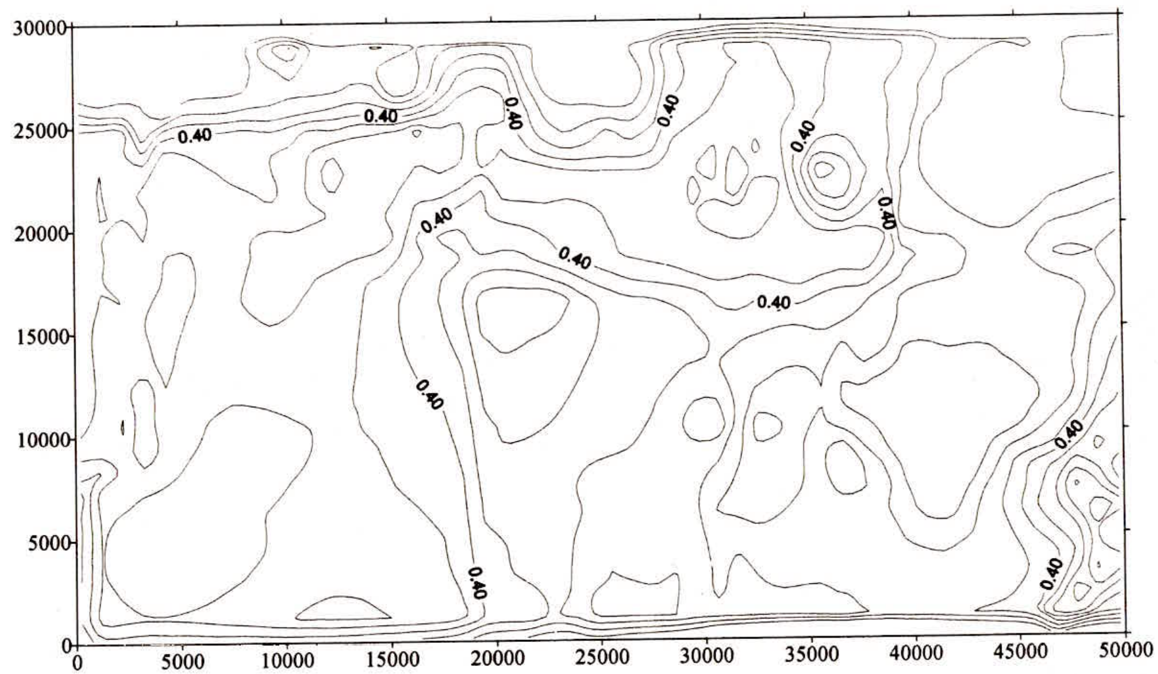


Figure 2.15 : Error map of water table of August 1998

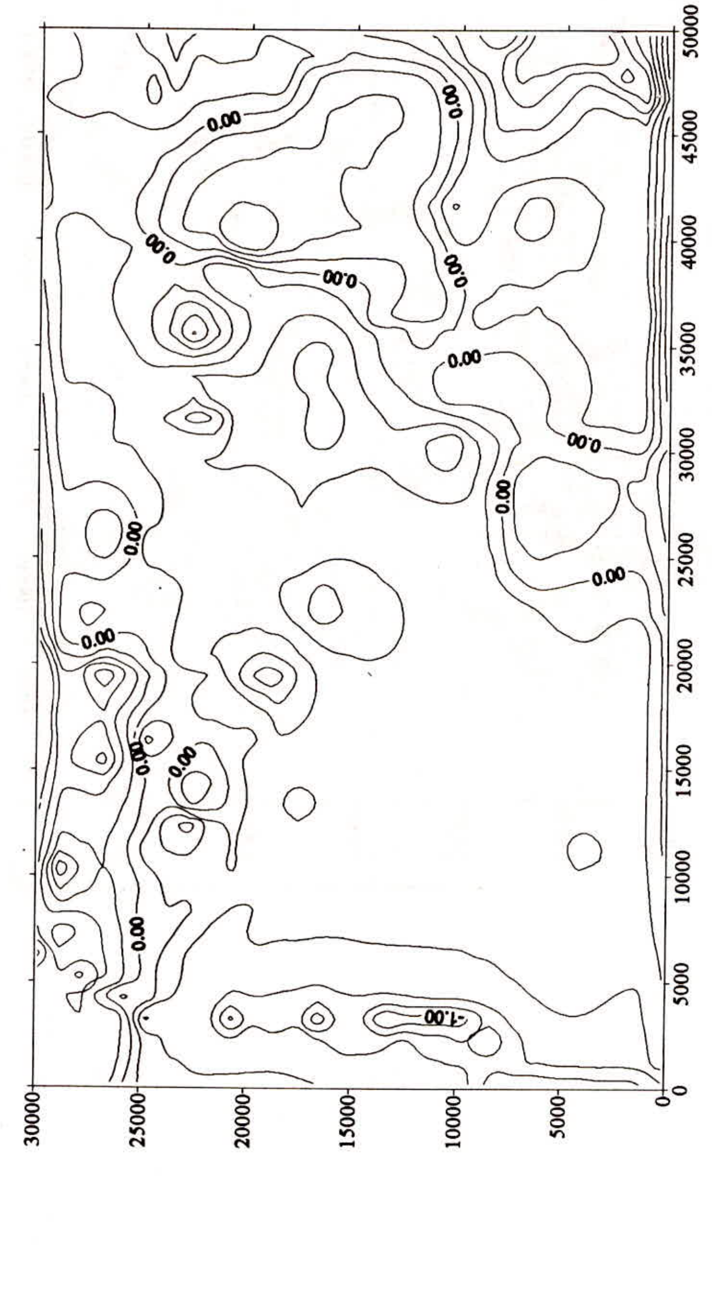
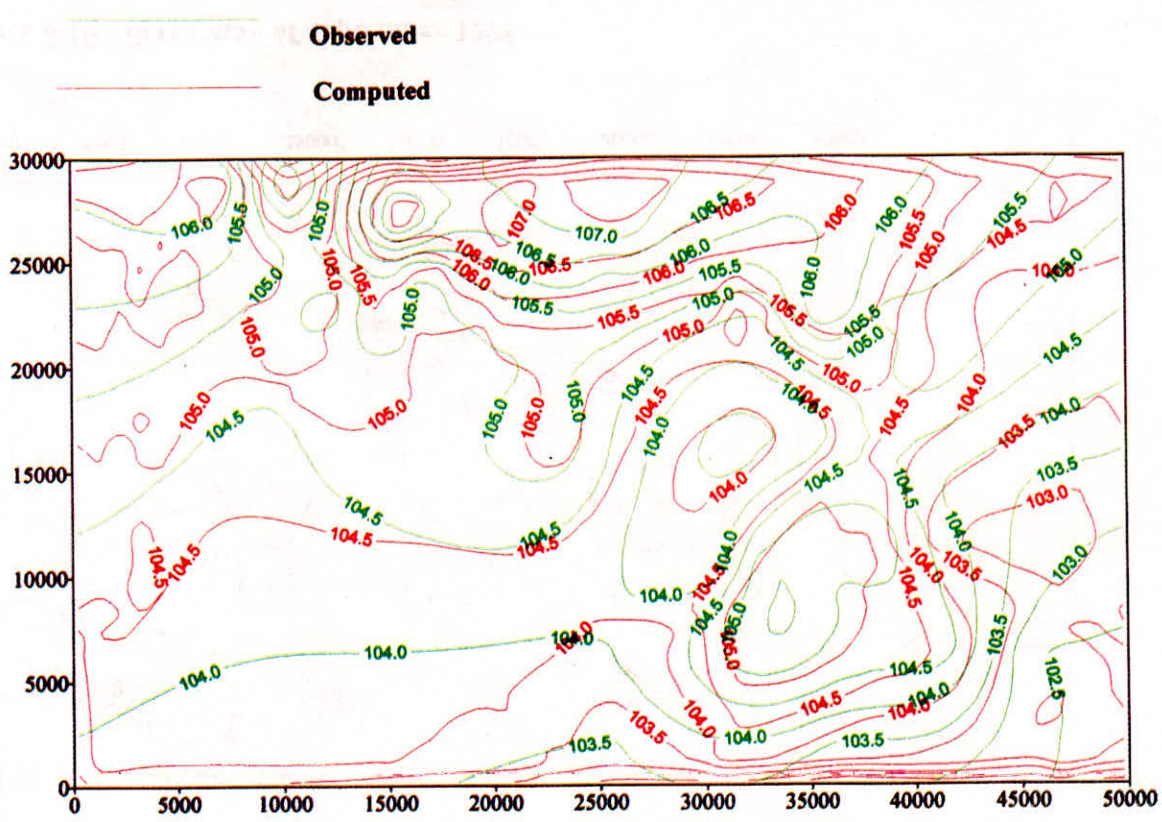
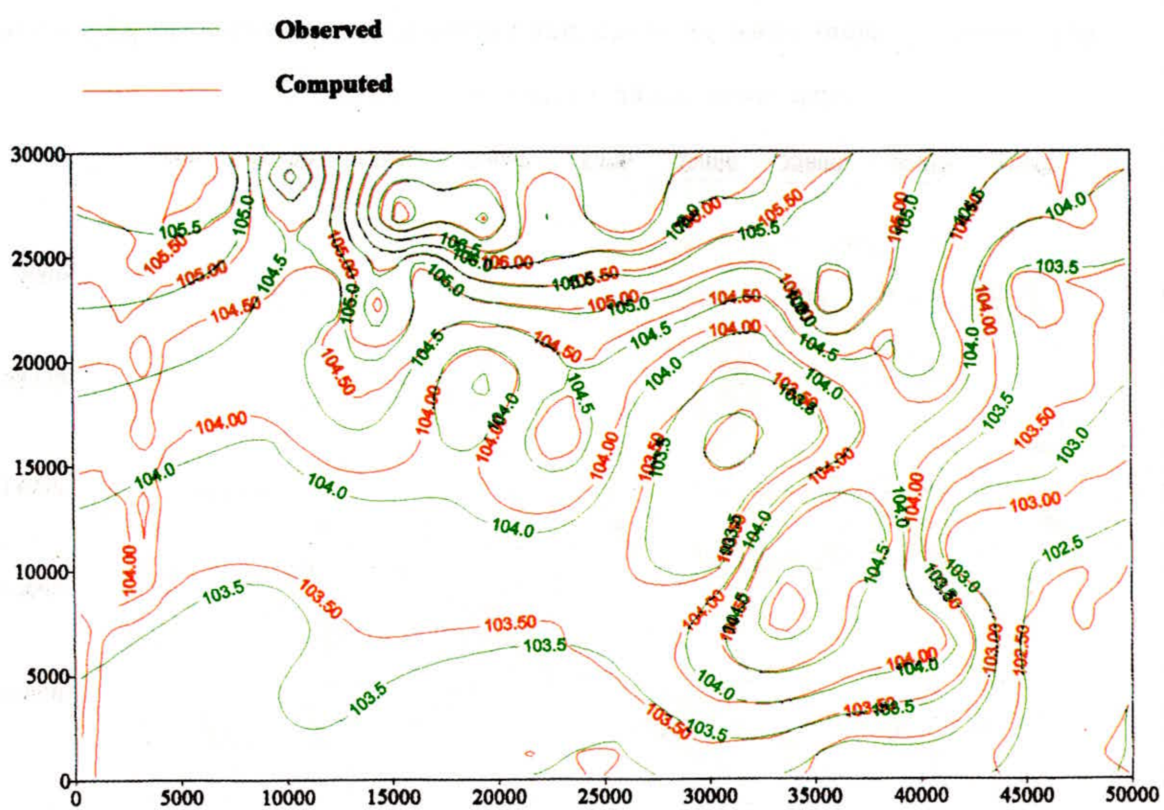


Figure 2.16 : Error map of September 1998



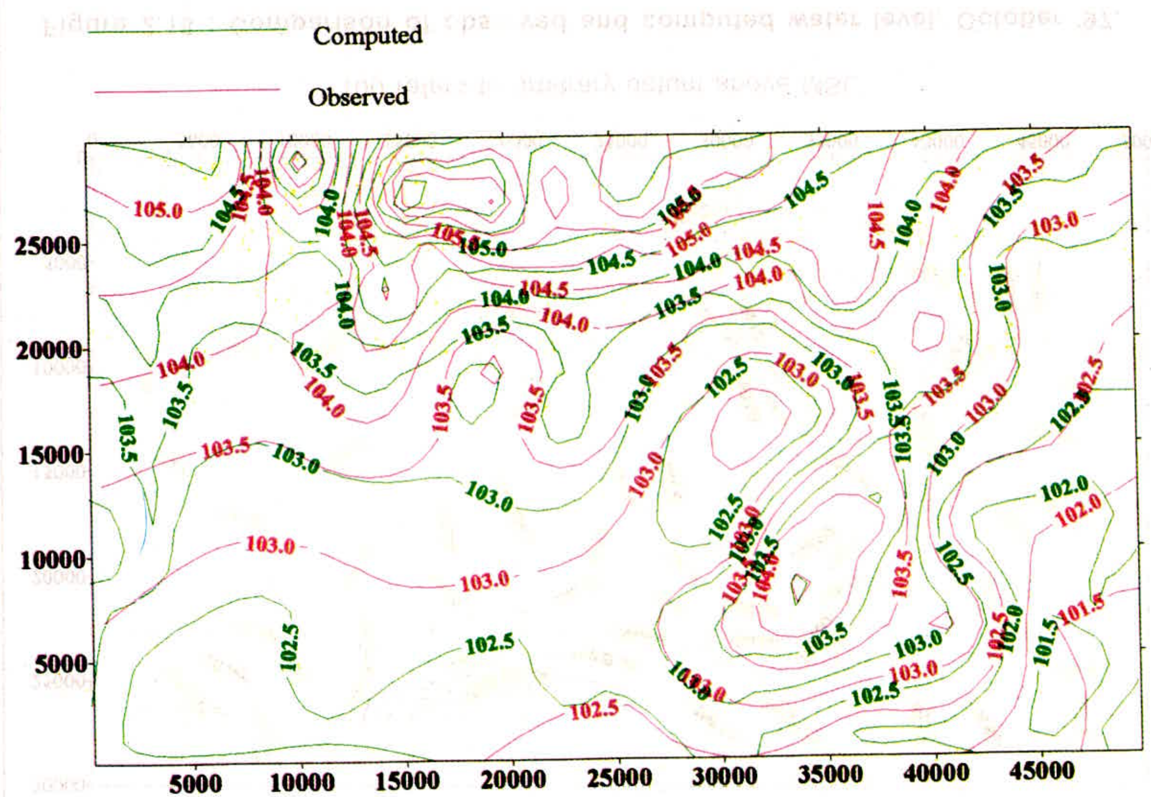
* 100 refers to the arbitrary datum above MSL

Figure 2.17 : Comparison of observed and computed water level, August



* 100 refers to arbitrary datum above MSL

Figure 2.18 : Comparison of observed and computed water level, October '97.



* 100 refers to the arbitrary datum above MSL

Figure 2.19 : Comparison of computed and observed water table, February 1998.

PART - III

TRANSPORT MODELLING AND ANALYSIS OF TRANSPORT PHENOMENA

3.0 TRANSPORT MODELLING

Transport modelling is envisaged to simulate the spatial and temporal variation of concentration under different external stresses with known initial and boundary conditions. The variation of concentration (Eq.2) is dependent on the flow advective velocity and, the dispersivities besides external stresses and the chemical reaction of the contaminants with the aquifer materials and the pore water. These factors need to be ascertained prior to simulation of the transport model. The advective velocity is obtained from the flow modelling, while the dispersivity is usually determined from the time-concentration data measured in the field. The stresses in a transport problem usually are due to the entry of pollutant into the domain or exit/loss from the domain. The entry of pollutants is usually characterized as: leaching of pollutant with areal recharge, interaction between surface and groundwater system and due to the external mass flux into the domain. The entry of pollutants can, however, also be due to the chemical transformation of trapped aquifer materials. The exit or the loss of pollutant is usually due to pumpage from the aquifer, interaction of surface and groundwater system, and due to decay and/or due to mass flux going out from the domain. In the present study domain, sources being unknown, transport phenomena has been studied under different probable situations of source of pollutants in order to obtain a real life situation. The probable sources of pollutants considered are due to: i) the entry of pollutants from river Bhagirathi, ii) the General Head Boundary at the northern side, iii) in-situ point sources at localized pockets. No mass loss has been considered due to withdrawal of water from the domain.

3.1 ESTIMATION OF PARAMETERS

Dispersivities in three cartesian co-ordinates and the chemical reaction kinetics viz: retardation, adsorption/disorption are the parameters in transport modelling. Dispersivity, which characterizes the spreading of pollutants, depends upon the concentration gradient and the velocity gradient of flow and is an important parameter for modelling the transport phenomena. There is no straightforward approach to determine the dispersivities. But the longitudinal dispersion coefficient, (D_x) can roughly be estimated from the time-concentration data of two stations in the following way:

Where, σ_1^2, σ_2^2 are the variances of the time-concentration data at the nearest and the farthest measuring stations respectively; t_1 and t_2 are their mean; and `v' is the mean velocity of flow between the two stations.

Estimation difficulties of longitudinal dispersion coefficient from the time-concentration data collected from field measurement (specific trend is absent), led to initialisation of this parameter and verification of the value through calibration/validation. Dispersion coefficient $[L^2T^{-1}]$ of a transport process in a groundwater system are usually represented by:

$$D_x = \alpha\, v_x \qquad D_y = \beta\, v_y \qquad D_z = \theta\, v_z$$

where, α, β and θ are the longitudinal, transversal, and vertical dispersivities [L] respectively and v_x, v_y, v_z are velocity vectors in three cartesian co-ordinates. The longitudinal dispersivity is in the direction of flow. Observed and computed water levels demonstrate that flow direction changes from cell to cell, and so is the velocity vectors. Keeping in view the overall trend of flow direction which is from north-west to south-east, the value of `α' is assumed as one half of the smaller dimension of the gridal mesh (this has been established by many investigators), i.e α = 300/2 = 150m. In the transverse and vertical directions the dispersivities are usually 0.1 and 0.01 times of longitudinal dispersivity. Thus, against the longitudinal dispersivity of 150 m, the dispersivity in the transverse and vertical directions is initially assumed to be 15m and 1.5 m respectively.

The other parameters needed in transport modelling are the parameters in the chemical reaction term indicated in Eq.(2). Assuming only equilibrium-controlled linear or non-linear sorption and first-order irreversible rate reactions are involved in the chemical reaction term in Eq. (2), the chemical reaction term can be expressed as:

$$\sum_{k=1}^{N} R_k = -\frac{\rho_b}{n}\frac{\partial \bar{C}}{\partial t} - \lambda\left(C + \frac{\rho_b}{n}\bar{C}\right)$$

$$\sum_{k=1}^{N} R_k = -\frac{\rho_b}{n}\frac{\partial C}{\partial t}\frac{\partial \bar{C}}{\partial C} - \lambda\left(C + \frac{\rho_b}{n}\bar{C}\right) \qquad (5)$$

Where,

ρ_b is the bulk density of the porous medium, $[ML^{-3}]$;

$\bar{C}$ is the concentration of contaminants sorbed on the porous medium, $[MM^{-1}]$;

λ is the rate constant of the first-order rate reactions, $[T^{-1}]$.

substituting equation (5) in (2) gives:

$$\frac{\partial C}{\partial t}=\frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C}{\partial x_j}\right)-\frac{\partial}{\partial x_i}(v_i C)+\frac{q_s}{n}C_s-\frac{\rho_b}{n}\frac{\partial \bar{C}}{\partial C}\frac{\partial C}{\partial t}-\lambda\left(C+\frac{\rho_b}{n}\bar{C}\right)$$

Moving the fourth term on the right hand side of the above equation to the left hand side:

$$R\frac{\partial C}{\partial t}=\frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C}{\partial x_j}\right)-\frac{\partial}{\partial x_i}(v_i C)+\frac{q_s}{n}C_s-\lambda\left(C+\frac{\rho_b}{n}\bar{C}\right) \tag{6}$$

where, R is the retardation factor, defined as:

$$R = 1 + \frac{\rho_b}{n}\frac{\partial \bar{C}}{\partial C} \tag{7}$$

The consideration of parameters in the chemical reaction term largely depends on the nature of pollutant. In the present case, the constituent of pollutant is Arsenic. Literature reveal that the chemical kinetics of Arsenic is complicated in nature and is affected by a variety of processes, including mineral dissolution-precipitation, oxidation-reduction, and adsorption, as well as biologically mediated reactions. These factors being unknown and statistical analysis of observed data also failing to demonstrate any functional relationship of chemical reactions, the chemical reaction part has not been considered in the transport modelling although this appears to be crucial for the present study domain.

3.1.1 Initial and Boundary conditions

Following initial conditions were considered for simulation of the transport phenomena:

i. Bhagirathi river as a source.
ii. From the northern boundary.
iii. Sources of Arsenic in localised pockets where maximum-recorded value of Arsenic concentration has been observed.

As far as the boundary conditions are concerned, all cells in the gridal network have been considered as active cells with no specific boundaries.

3.1.2 Input data

All cells in the domain have been considered as active cells. Observed arsenic concentration data monitored at 58 locations over different months neither represent any areal trend nor depicts any picture of migration of pollutants from one point to another. However, the concentration plot of observed Arsenic concentration data shows that there are six localized pockets of Arsenic (Fig 3.2) with scattered distribution surrounding these pockets have the maximum Arsenic concentration with sharp peaks (Figure 3.1). This eventually puts a line of thought for consideration of sources at thsse six points. The recorded maximum concentrations at six localised pockets are as follows:

Khusbasi (Chakdah block)= 0.260 mg/l;
Kundalia (Chakdah block)= 0.180 mg/l;
Maslandpur(Swarupnagar block)= 0.219 mg/l;
Mandalhat (Chakdah block)= 0.130 mg/l
Devipur (Gaighata block) = 0.246 mg/l
Ashoknagar(Habra-I block)= 0.255 mg/l

Assuming the above six pockets as the source of pollutants in the flow domain, the above condition of concentration has been achieved by introducing mass flux during the recharge period. For other boundary conditions arbitrary input values of concentration were assigned to see the transport behaviour in the model domain.

The dispersivity values were assumed constant for all the cells.

3.2 CALIBRATION OF THE MODEL

In the present study, neither the exact location of source of pollutants, nor any trends of areal spreading of pollutants are available. Moreover, the causes of propagation of sources, releasing pattern and the geo-chemical behaviour of the pollutants are also not known. Arsenic concentration data monitored over different months at 58 observation wells (Table A.4 in appendix) do not represent any specific trend over space and time. However, they depict activation and de-activation trend of concentration when compared with water level data of respective locations, i.e, concentration increases at the beginning of recharge period and declines to its minimum level at the end of discharge period. This eventually reflects that during recharge period (May-July), pollutants are available in dissolved form in the flow domain and get transported to nearby areas during discharge period. The period from May to July thus can be described as activation period and the period from August to April as de-activation period of Arsenic contents.

The kinetics of geo-chemical processes of Arsenic though play a crucial role in time and space distribution of concentration, but from the available information it is difficult to establish any trend of chemical kinetics. Hence simulation of contaminants' transport has been done considering advective-dispersive phenomena. Surface plot (Fig. 3.1) and contour plot (Fig.3.2)

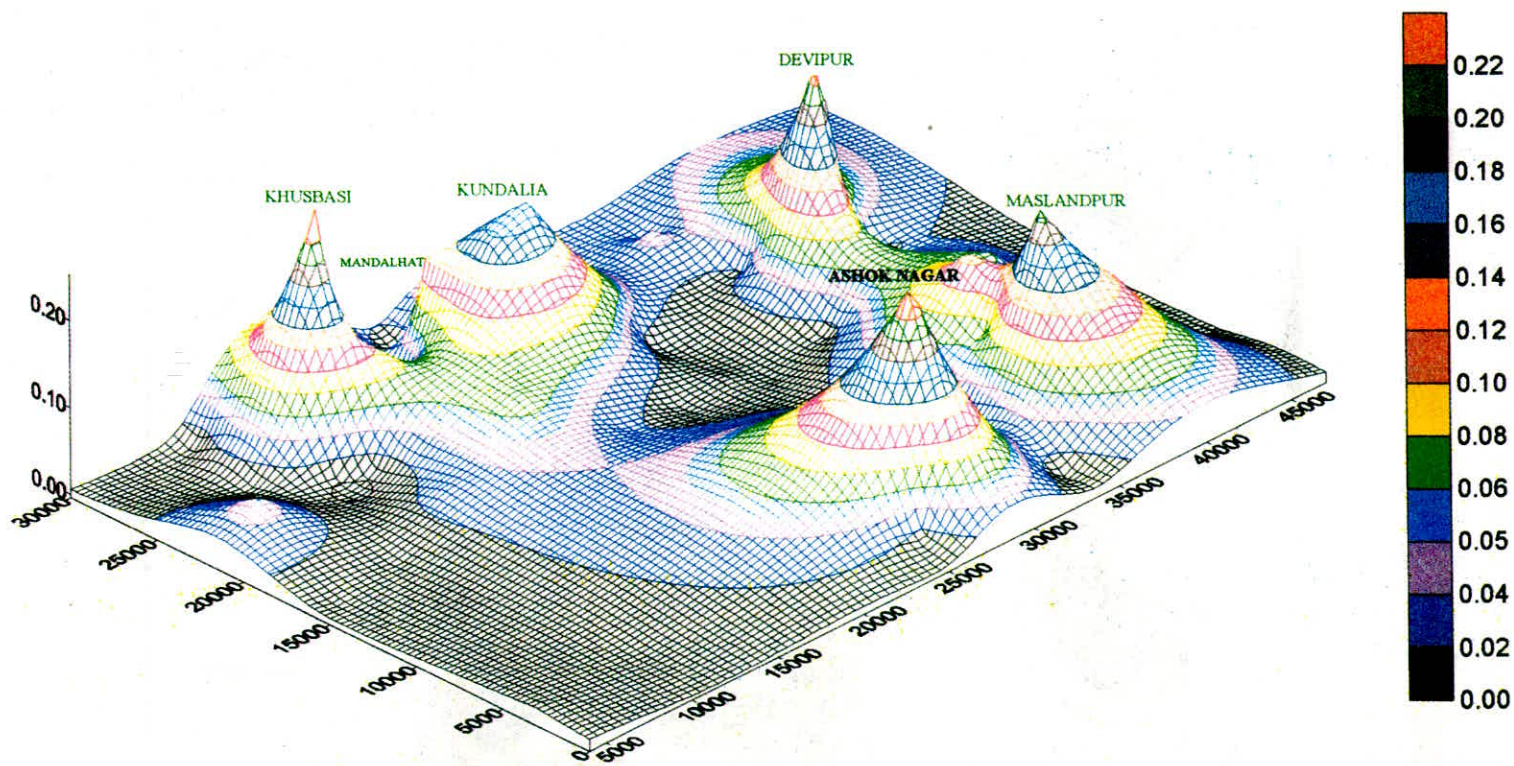


Figure 3.1 : 3-Dimensional plot of maximum observed Arsenic concentration (April '97 - May '98).

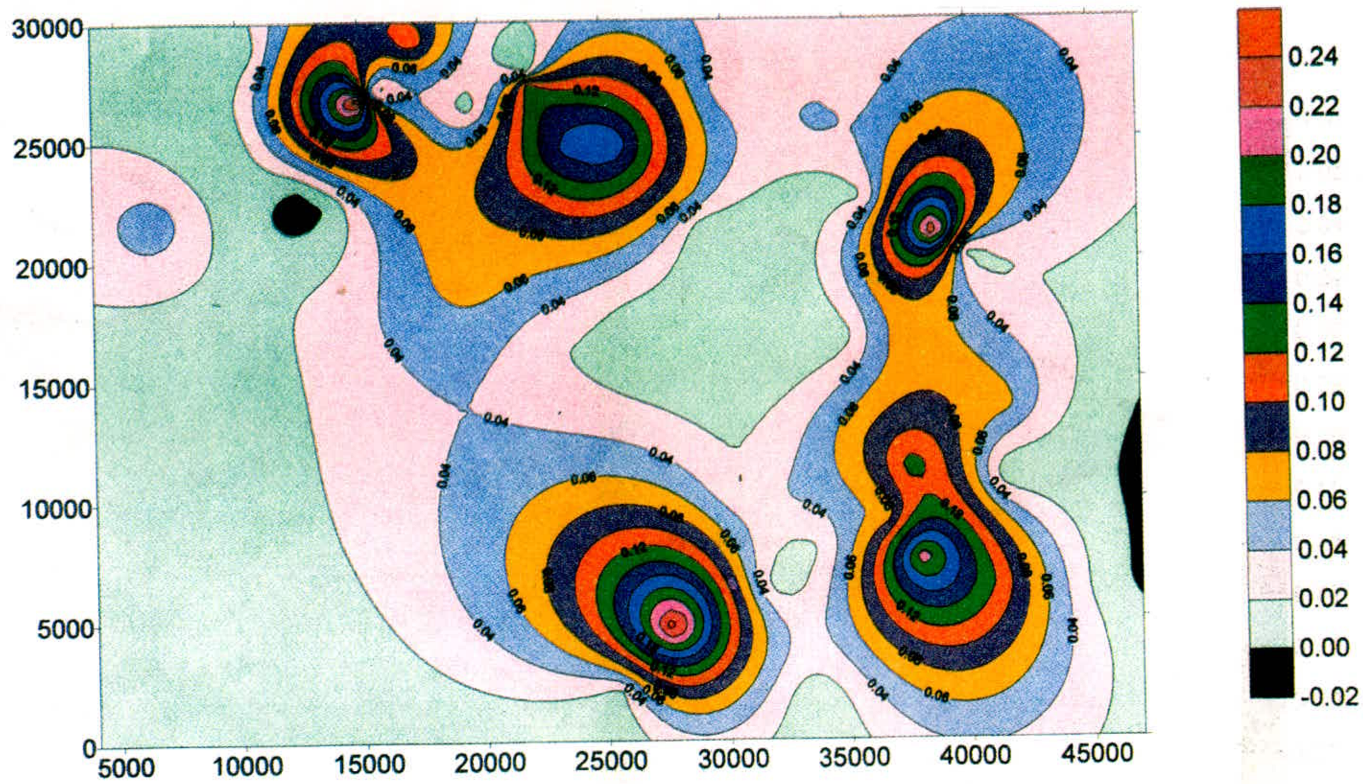


Figure 3.2 : Space distribution of maximum value of observed Arsenic concentration (April '97 - May '98).

of observed Arsenic concentration data (Table A.4 in appendix) reveal that concentration at six locations namely; Ashoknagar, Khusbasi, Mandalhat, Kundalia, Devipur, and Maslandpur have maximum value with scattered traces in the nearby areas. These places are at a considerable distance from one another and do not depict any trend of linkages. Since Surfer package interpolate values for other locations based on the given set of values by linear interpolation, the plot shown in Figs. 3.1 and 3.2 may not be the actual scenario of Arsenic distribution prevailing in the field which is also clear from Fig. 3.3. However, a trend of data linkages can be obtained. Assuming that concentration of Arsenic measured at above six points is due to the activation of in-situ sources located in and around these points (not necessarily sources at these places only), transport phenomena has been studied considering same transient condition prevailing for 5 years.

3.3 DISCUSSION AND ANALYSIS OF RESULTS

Since the flow and transport models are inter-linked, and velocity vectors generated from the simulated run of transient flow conditions corresponding to the month of September,'97, the initial condition assigned in the transport modelling study also correspond to September, '97.

Using the observed concentration distribution data of September'97 as the initial concentration scenario in the flow domain, transport phenomena were simulated assuming sources of pollution from the upstream part of river Bhagirathi and northern boundary separately. Since the objective is to examine whether the Arsenic concentration observed in the flow domain has any linkage with these external boundaries, an arbitrary value of continuous concentration fluxes were assumed as input from these boundaries. However, the input from these boundaries showed no such linkages even after 5 years of simulation. Thus, further trials of simulation did not appear to be logical and hence were not explored.

Focus was then diverted towards exploring the third possibility as mentioned in section 3.1.1 i.e, consideration of in-situ sources at six localised pockets. The observed Arsenic concentration data (Table A.4 in appendix) from April'97 to May'98 reveal that the maximum value of concentration at different locations reduces during the recharge months (May to July), in general, with reduction of peak value. After attaining a peak value, gradually reduces due to localised effect of fluctuation of water table (Table A.2 in appendix). Considering the maximum observed concentration at these locations to be occurring in the recharge months, the concentration distribution after this period was taken as the scenario prevailing at the beginning

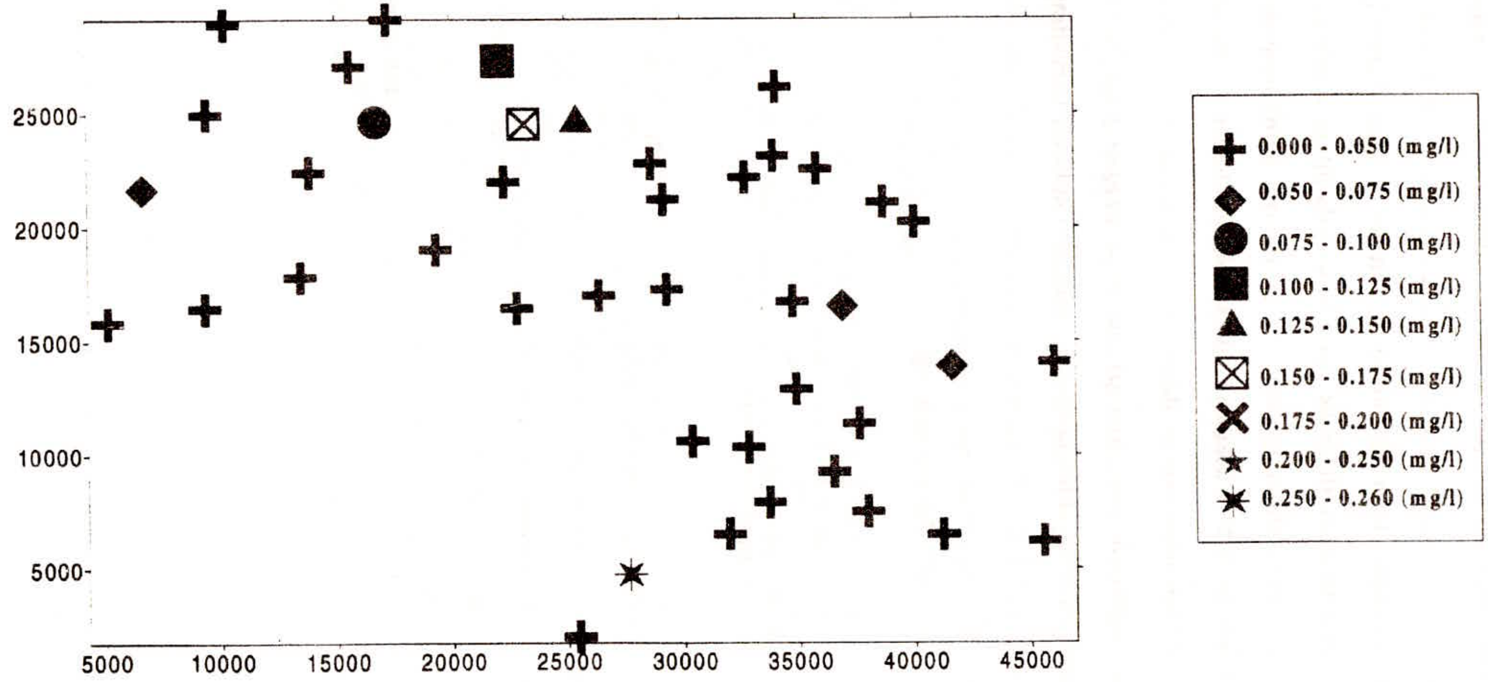


Fig 3.3 : Distribution of observation points in the Yamuna sub-basin

of September which is the initial condition for the transport simulation. The period after September up to beginning of May being the discharge months, no external input was considered in between this period. Literally these processes can be explained as: during discharge months (August-April) due to the lowering of water table unsaturated condition prevails which induces oxidation process of in-situ Arsenic; the oxidised Arsenic becomes available and spreads further once it gets dissolved as the water table rises during the recharge months.

Making use of these processes, transport phenomena was simulated for the discharge period (August to April). While for the recharge period (May to July), the condition of activation of concentration was achieved by introducing mass flux at these locations. One may certainly find this in contradiction with the field condition. However this artificial introduction of mass flux is nothing but to incorporate the effect caused due to oxidation-reduction process actually occurring in the sub-surface. Mathematically the effects of these two processes have the same meaning.

Adopting this mechanism, the transport phenomena was simulated for five years in the following way keeping the same flow field: The concentration scenario developed after each year of transport run was considered as the initial condition for the subsequent year with other input conditions remaining same.

The output of the model after 5 years of simulation (Figure 3.4) shows a similar trend of spreading when compared with the observed spatial distribution (Figures 3.1 and 3.2) except the magnitude of the computed and observed concentration distributions. The influence of the localised sources with the given input condition was found to be of the order of 2 km from these sources. The spatial distribution of concentration obtained from the model output further depicts that the occurrence of Arsenic at a place has no bearing with the transport of Arsenic from other sources - but - in a localised scale the spreading is due to the transport of in-situ activation.

The time-concentration outputs of the model for five years of simulation were recorded at the source point and at a distance of 500 m, 1000 m and 1500 m along the longitudinal direction for all the localized pockets. These are shown in Figures 3.5 to 3.10. The Figures 3.5(a) to 3.10(a) exhibit that for same quantum of occurrence of Arsenic during recharge period, the magnitude of concentration during the de-activation period increases in the corresponding periods of the subsequent years, whereas away from the source, concentration increases over time (Figures 3.5(b) to 3.10(b)). This is due to the fact that contaminants which spreadsduring an year are available as source during subsequent years. No major variation was found in the other direction.

It can further be inferred from the observed Arsenic concentration data (Table:A.4 in appendix) that concentration at a place suddenly rises to a detection limit and goes down to below detection limit even during the recharge period. This may be due to the localised effects of water table fluctuation. Except the localised effects of water table fluctuation, the overall trend exhibits that the processes of oxidation and reduction (termed here as activation and de-activation) largely depend upon the recharge and discharge pattern of the flow domain. In physical sense, it means that once the water table declines below a certain depth (the depth where Arsenic bearing compound is entrapped), oxidation process starts due to unsaturated condition of soils. The oxidised material enters to the groundwater in dissolved form when the water table rises due to recharge.

The transport of Arsenic in the vertical direction computed at 8 m below the source point reveals shift of peak concentration, which is obvious, however, the trend remains similar (Figure 3.11 to 3.16).

Further, the superimposed plots of observed Arsenic concentration, storativity, and transmissivity (Figure 3.17) reveal that the point of maximum concentration of Arsenic and the contour of minimum value of transmissivity coincide. The minimum transmissivity occurs where there are clay pockets. This eventually reflects that clay lenses have the tendency to entrap Arsenic. In view of the above, the role of geo-chemical processes in the transport of Arsenic at localised pockets needs to be investigated.

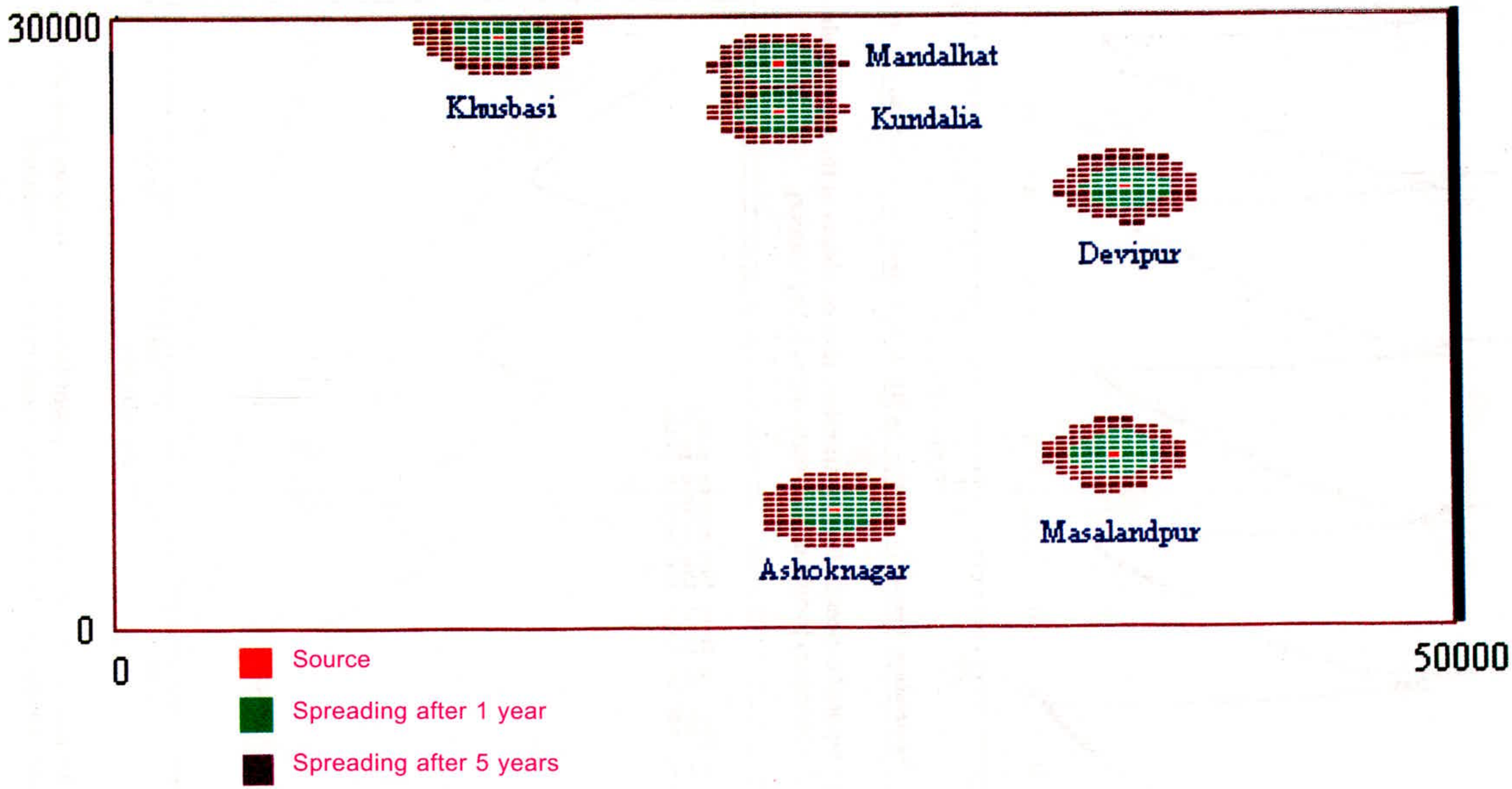


Figure 3.4 : Computed extent of spreading of point sources at the end of 5 years

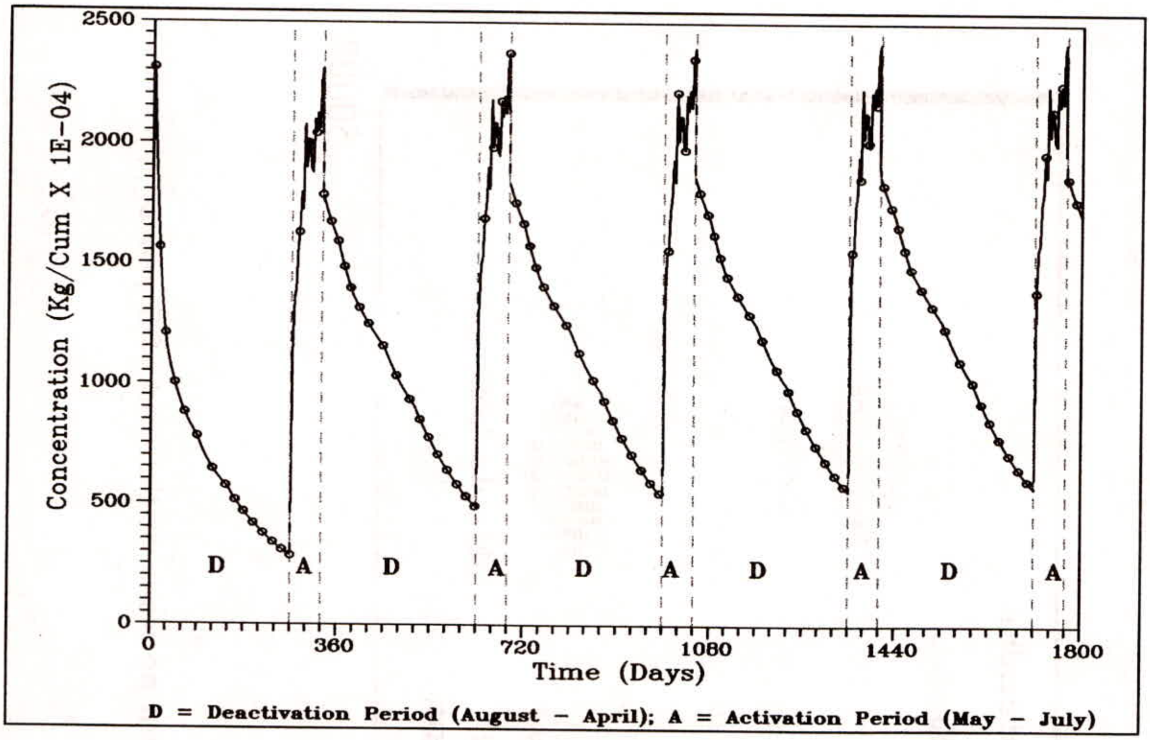


Figure 3.5(a): Computed concentration for transient flow condition at the source point (Ashoknagar) [origin of time scale refers to September].

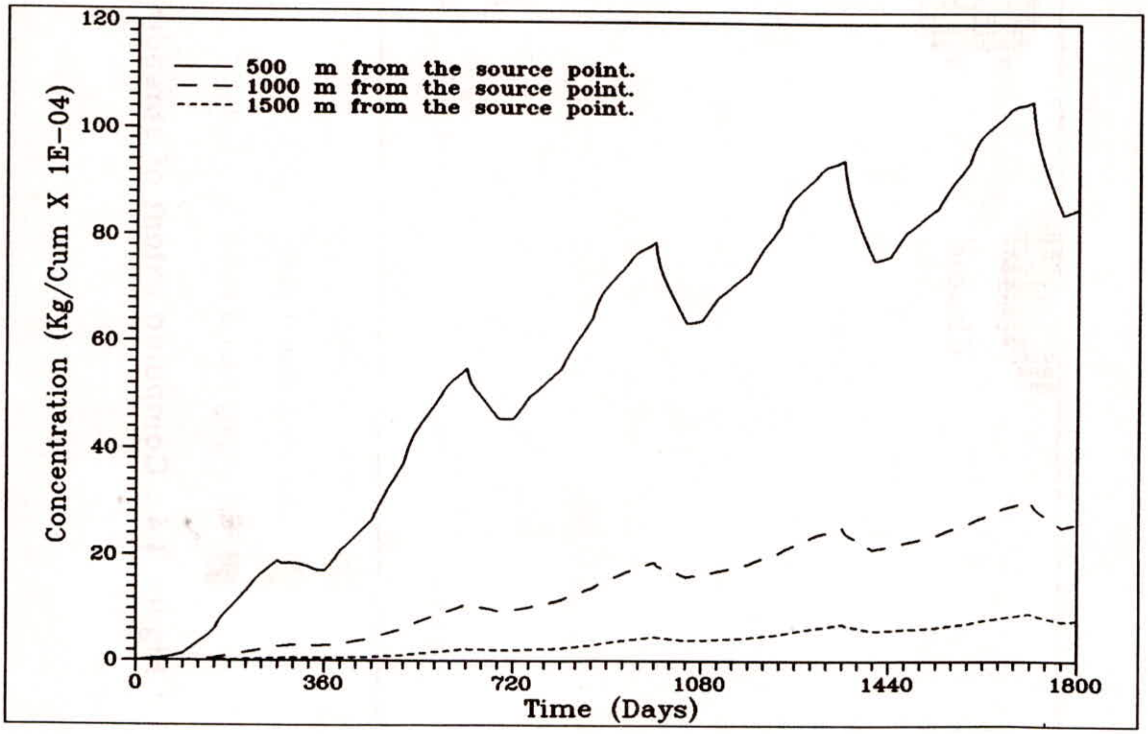


Figure 3.5(b): Computed concentration for transient flow condition away from the source point (Ashoknagar) [origin of time scale refers to September].

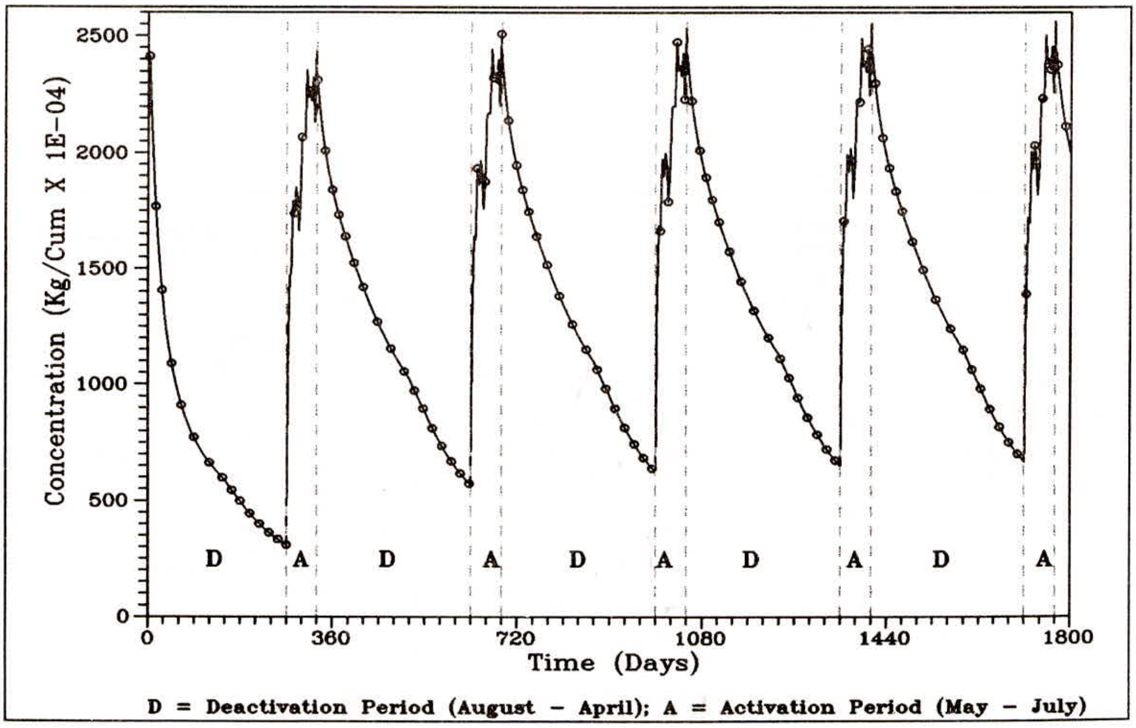


Figure 3.6(a): Computed concentration for transient flow condition at the source point (Khusbasi) [origin of time scale refers to September].

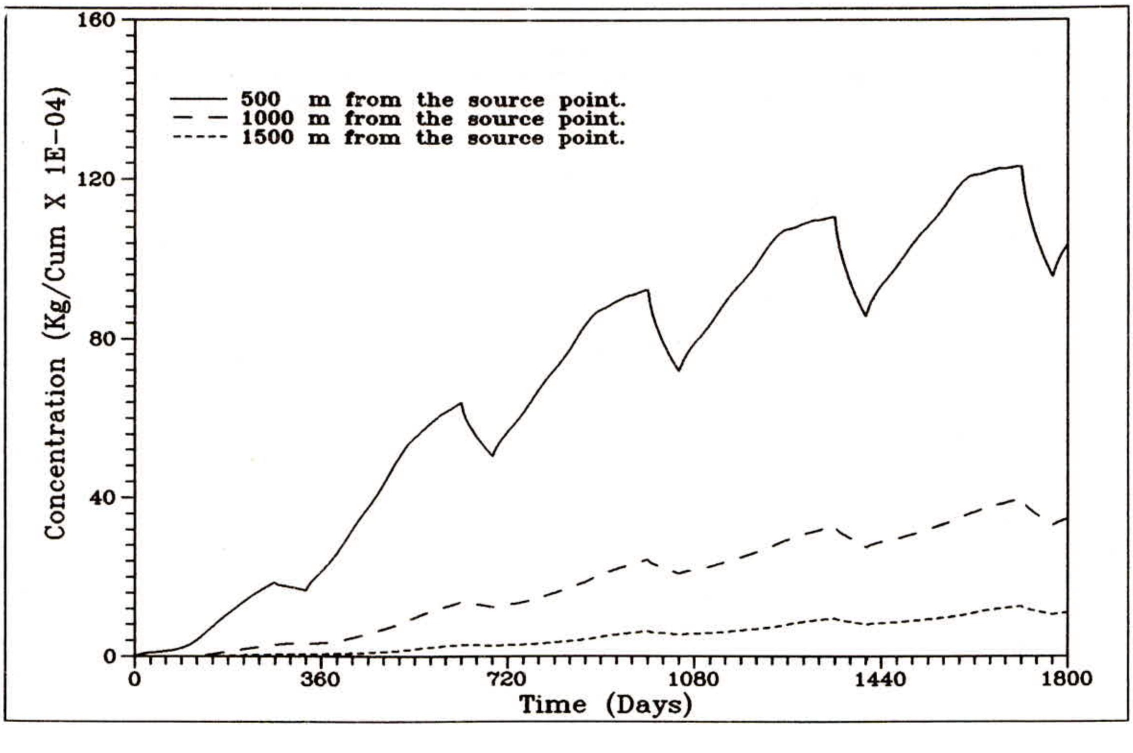


Figure 3.6(b): Computed concentration for transient flow condition away from the source point (Khusbasi) [origin of time scale refers to September].

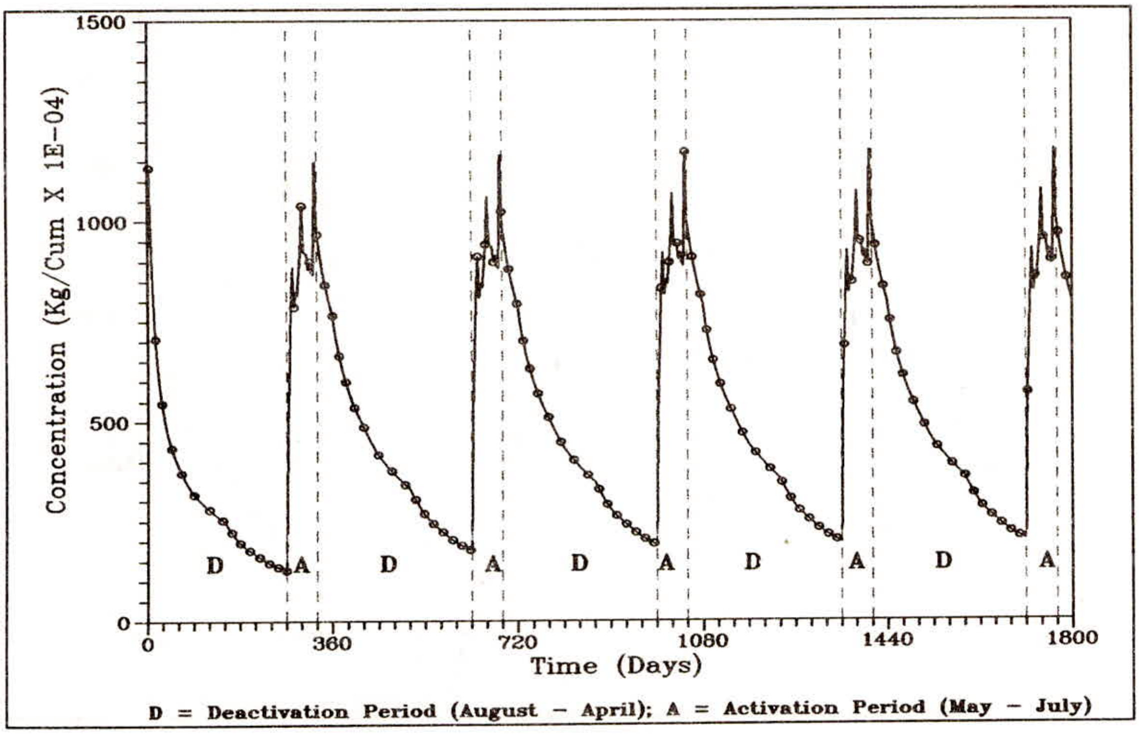


Figure 3.7(a): Computed concentration for transient flow condition at the source point (Mandalhat) [origin of time scale refers to September].

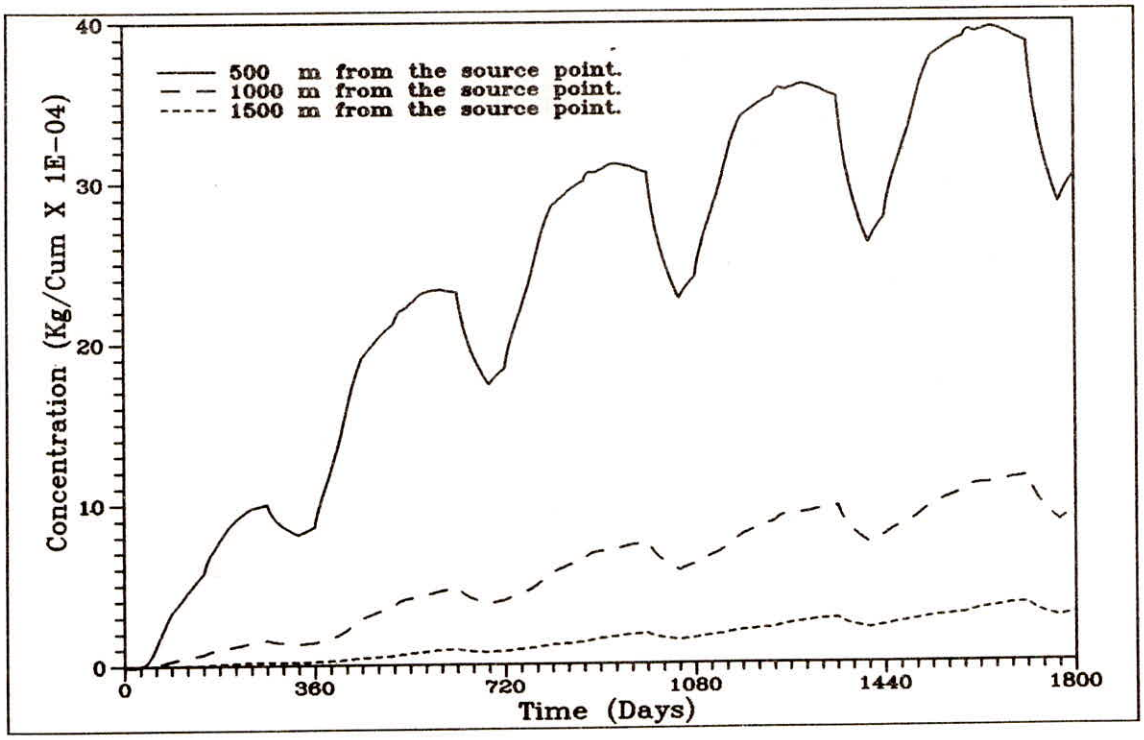


Figure 3.7(b): Computed concentration for transient flow condition away from the source point (Mandalhat) [origin of time scale refers to September].

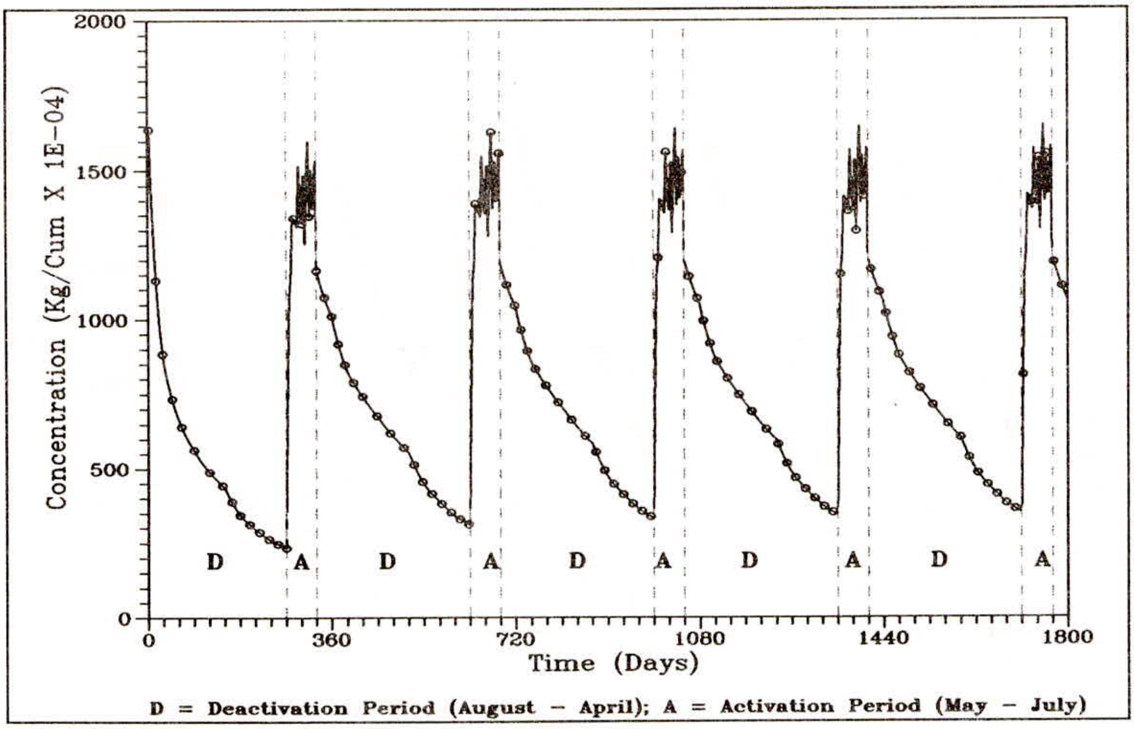


Figure 3.8(a): Computed concentration for transient flow condition at the source point (Kundalia) [origin of time scale refers to September].

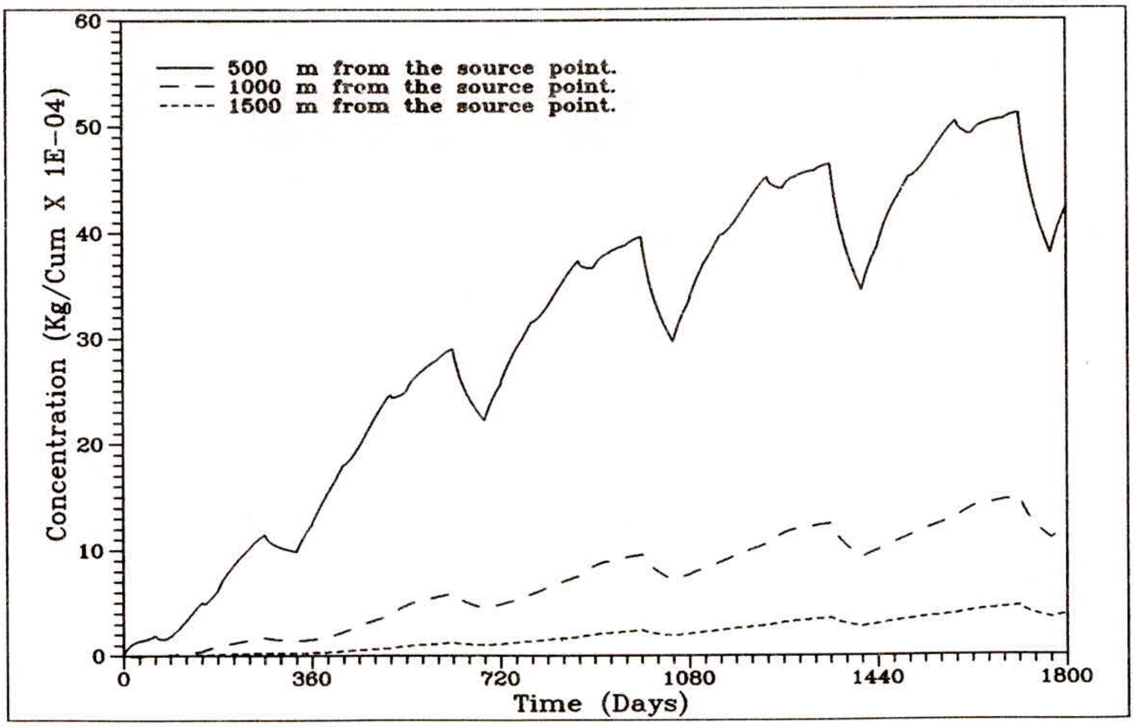


Figure 3.8(b): Computed concentration for transient flow condition away from the source point (Kundalia) [origin of time scale refers to September].

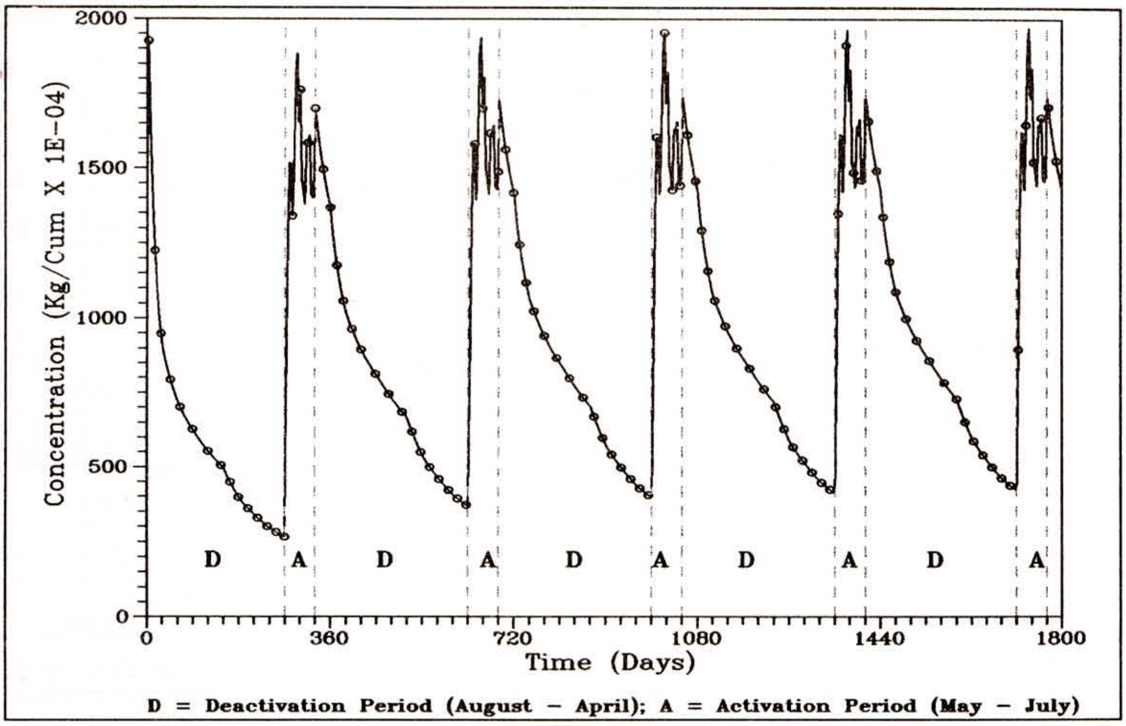


Figure 3.9(a): Computed concentration for transient flow condition at the source point (Maslandpur) [origin of time scale refers to September].

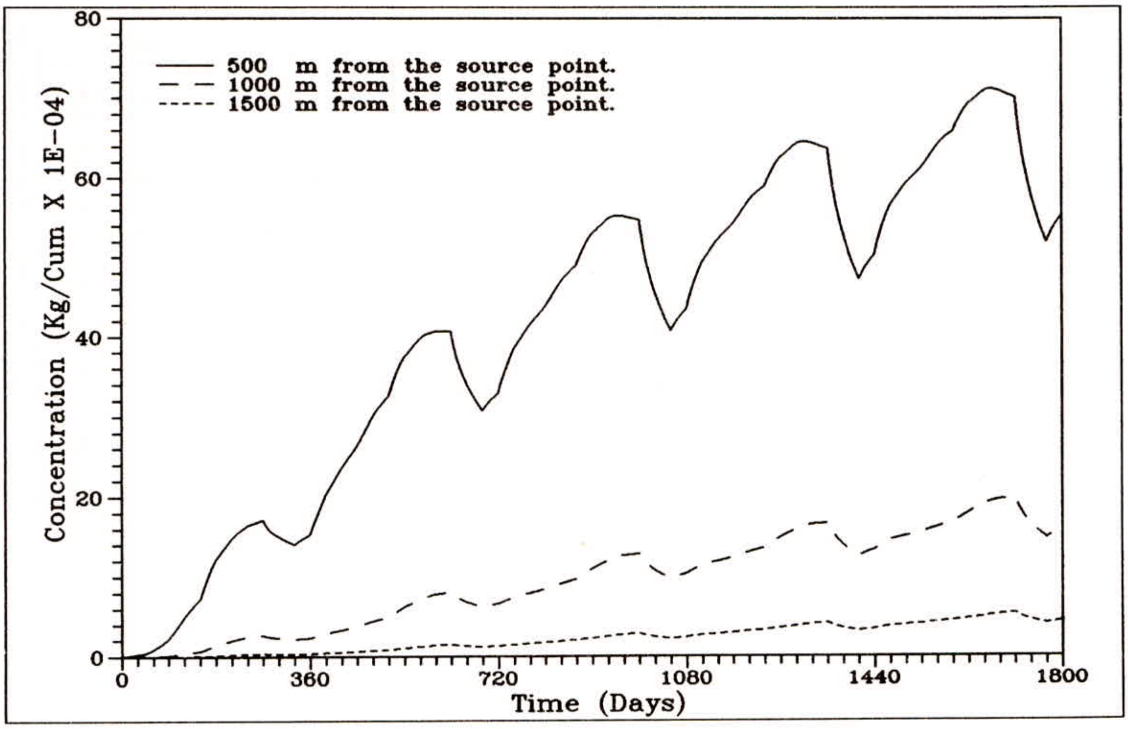


Figure 3.9(b): Computed concentration for transient flow condition away from the source point (Maslandpur) [origin of time scale refers to September].

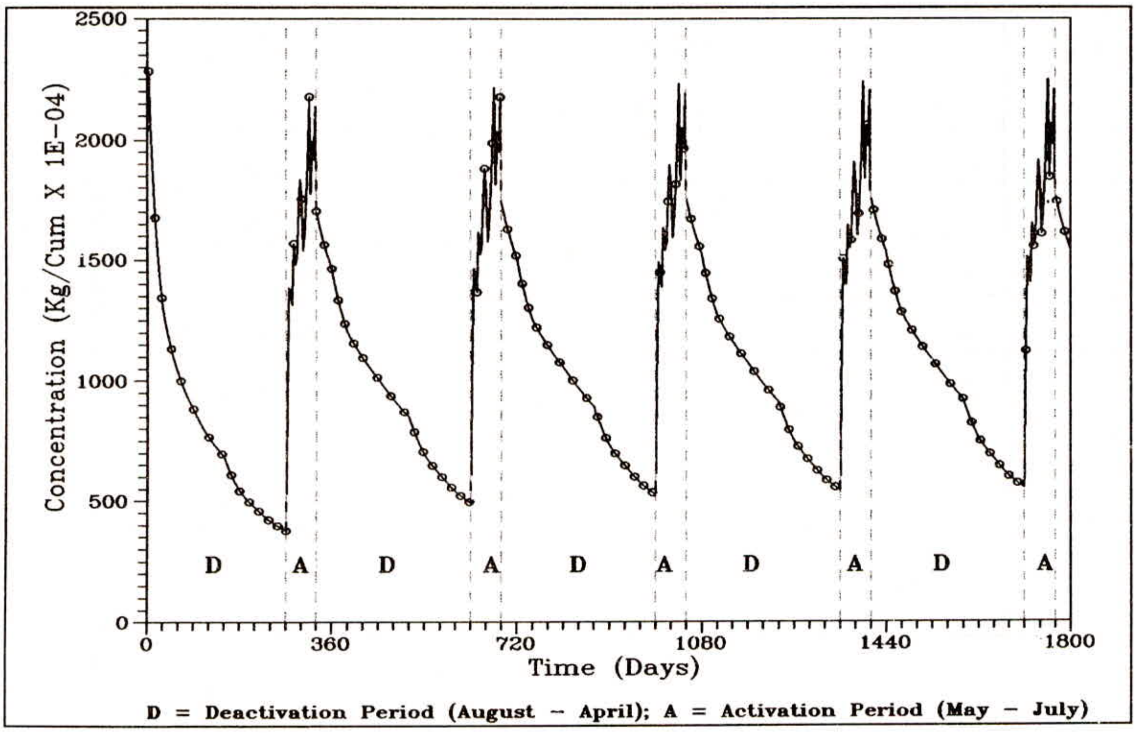


Figure 3.10(a): Computed concentration for transient flow condition at the source point (Devipur) [origin of time scale refers to September].

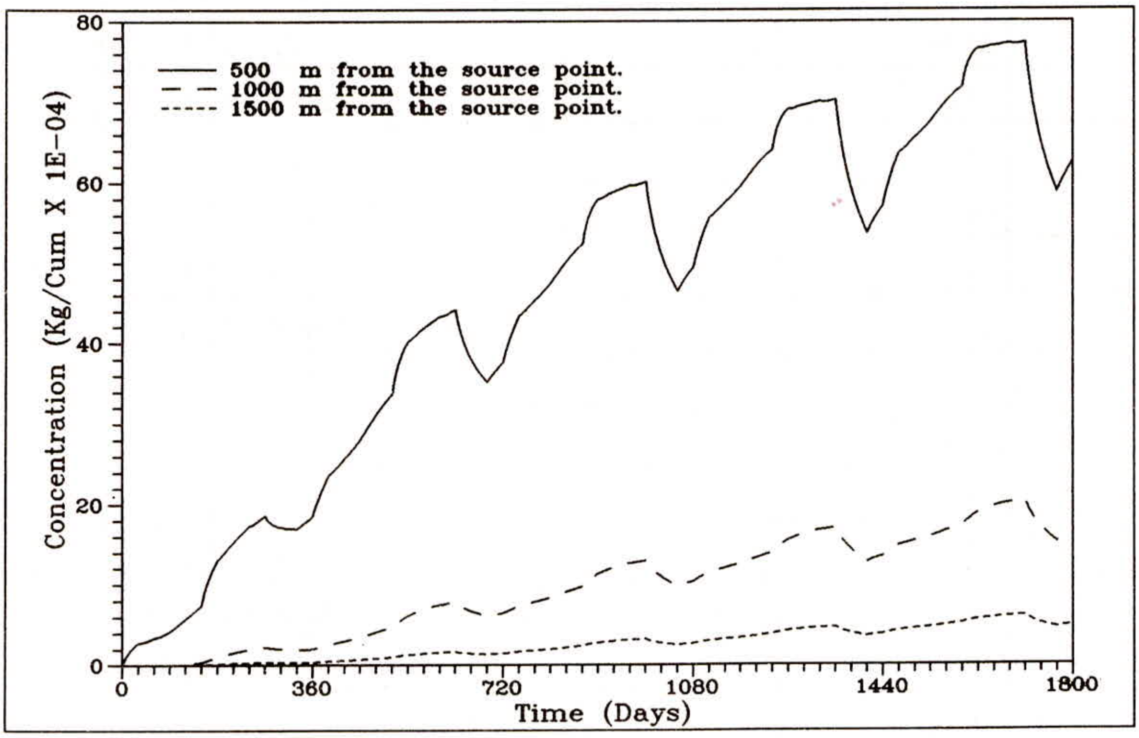


Figure 3.10(b): Computed concentration for transient flow condition away from the source point (Devipur) [origin of time scale refers to September].

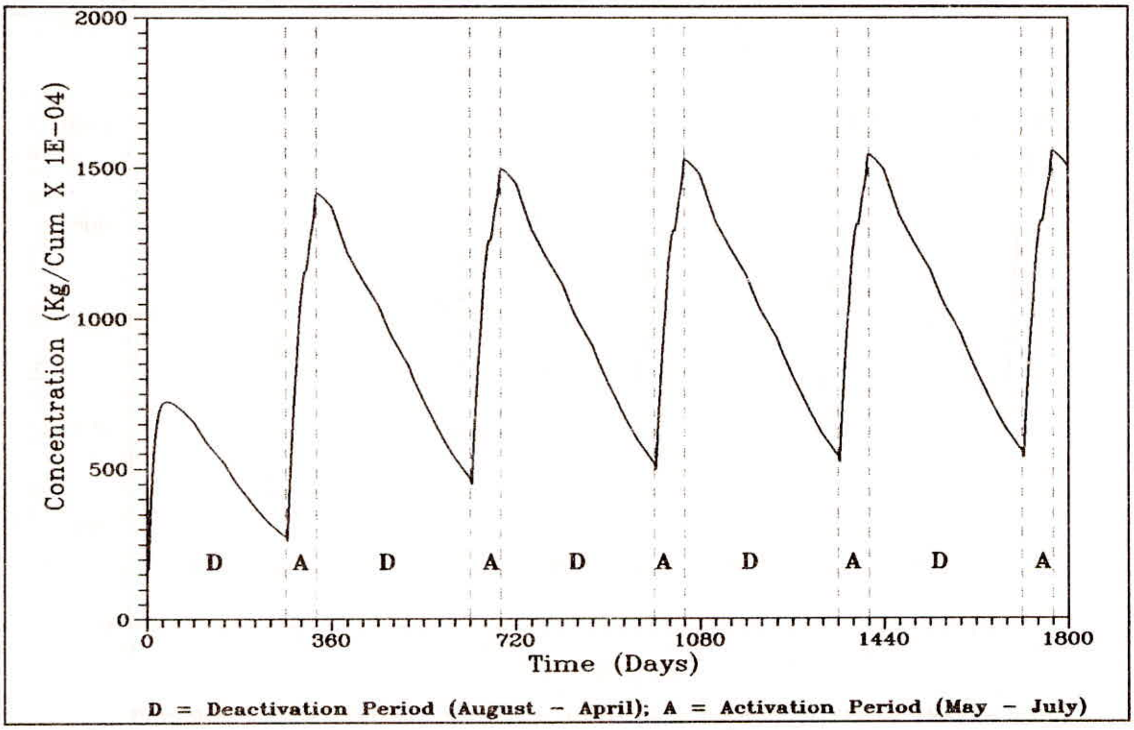


Figure 3.11: Plot of variation of concentration at 8.0 m below the source point (Ashoknagar) [Origin refers to September].

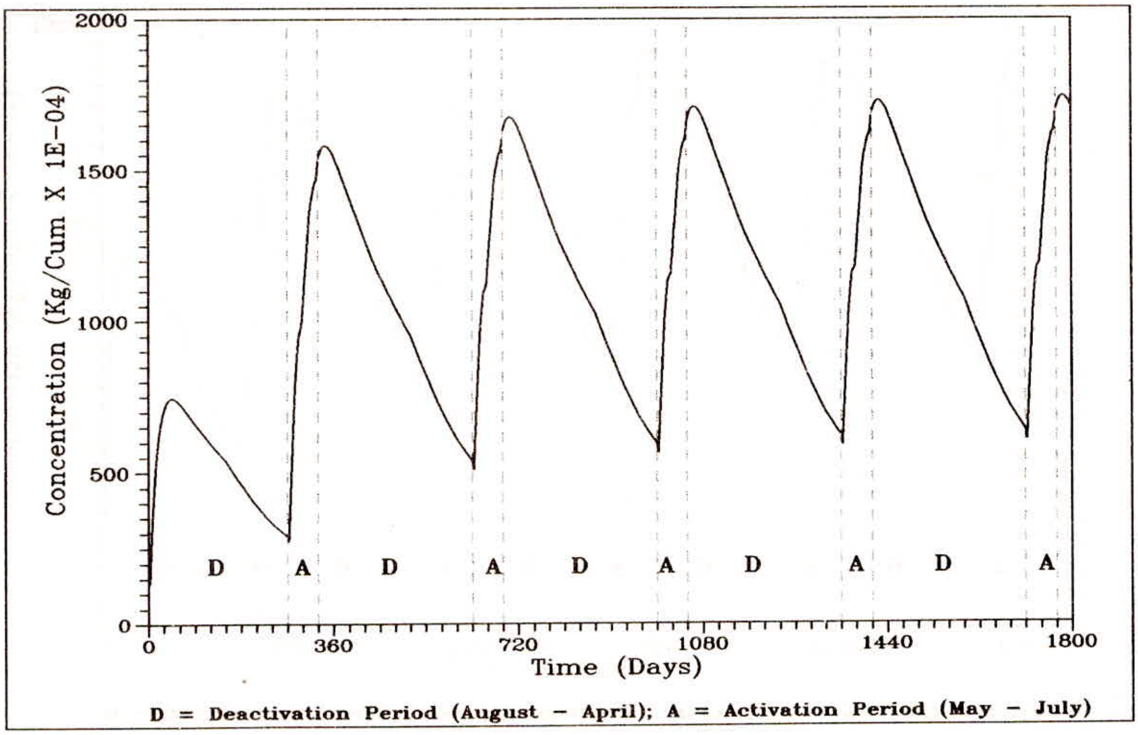


Figure 3.12: Plot of variation of concentration at 8.0 m below the source point (Khusbasi) [Origin refers to September].

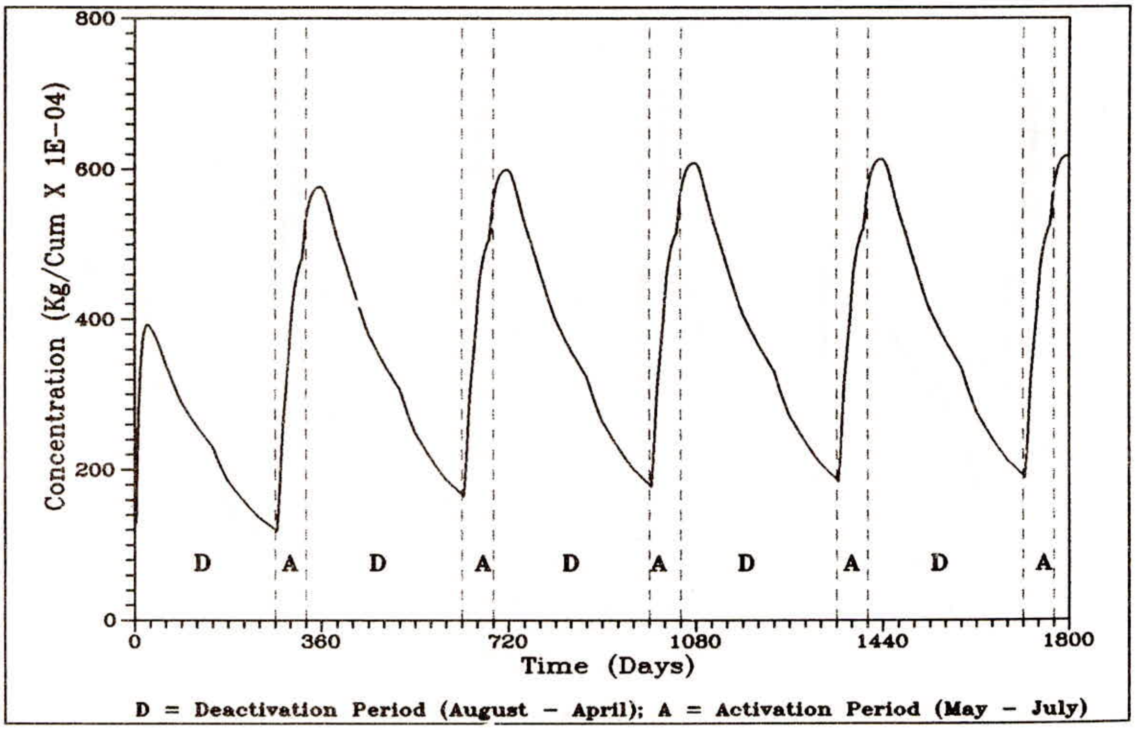


Figure 3.13: Plot of variation of concentration at 8.0 m below the source point (Mandalhat) [Origin refers to September].

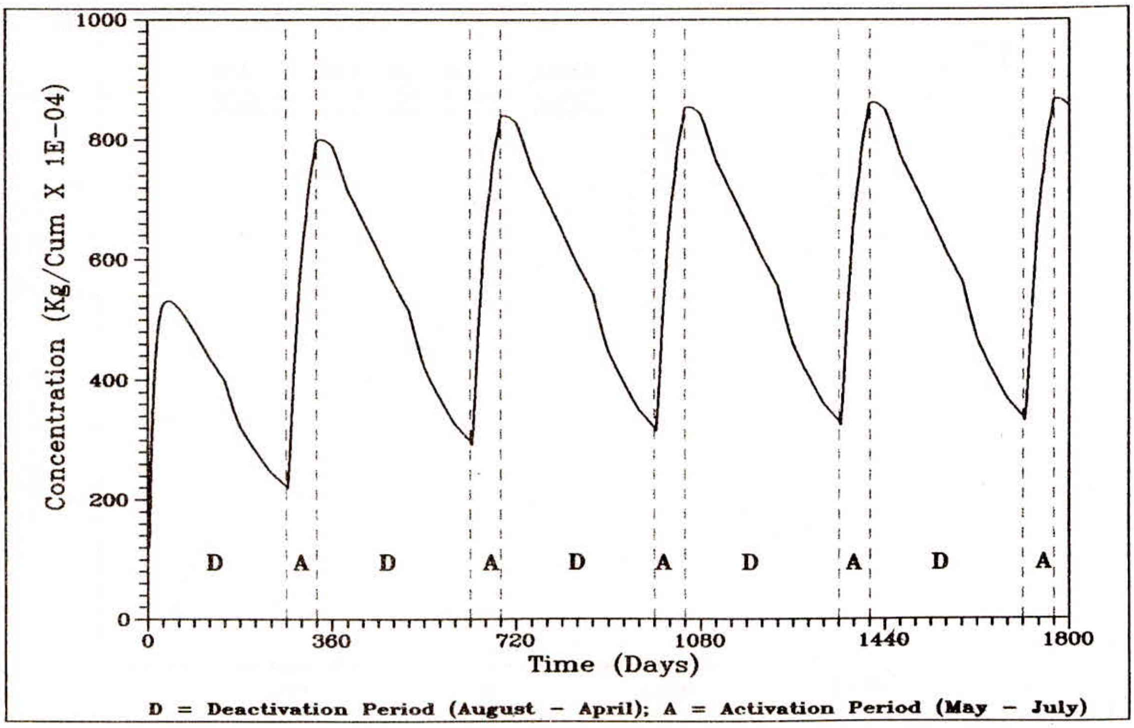


Figure 3.14: Plot of variation of concentration at 8.0 m below the source point (Kundalia) [Origin refers to September].

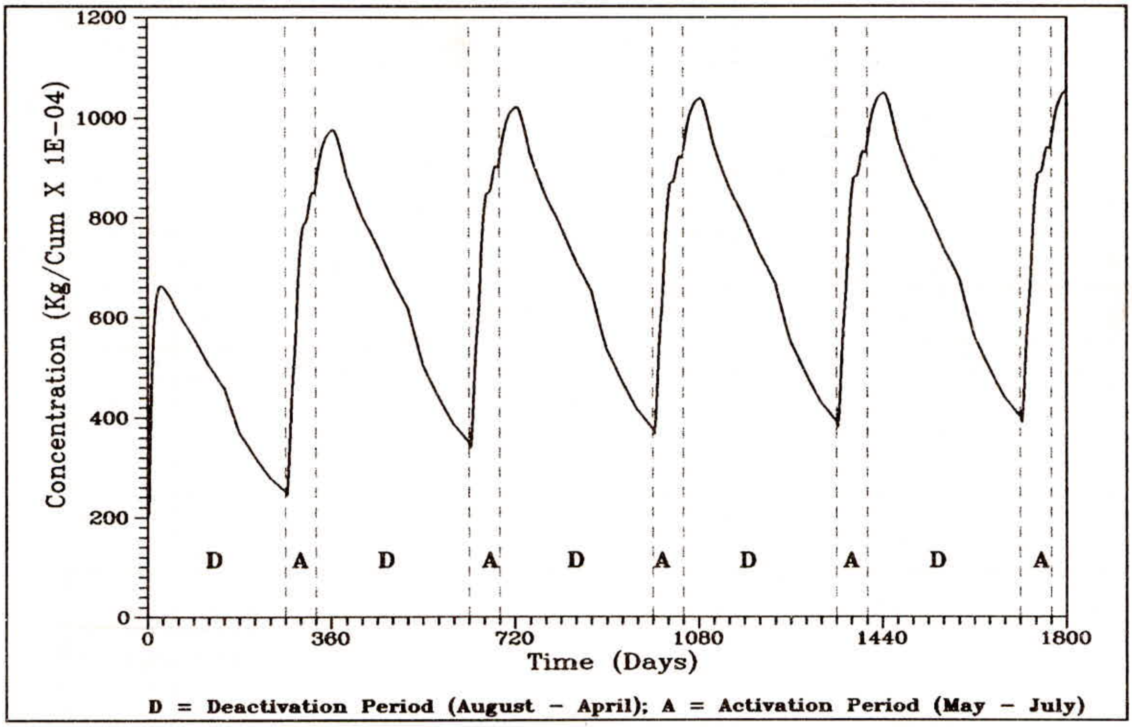


Figure 3.15: Plot of variation of concentration at 8.0 m below the source point (Maslandpur) [Origin refers to September].

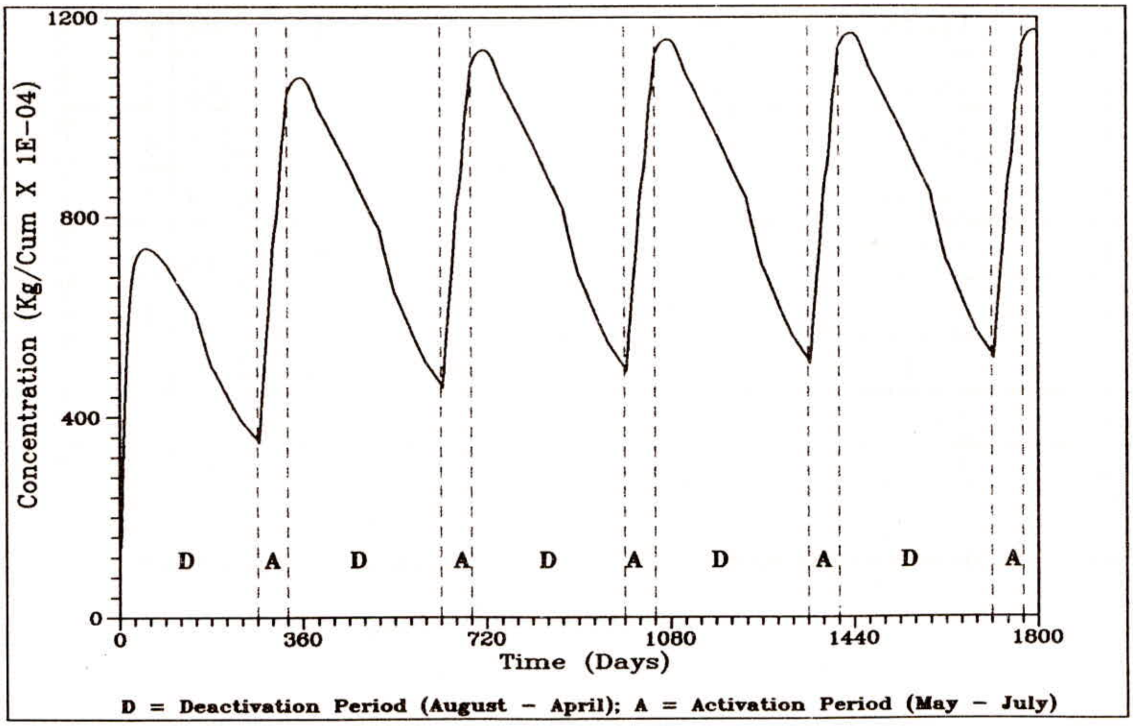


Figure 3.16: Plot of variation of concentration at 8.0 m below the source point (Devipur) [Origin refers to September].

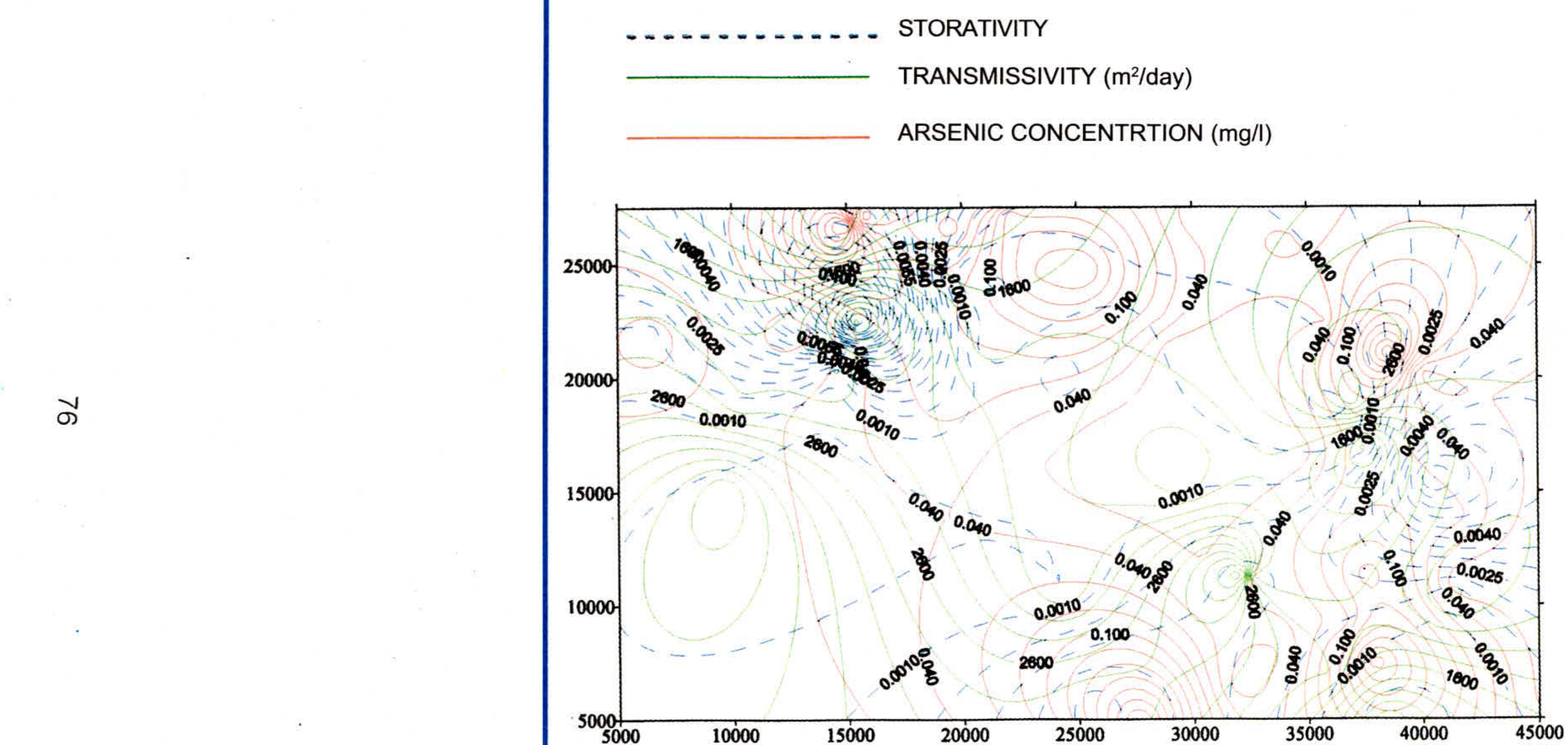


Figure 3.17 : Superimposed plots of Storativity, Transmitivity and Arsenic concentration values.

PART - IV

ANALYSIS OF REMEDIAL OPTIONS

4.0 MODEL RESPONSES TO DIFFERENT REMEDIAL OPTIONS

A close look at observed Arsenic concentration data (Table A.4 in appendix) and the analysis of transport phenomena clearly show that the processes of activation and de-activation of Arsenic in the flow domain is related to the fluctuation of water table. Elaborating more precisely, in-situ entrapped compound of Arsenic bearing material (common form is Arsenopyrite (FeAsS)) oxidizes during un-saturated condition of the sub-surface that occurs when water table declines, and gets entry into the groundwater in dissolved form when water table rises due to the recharge. Monthly hydrograph data (1987-1996) of some of the monitoring stations located in the study domain (Figure A.5 to A.8 in appendix) indicate that the flow domain was under the maximum stress of withdrawal during years 1993 and 1995, when the water table declined to its minimum level during the month of April. This decline in water table was about 2 to 4 m more than the average normal decline recorded for the month of April during previous years. The oxidation process might have started due to the excessive fall of water table some time in between that period or earlier to that period, and, thereafter, the phenomena of oxidation and reduction and thereby spreading continued.

The solutions, one can visualises as remedial measure, are to ensure that water table does not go below certain limit so that the process of activation and de-activation is minimised. Alternately, there can be an attempt to arrest the intrusion of Arsenic in the unaffected areas by providing hydraulic barriers between the interfaces of affected and unaffected zones. In the later case, one has to be sure about the localised pockets of in-situ source and its extent of spreading while the earlier case deals with the restoration of water table in the whole study domain.

Keeping the above points in view, following remedial options have been analysed to quantify the model response. The concentration scenario developed at the end of 5 years of simulation has been taken as input concentration distributions in the flow domain for analysis of the following remedial options:

i. Defuncting withdrawal from wells of the Arsenic spreaded areas in the model domain.

ii. Stepwise reduction in the withdrawal pattern of groundwater from the whole flow domain.

iii. Installing battery of recharge wells around the Arsenic affected zones to create a hydraulic barrier.

Before exercising the above options, flow simulation was carried out for three years under transient condition keeping same stresses of the corresponding months in the subsequent two years. The scenario at the end of 3 years is depicted in Figure 4.1. The head (water table) versus time plot for six locations is given in Figure 4.2. The declining trend of heads in subsequent years was due to the deficit in recharge.

4.1 Option No. (i):Defuncting withdrawal from Arsenic spreaded area

Assessment of recharge and discharge (Table- 2.6(a) and (b)) reveal that each cell of size 500 m x 300 m in the respective Arsenic affected area is under considerable influence of external stresses (withdrawal) from August through April. For example, each cell (500 m x 300 m) in Arsenic affected area in Chakdah, Habra-I, Swarupnagar, and Gaighata blocks is under the pressure of withdrawal ranging from 412 m^3/day to 448 m^3/day over different months. If this figure is converted to number of wells in operation in each cell, it shows a distribution of about 1-2 shallow wells per cell with yielding rate of 35 m^3/hr or lesser number for higher yielding rate. Five year simulation of transport model shows a spreading of contaminants radially in an area of about 7.0 km^2 around the respective source points. This 7.0 km^2 contains 47 celis of size 500 m x 300 m having different withdrawal rates during the period from August through April.

Defuncting withdrawal from these cells (which means Arsenic contaminated area are to be protected from withdrawal), the flow is simulated for 3 years under transient condition keeping stresses (withdrawal) of remaining areas unchanged. Three years period is chosen to see the effect in the long run. Scenarios of the predicted water table at the end of the 3 years are shown in Figure 4.3. Graphical plot of head versus time for six places is shown in Figure 4.4, and Figure 4.5 gives the plot at the interfaces of the no withdrawal zone and the withdrawal zone of the respective areas.

It can be seen from Figure 4.4 that due to the defunct of withdrawal from these localised areas, the water table during the discharge months rises by 1.50 m to 2.50 m over the minimum level of the respective places. During subsequent years, the water table rises still further during the recharge months.

Simulation of transport phenomena corresponding to this flow scenario do not show appreciable reduction in spreading but do show the effect of dilution of concentration which is obvious. However, the arrest in the fall of water table would minimize the oxidation process of Arsenic, which would subsequently control further introduction of Arsenic in the flow domain.

The risks associated with this approach are: water table has a positive gradient towards outer domain (non-defunct zone), therefore, any untoward or incidental introduction of Arsenic in the defunct zone will have a tendency to move towards the outer domain.

4.2 Option No. (ii) Stepwise reduction in the withdrawal of groundwater from the whole domain

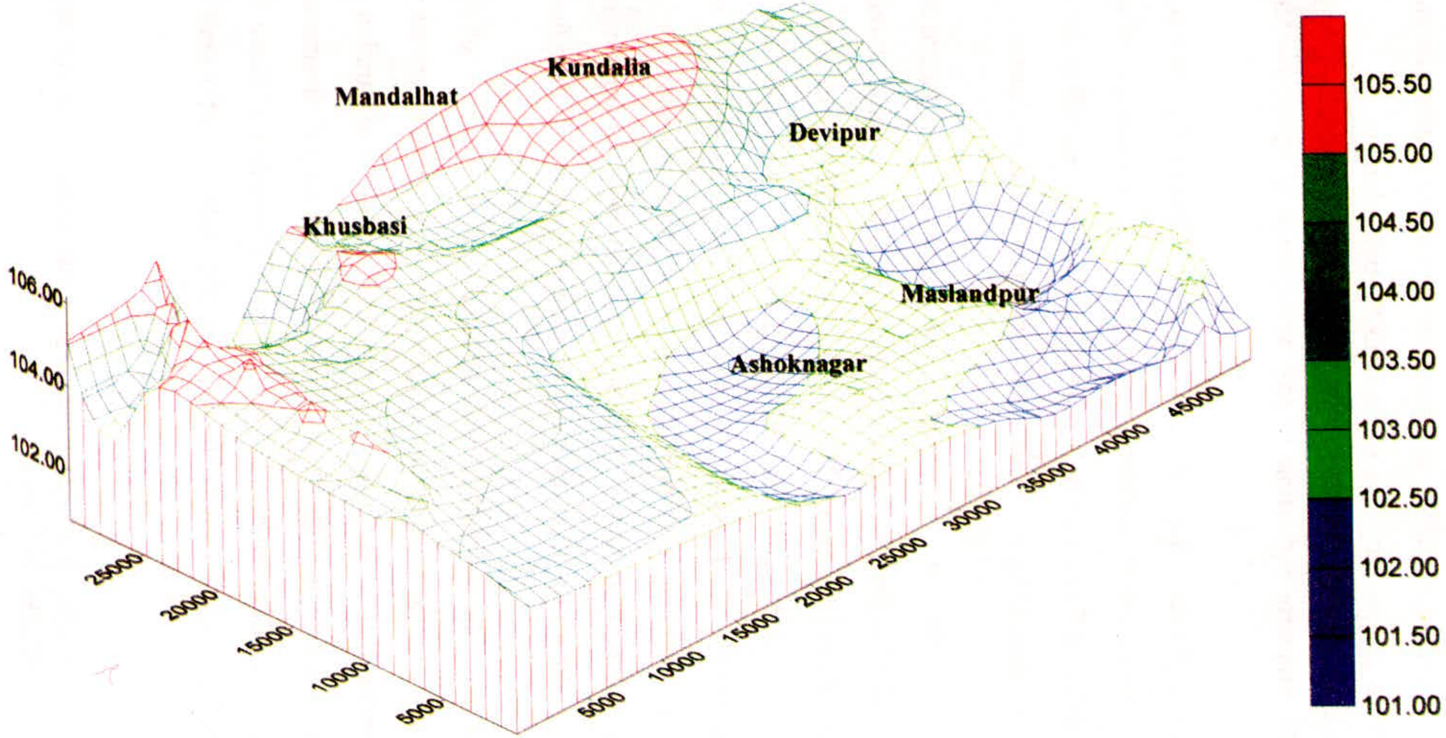
Estimation of withdrawal (Table 2.5(a)) of the study area indicates that its magnitude has increased by 1.35 to 3.0 times in different blocks in comparison to the assessment made in year 1990. Reduction of withdrawal from the whole flow domain means controlling the lowering of water table and, therefore, minimising the oxidation/reduction processes of Arsenic.

Keeping this in view, the flow was simulated reducing withdrawal pattern of the whole domain by 10%, 20%, and 30% for 3 years under transient condition keeping all other external stresses (recharge, GHB, rivers) the same. The graphical plots of head versus time at the six places corresponding to the 10%, 20%, and 30% reduction of withdrawal from the whole domain have been shown in Figures 4.6 to 4.8. Comparison of the Figs. 4.6 to 4.8 with Fig. 4.2 (representing the plot of continuance of prevailing situation) although shows a rise in the overall water table for different amount of reduction in withdrawal but improvement in the elevation of water table in the localised places is not appreciable as apparent from the Table 4.1.

Water table position, which would control activation and de-activation of Arsenic, can be obtained when the level of the source point is known. However, the observed water table data (Table A.2 in appendix) and the corresponding measured Arsenic concentration data (Table A.4 in appendix) show that, by and large, Arsenic concentrations started dis-appearing in the domain from the beginning of November. If water table of November at these locations is considered as the safe level, this level is not achieved even after reduction of overall withdrawal by 30%.

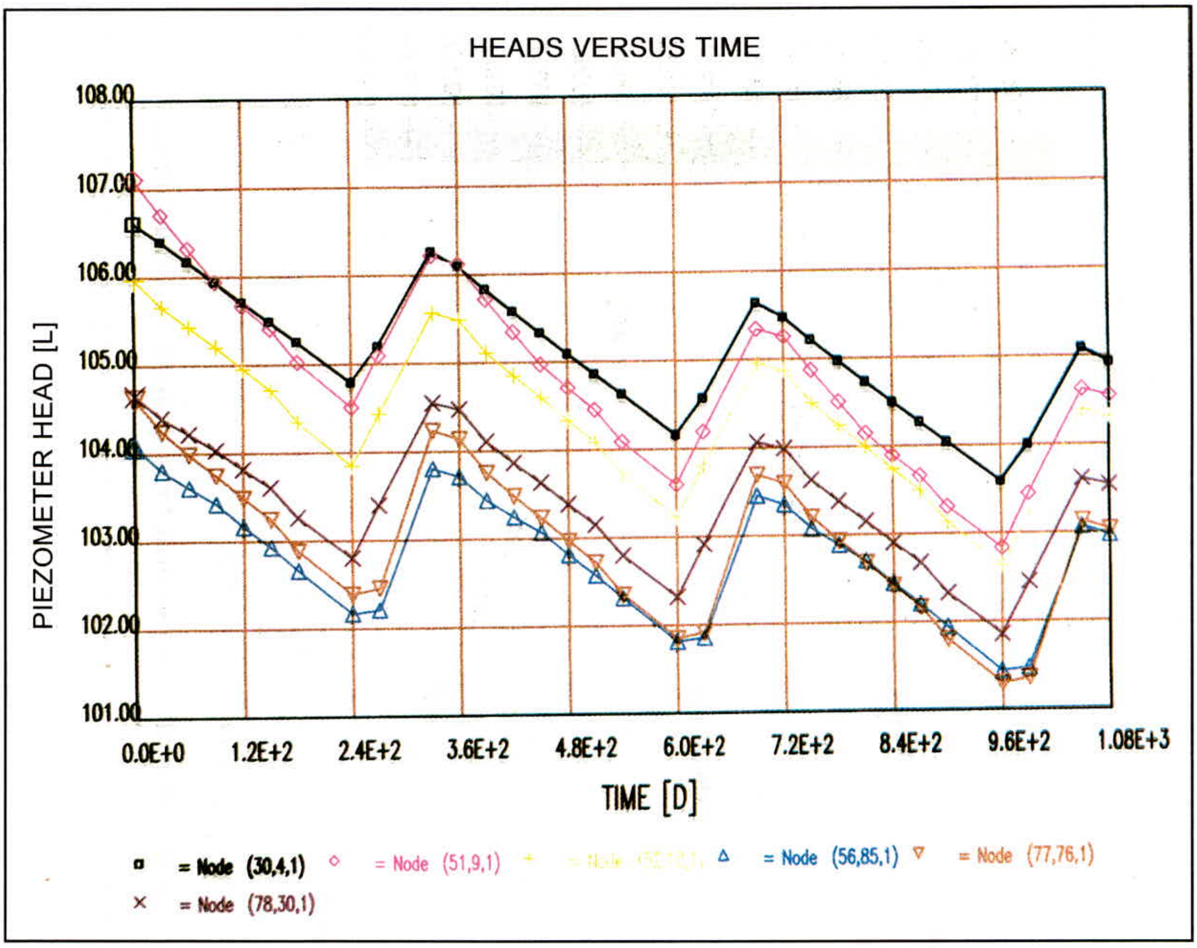
4.3 Option No. (iii) Installing battery of recharge wells around the Arsenic affected zones to create a hydraulic barrier.

The concept of introducing battery of recharge wells around the Arsenic affected zones is to create a hydraulic barrier between the non-affected and affected Arsenic zones. For doing this, spreading of Arsenic computed at the end of 5 years of simulation of transport was considered as the Arsenic affected zones for the six localized points. A series of recharge wells (considering



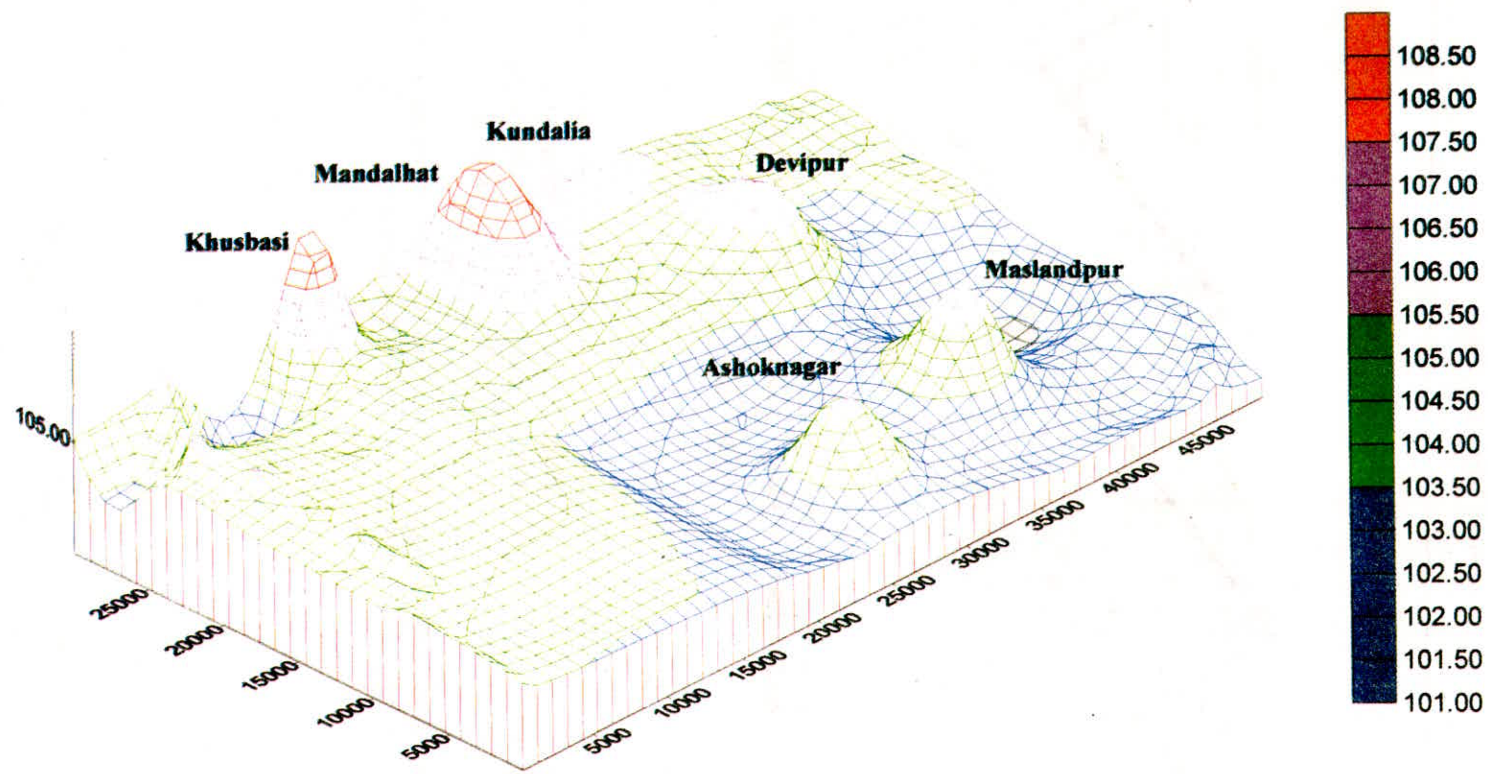
* 100 refers to the arbitrary datum above MSL

Figure 4.1 : Scenario of the flow domain at the end of three years simulation of flow with existing stresses.



Node [30,4]	:	Khusbasi,	Node [51,9]	:	Mandalhat
Node [52,18]	:	Kundalia,	Node [56,85]	:	Ashoknagar
Node [77,76]	:	Maslandpur,	Node [78,30]	:	Devipur

Figure 4.2 : Head vs. time plots of six localized points with continuance of existing stresses (Origin of time scale refers to September).



* 100 refers to the arbitrary datum above MSL

Figure 4.3 : Scenario of flow domain after defuncting withdrawal from Arsenic affected zones.

artificial injection of water to the groundwater) is considered to be in operation around the Arsenic affected zones from November to April i.e., till beginning of recharge period. The period of six months (November to April) of artificial injection was taken since Arsenic concentrations were mostly below detection limit during November, and concentration rises at the beginning of May (i.e. beginning of recharge period). The injection rate of the wells around the respective places was estimated in the following way:

$$Q_i = \frac{W_t}{T} \tag{8}$$

where Q_i is the total injection rate for the zone (m^3/day), W_t is the total withdrawal from the zone during November to April, and T is the time period between November to April , i.e., 180 days. The rate of injection of each well can be determined after fixing number of injection wells. In the present case, number of wells was estimated to be 30 having injection rate, for Mandalhat (1650 m^3/day), Kundalia (1650 m^3/day), Ashoknagar (1800 m^3/day), Maslandpur (1250 m^3/day), Devipur (1600 m^3/day), and Khusbasi (1650 m^3/day).

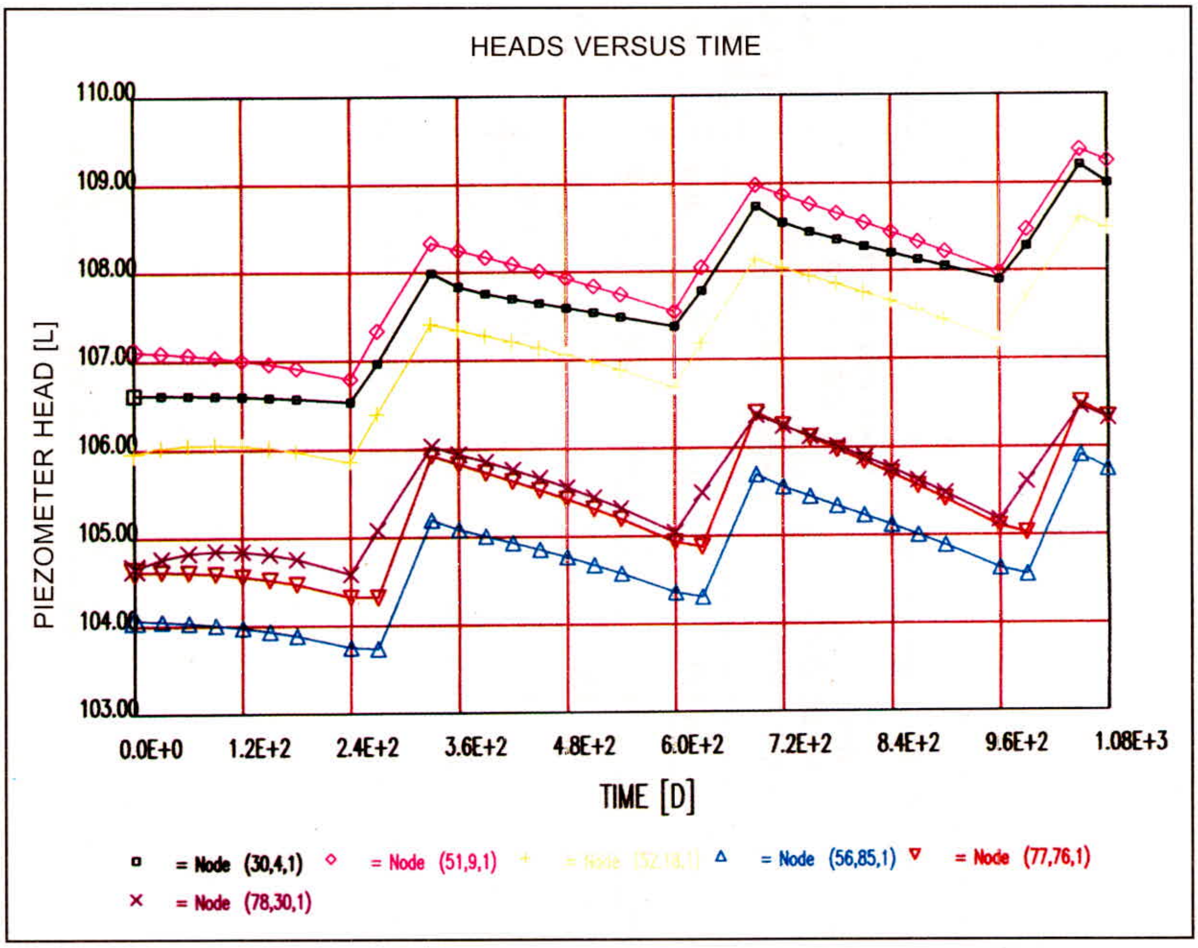
Keeping all other stresses unchanged including the stresses in Arsenic affected zones, the flow was simulated for 3 years under the transient condition. The scenario of the predicted water table at the end of 3 years is shown in Fig. 4.9. The graphical plot showing the effect on head over time for six localized pockets is given in Fig. 4.10, and Fig. 4.11 gives effect of injection wells at the interface. Although the hydraulic barrier as clear from Figure 4.1 shows a minimum improvement on water table at the nucleus of the source points -but- its anticipated effect can be appreciated at the interface (Fig. 4.11) where the barrier exists which is 1.5 km away from the source points.

Introduction of artificial recharge at the interface increases the head at the interface and forms a kind of heap (hydraulic barrier) from where the velocity gradient would be in the opposite directions - one directed towards the source points and the other outwards. The effect of this measure can be seen in Figures 4.9 and 4.11. It can be seen from Figure 4.11 that the water level of November is maintained up to April after which rainfall recharge starts. At the nucleus of the sources, the minimum water table improves in the subsequent years. It implies that the effect of this measure would ultimately *maintain the water table of November* (thus minimising oxidation/reduction process) on one side, and on the other side would *prohibit the spreading of Arsenic* from the localized pockets.

Comparison of different remedial measures analysed above is shown in Table 4.1. It is evident from Table 4.1 that Option No. (i) [Defunct of withdrawal from the Arsenic affected zones] shows *maximum improvement* of water table for all localized pockets -but- spreading of contaminated water (which already exists) remains unhindered. Option No. (ii) does not show intended effect. Option No. (iii) [Installation of battery of recharge wells around the source points] definitely proves to be effective in terms of *maintaining the water table* and *spreading of contaminated water* from the localized pockets. The elevations of water table speculated to control the chemical activation in these locations are: *6.25 m for Khusbasi; 6.00m for Mandalhat; 5.50 for Kundalia; 3.60 m for Ashoknagar; 4.00 m for Maslandpur and 4.25 m for Devipur above MSL.*

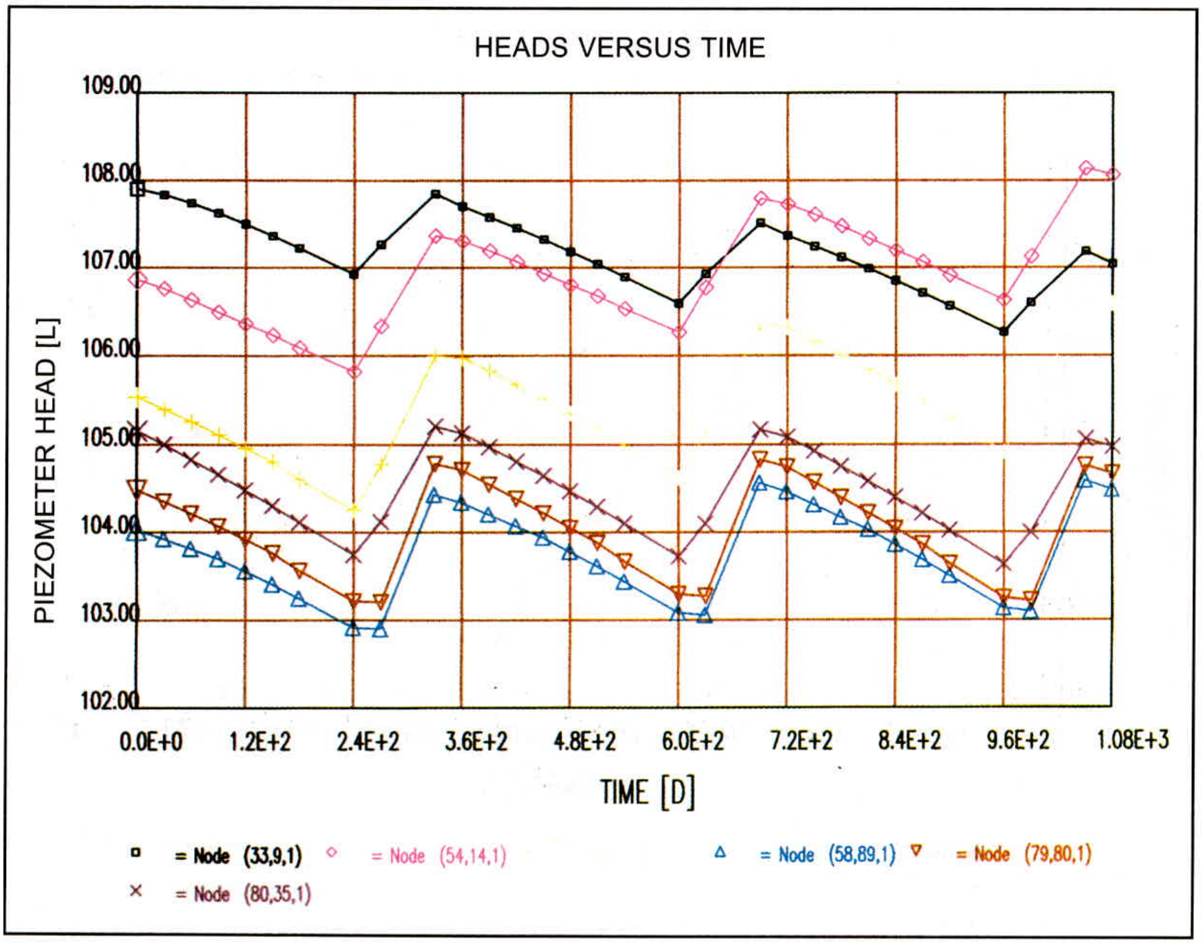
Table 4.1: **Comparison of performance of different remedial options.**

Location	Observed water table		Computed water table		Defuncting withdrawal (Min. level)	% Reduction of withdrawal (Min. level)			Recharge wells (Min. level)
	November	Minimum	November	Minimum		10%	20%	30%	
Khusbasi	6.515	4.815	6.200	4.800	6.500	5.000	5.150	5.400	5.000
Mandalhat	5.425	3.895	6.300	4.600	6.800	4.800	5.000	5.350	4.800
Kundalia	5.560	4.490	5.400	3.850	5.850	4.150	4.400	4.500	4.500
Ashoknagar	3.560	2.030	3.700	2.150	3.700	2.300	2.600	2.800	2.750
Maslandpur	4.105	2.555	4.000	2.400	4.350	2.600	2.800	3.100	2.850
Devipur	4.255	2.385	4.250	2.850	4.500	3.000	3.300	3.500	3.500



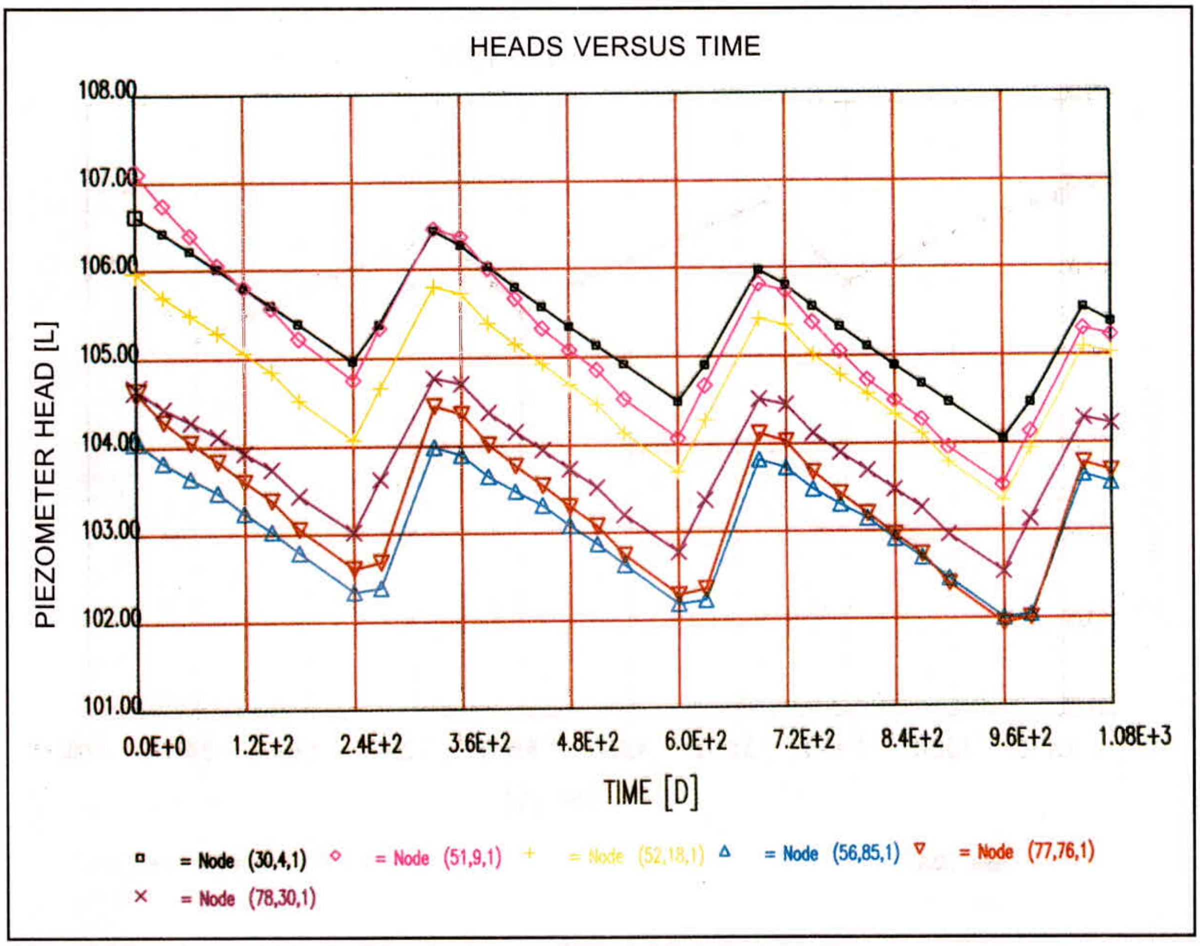
Node [30,4]	:	Khusbasi,	Node [51,9]	:	Mandalhat
Node [52,18]	:	Kundalia,	Node [56,85]	:	Ashoknagar
Node [77,76]	:	Maslandpur,	Node [78,30]	:	Devipur

Figure 4.4 : **Head vs. time plots of six localized points after defuncting withdrawal from Arsenic affected zones (Origin of time scale refers to September).**



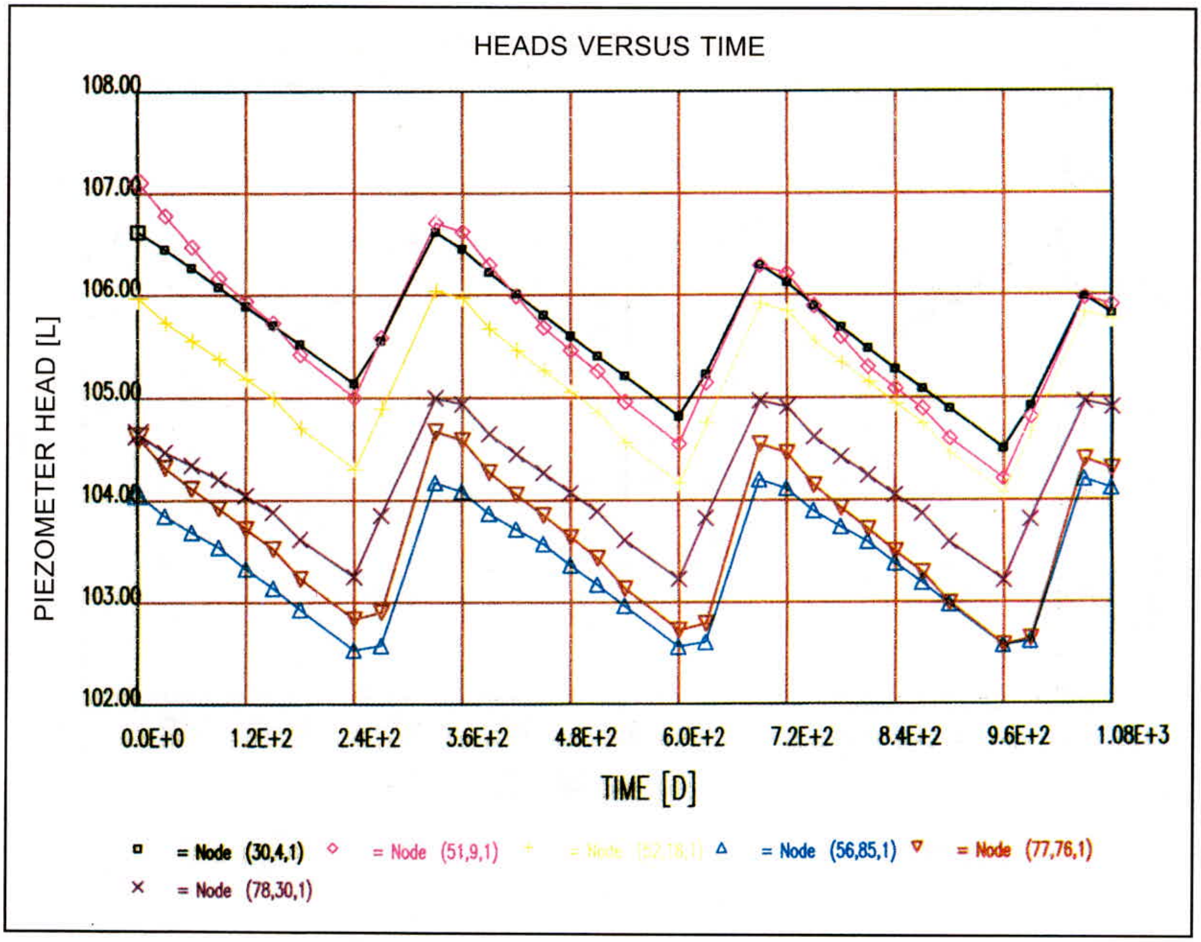
Node [30,4]	:	Khusbasi,	Node [51,9]	:	Mandalhat
Node [52,18]	:	Kundalia,	Node [56,85]	:	Ashoknagar
Node [77,76]	:	Maslandpur,	Node [78,30]	:	Devipur

Figure 4.5 : Head vs. time plots of six localized points at the interface of defunct and non-defunct zones (Origin of time scale refers to September).



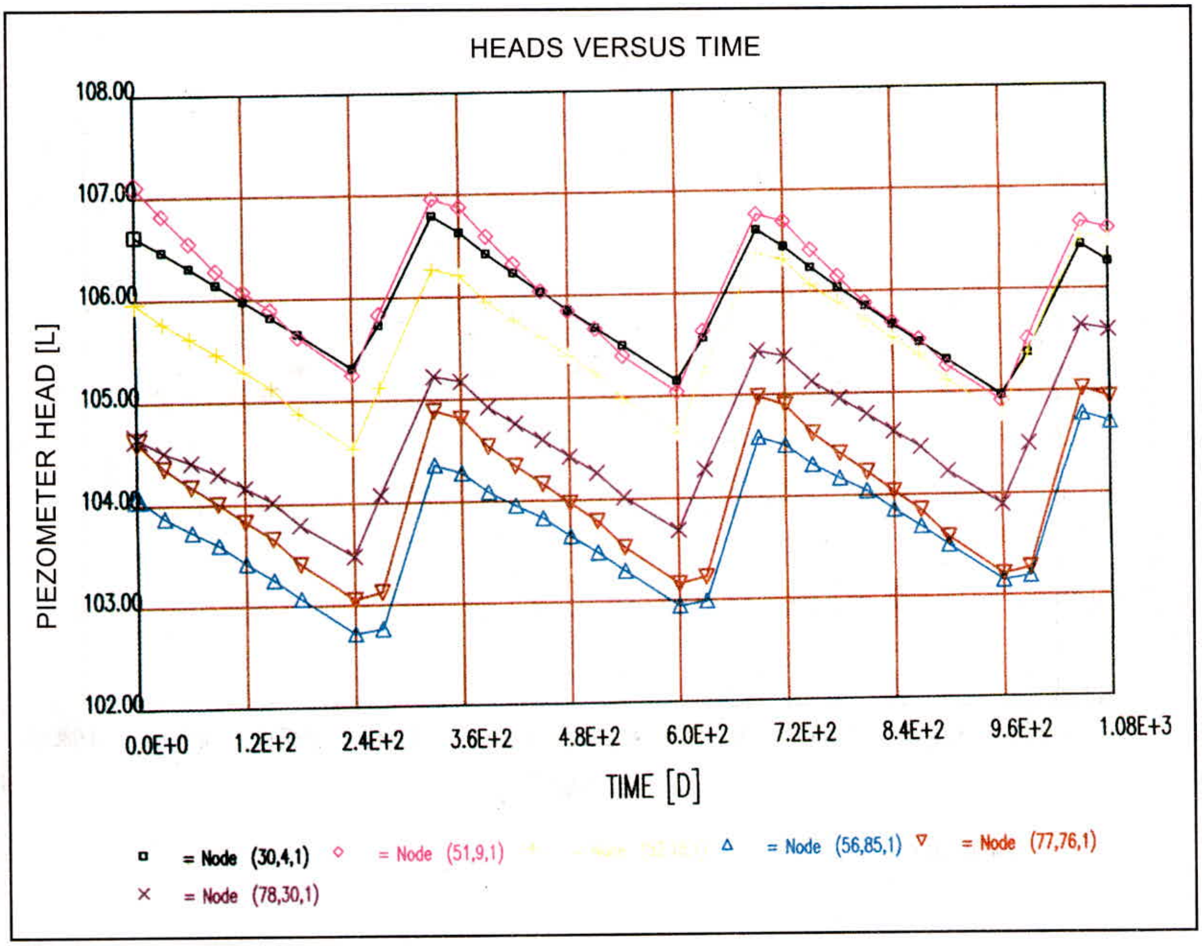
Node [30,4]	:	Khusbasi,	Node [51,9]	:	Mandalhat
Node [52,18]	:	Kundalia,	Node [56,85]	:	Ashoknagar
Node [77,76]	:	Maslandpur,	Node [78,30]	:	Devipur

Figure 4.6 : Head vs. time plots of six localized points reducing 10% of withdrawl from the whole domain (Origin of time scale refers to September).



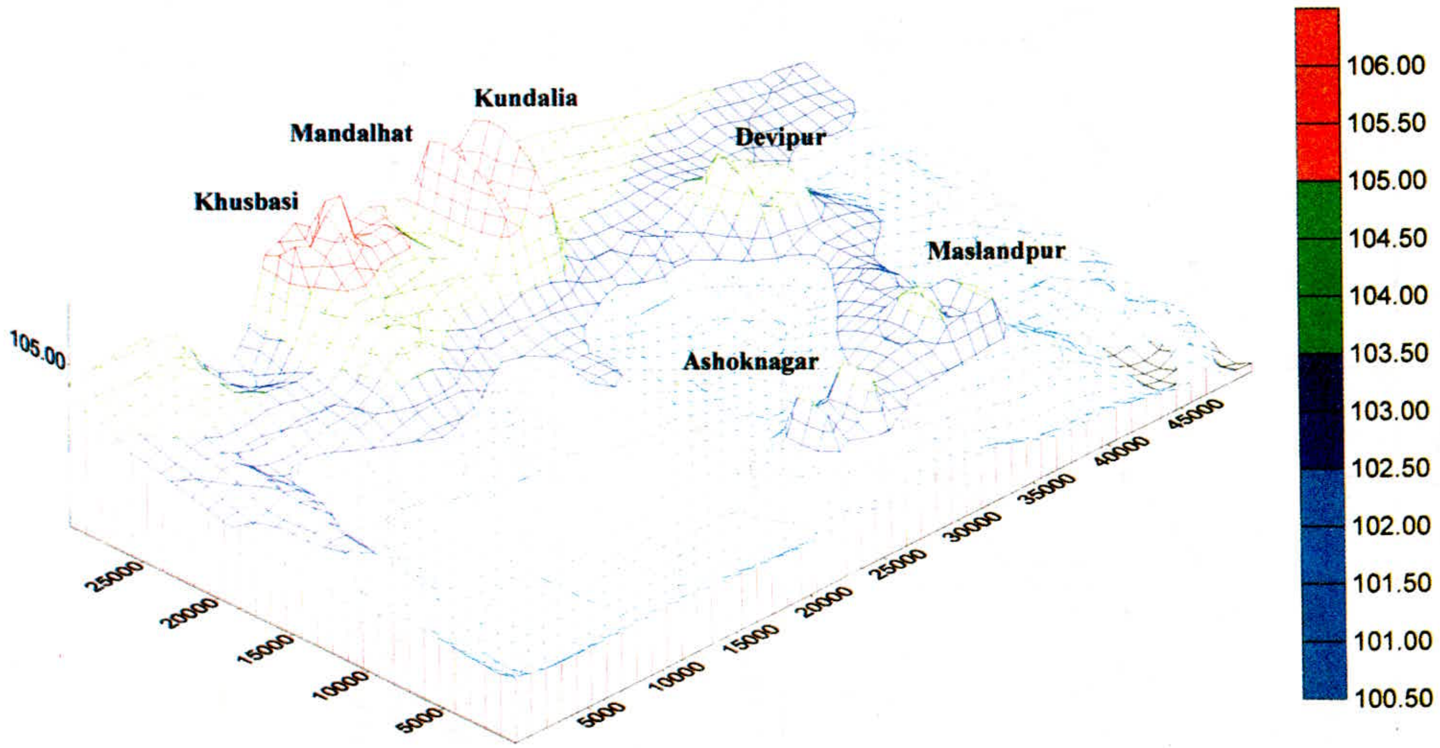
Node [30,4]	:	Khusbasi,	Node [51,9]	:	Mandalhat
Node [52,18]	:	Kundalia,	Node [56,85]	:	Ashoknagar
Node [77,76]	:	Maslandpur,	Node [78,30]	:	Devipur

Figure 4.7 : Head vs. time plots of six localized points reducing 20% of withdrawl from the whole domain (Origin of time scale refers to September).



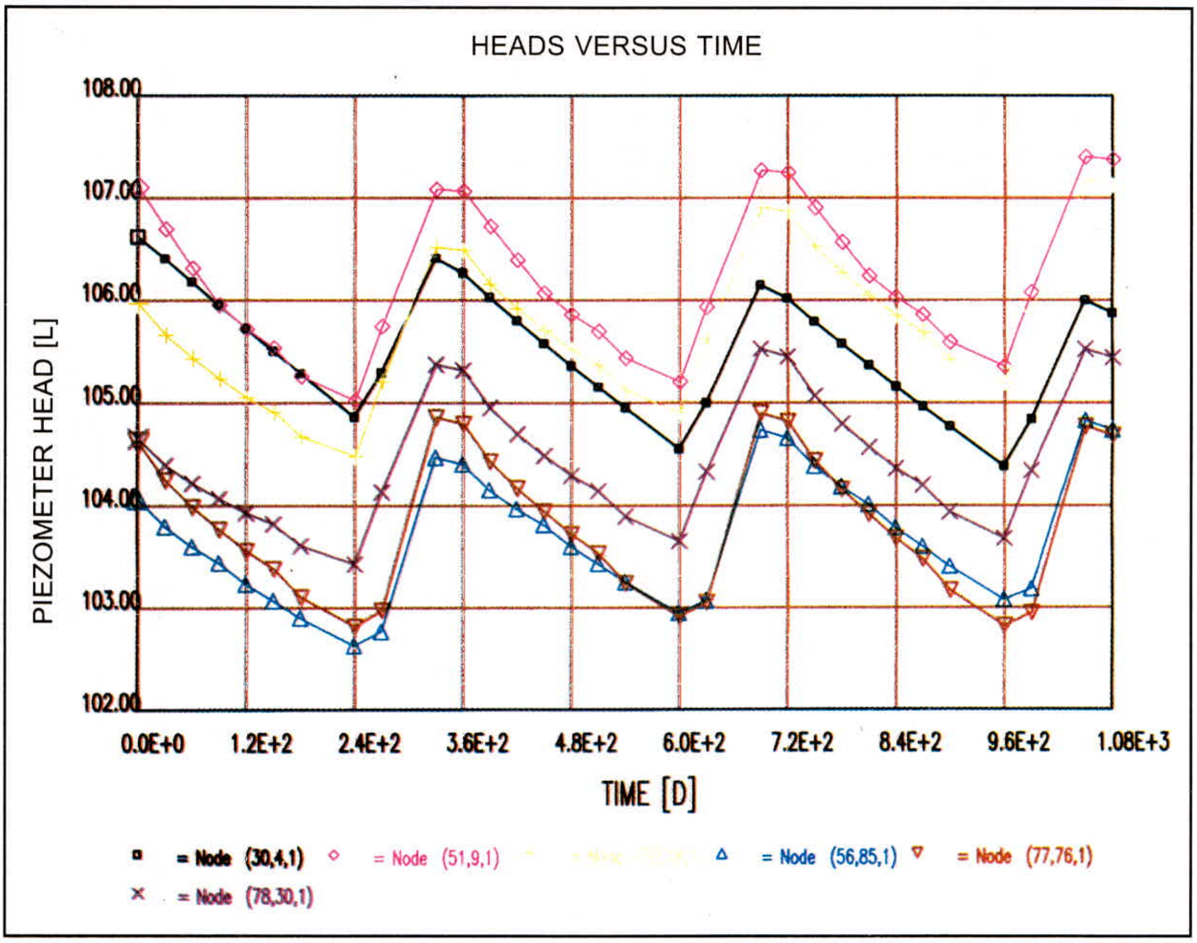
Node [30,4]	:	Khusbasi,	Node [51,9]	:	Mandalhat
Node [52,18]	:	Kundalia,	Node [56,85]	:	Ashoknagar
Node [77,76]	:	Maslandpur,	Node [78,30]	:	Devipur

Figure 4.7 : Head vs. time plots of six localized points reducing 30% of withdrawl from the whole domain (Origin of time scale refers to September).



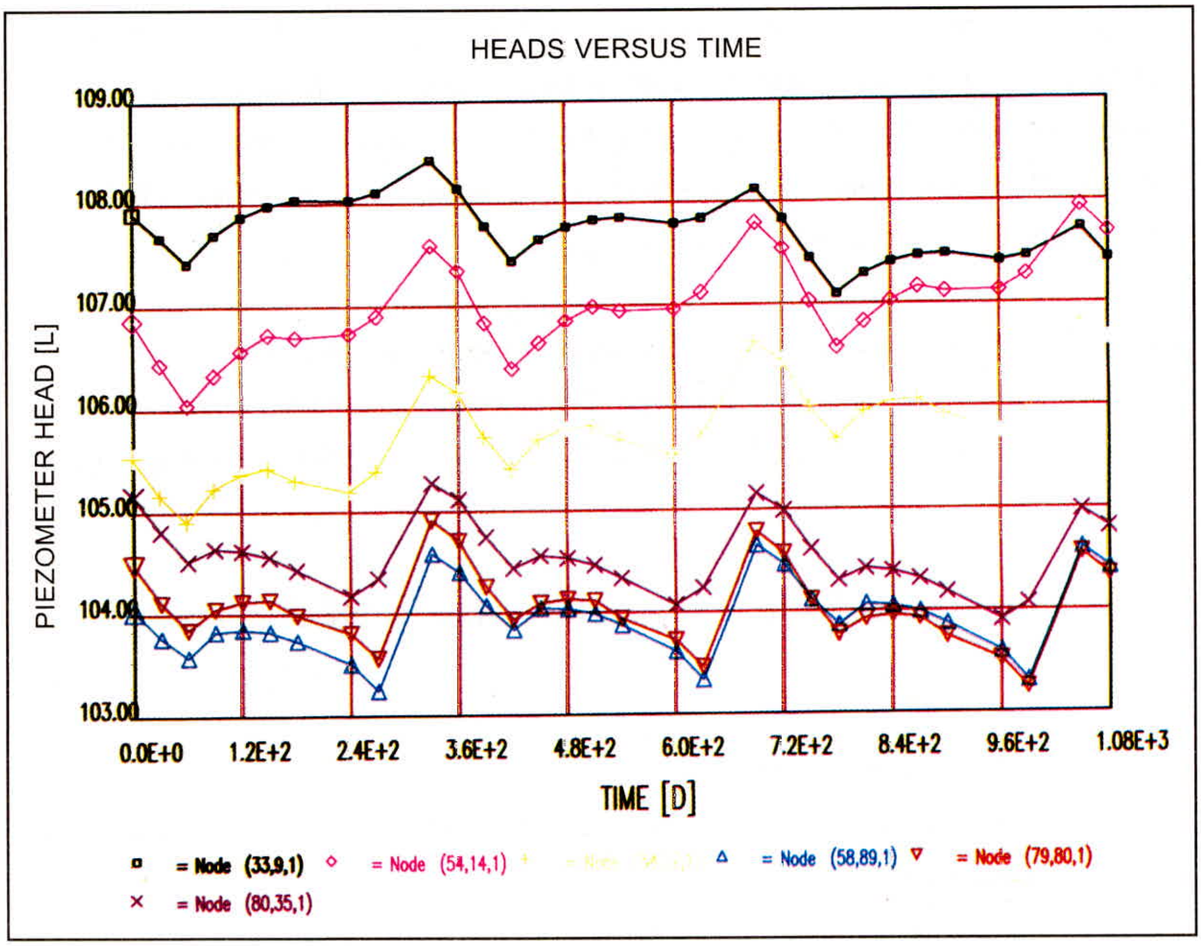
* 100 refers to the arbitrary datum above MSL

Figure 4.9 : Scenario flow domain consequence to the installation of recharge wells around Arsenic affected zones.



Node [30,4]	:	Khusbasi,	Node [51,9]	:	Mandalhat
Node [52,18]	:	Kundalia,	Node [56,85]	:	Ashoknagar
Node [77,76]	:	Maslandpur,	Node [78,30]	:	Devipur

Figure 4.10 : Head vs. time plots of six localized points with influence of recharge wells (Origin of time scale refers to September).



Node [30,4]	:	Khusbasi,	Node [51,9]	:	Mandalhat
Node [52,18]	:	Kundalia,	Node [56,85]	:	Ashoknagar
Node [77,76]	:	Maslandpur,	Node [78,30]	:	Devipur

Figure 4.11 : Head vs. time plots of six localized points at the interface of recharge wells (Origin of time scale refers to September).

5.0 CONCLUSIONS

The groundwater flow and transport of Arsenic in Yamuna sub-basin, Nadia and North 24-Parganas district of West Bengal have been analysed considering a three-dimensional system using MODFLOW for flow modelling and MT3D for transport modelling. Some possible remedial measures have also been analysed. From the analysis of flow and transport phenomena and remedial measures following inferences are drawn:

i. Flow model of the area has been developed. Zones of equal hydraulic conductivity and specific storage have been demarcated. The calibrated and validated model can be used to find the response of flow domain for any stress conditions including remedial measures.

ii. Prevailing scenario of recharge and withdrawal rate of the study area have been assessed.

iii. Prediction of heads beyond May 1998 were based on the scenario prevailing in year 1997-'98, i.e., based on one year data. Predicted heads need verification from measurement of water table data.

iv. A transport model considering the combined effect of advection and dispersion has been developed. The model requires verification of its performance after incorporating chemical reaction components, such as: adsorption, retardation and decay, which are crucial for Arsenic transport study.

v. Analysis of transport processes clearly indicate that presence of Arsenic concentration in the flow domain of the Yamuna sub-basin has no bearing with the influence of contaminants from external boundary sources or from other domain. Even occurrence of Arsenic in different pockets of this domain are also not due to the transport of Arsenic from one place to another, but these are due to the activation and spreading of in-situ source(s).

vi. Activation and de-activation processes of Arsenic in the flow domain, which perhaps physically represent the oxidation and reduction processes of Arsenic introduction in the groundwater system, have been established.

vii. From the analysis of Arsenic concentration data and studying the transport phenomena, it is suspected that Ashoknagar, Khusbasi, Mandalhat, Kundalia, Devipur and Maslandpur may have the localised in-situ source(s) material of Arsenic in and around and not necessarily at the places where measurements were taken.

viii. The spreading in the localised area is due to the transport of contaminants from the nearby in-situ source point(s).

ix. The cause of activation of Arsenic in the groundwater is suspected to be due to the oxidation of source material because of falling water table and dissolution/reduction during rising water table. This explanation needs validation by further geo-chemical analysis of the localised pockets.

x. The points of maximum concentration of Arsenic and the contour of minimum value of transmissivity coincide. The minimum transmissivity occurs where clay pockets exist. Eventually this signifies that clay pockets/lenses have the tendency to entrap the Arsenic. In these pockets further geological investigation needs to be carried out to identify the source of Arsenic.

xi. The analysis of hydrograph data (1987-1996) of some observation stations in the study area revealed that water table in the study domain had declined to its minimum level (3 to 4 metre below average) during the months of April-May in 1993 and 1995. Linking the processes of oxidation-reduction of Arsenic with the fluctuation of water table, three cases namely: i) defuncting withdrawal from the Arsenic affected area; ii) creating hydraulic barriers (in the form of battery of injection wells) around the Arsenic spreaded area; and iii) reducing withdrawal pattern from the study domain, have been analysed as remedial measures to arrest spreading.

xii. Analysis of remedial measures indicate that arrest of lowering of water table particularly during peak withdrawal months (November to April) below certain level would minimize the oxidation/reduction processes of Arsenic in the flow domain. For the

Yamuna sub-basin, in general, the water table of November 1997 was found to be the safe level of groundwater. The safe groundwater table for six localized pockets would be: 6.00 m for Mandalhat (Chakdah block), 6.25 m for Khusbasi (Chakdah block), 5.50 m for Kundalia (Chakdah block), 4.25 m for Devipur (Gaighata block), 4.00 m for Maslandpur (Swarupnagar), and 3.60 m for Ashoknagar (Habra I block) above MSL. To arrest the spreading of contaminated groundwater, creation of artificial hydraulic barrier by injection of recharge wells seemed to be a reliable option.

xiii. It was felt that detailed investigation at micro level can give better understanding of Arsenic mobilisation including understanding of geo-chemical processes in the flow domain rather than analysis and investigation in a large domain.

REFERENCES

1. McDonald, M.G., and A.W. Harbaugh, (1988), A modular three dimensional finite difference groundwater flow model – Techniques of Water Resources Investigations of the United States Geological Survey, Book. 6, Chap. A1, U.S. Geological Survey.

2. Zheng, Chunmiao, (1992), MT3D, Amodular three dimensional transport model, version 1.5: Documention and User's Guide, S.S. Paradopulos & Associates, Inc., Marryland.

APPENDICES

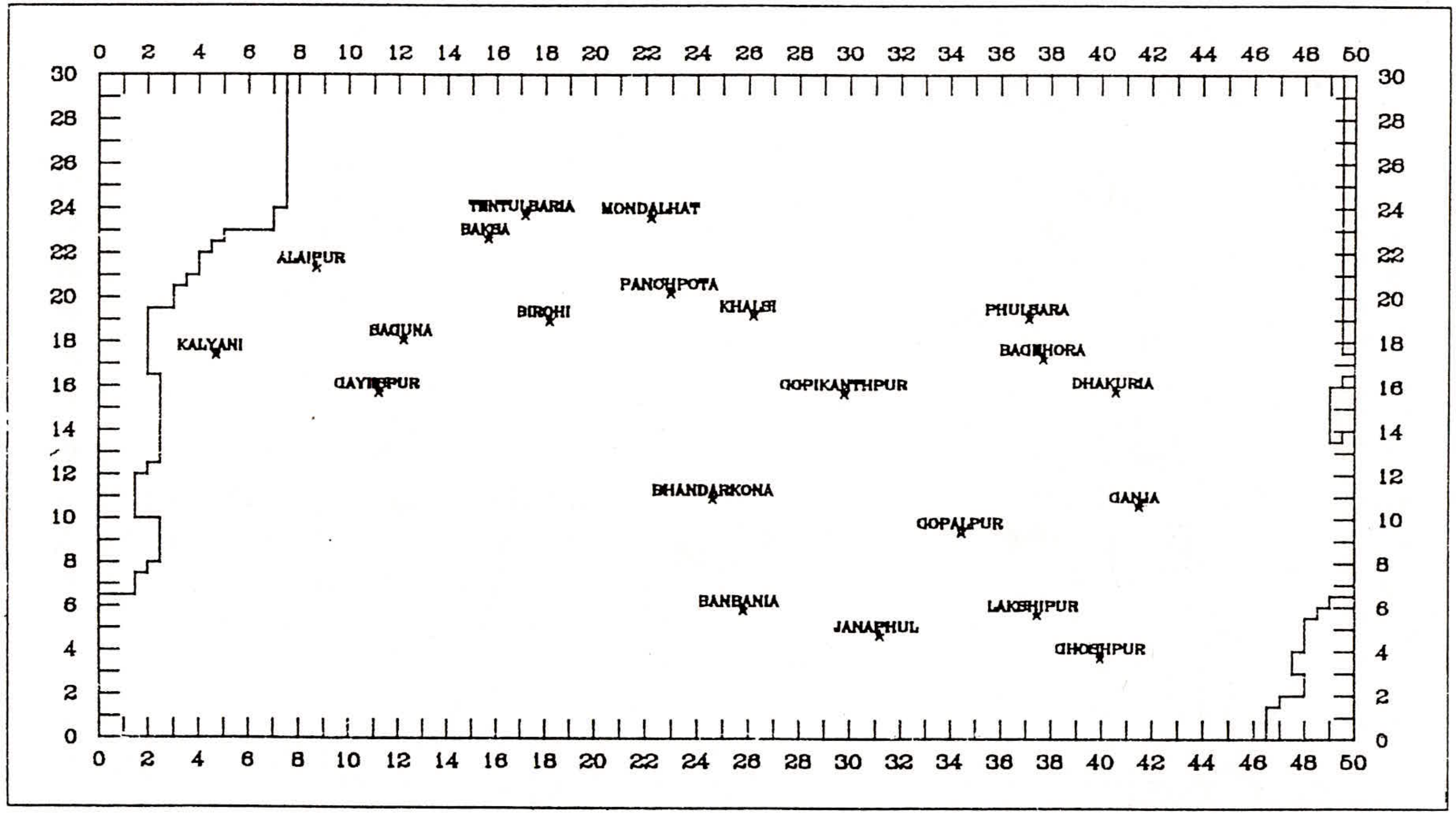


Figure A.1(a): Locations of Transmissivity values.

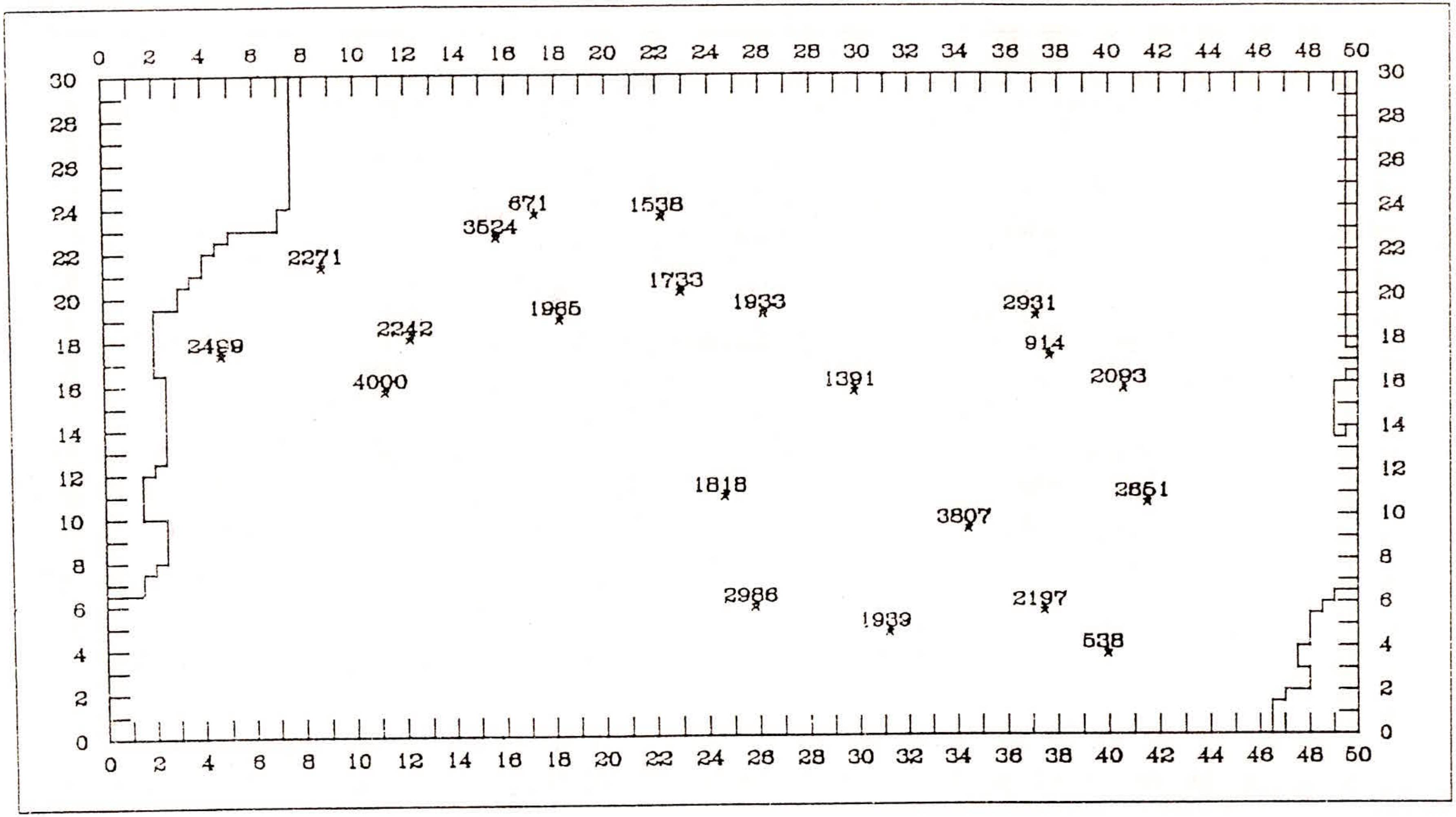


Figure A.1(b): Measured Transmissivity values (m /day).

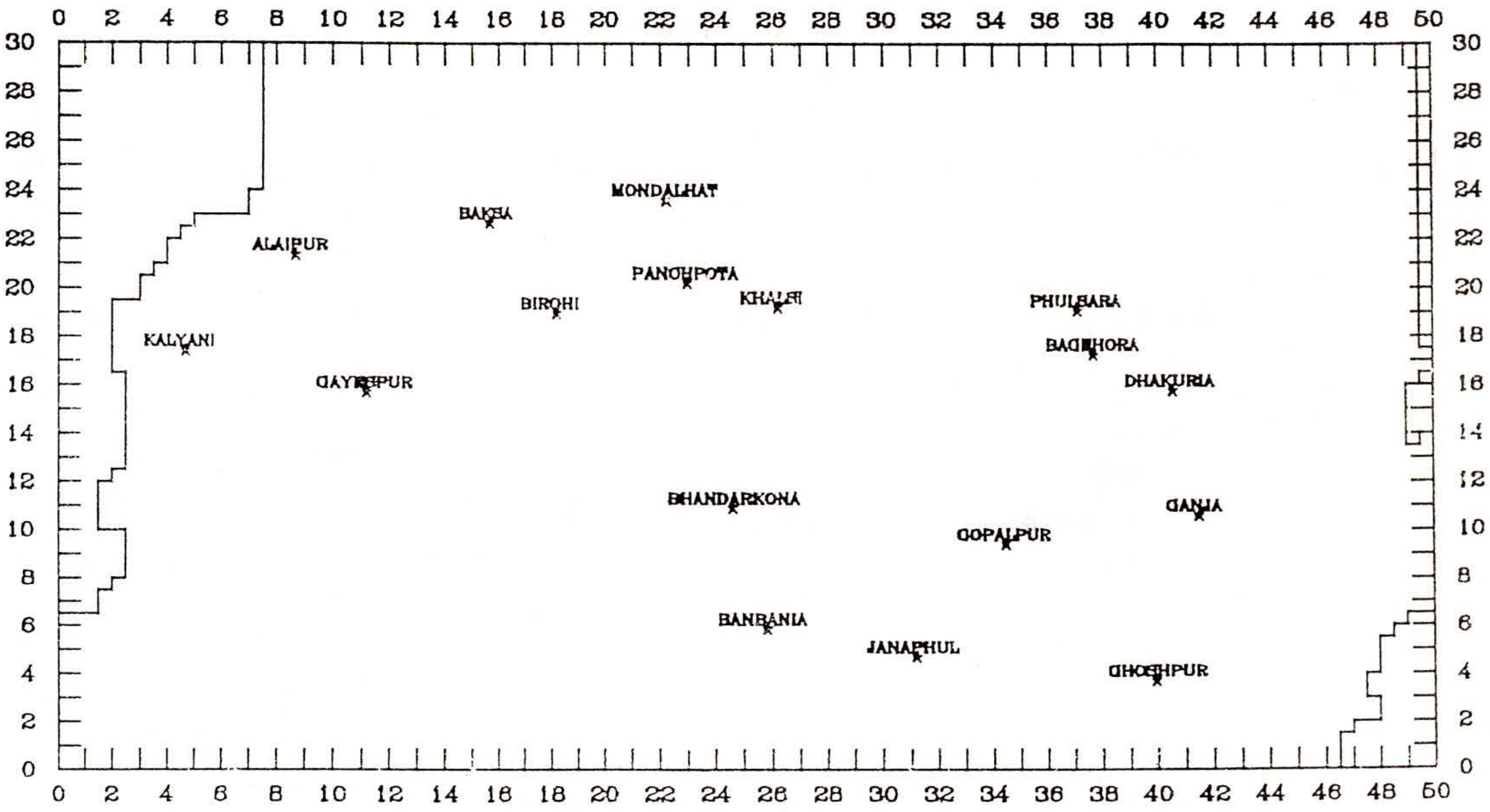


Figure A.2(a): Locations of Storativity values.

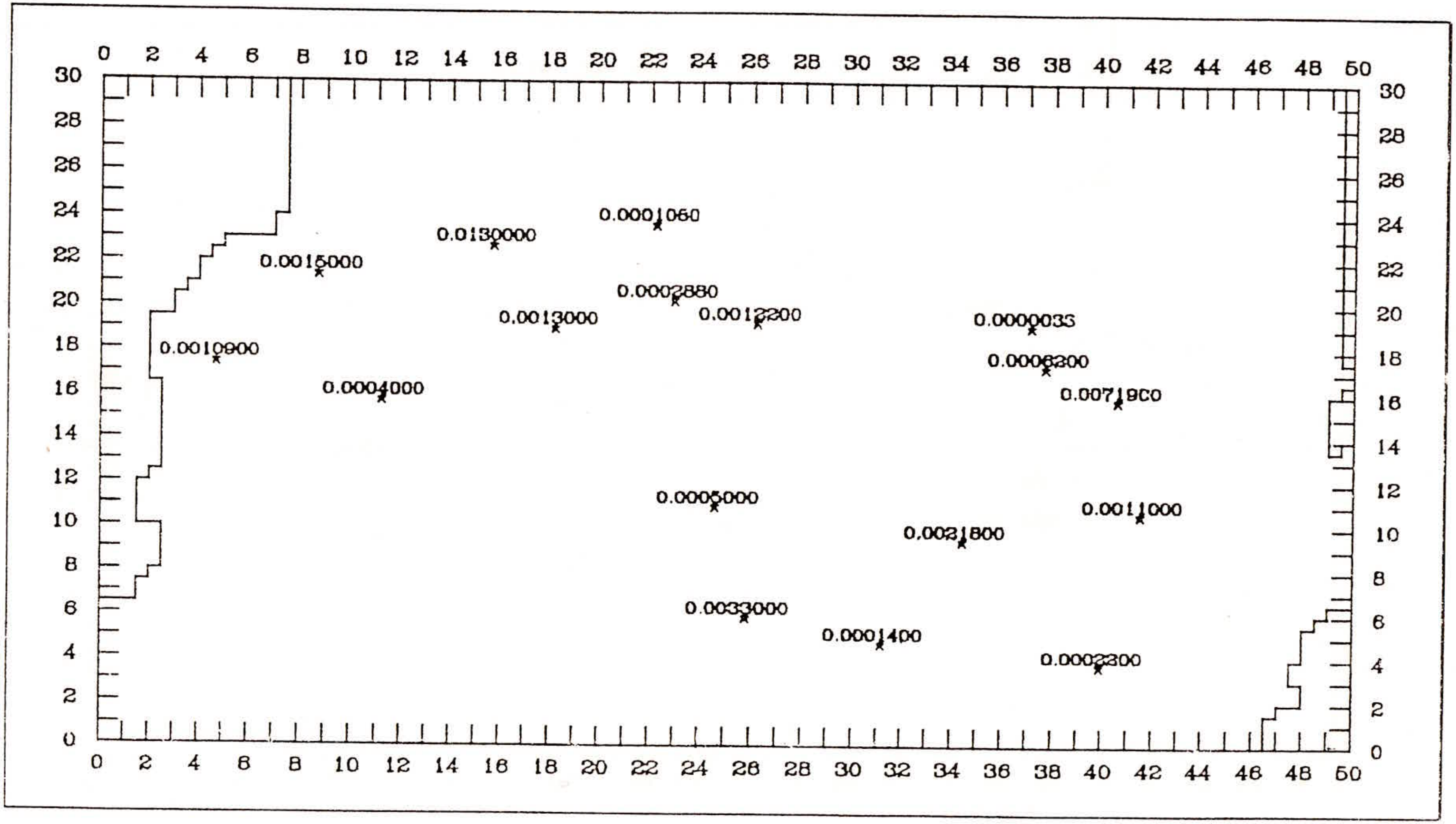


Figure A.2(b): Measured Storativity values.

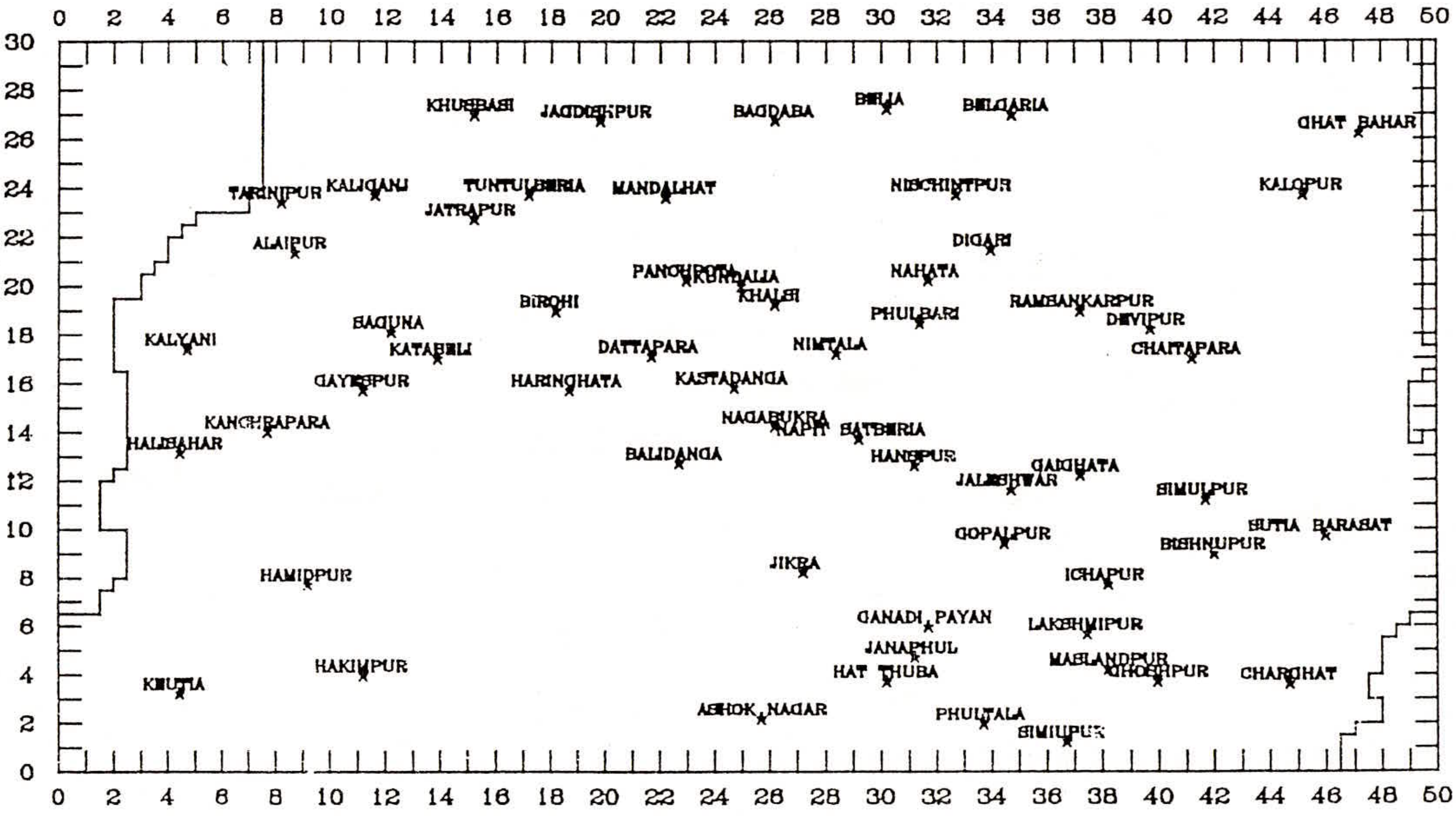


Figure A.3: Location of observation wells in the study area.

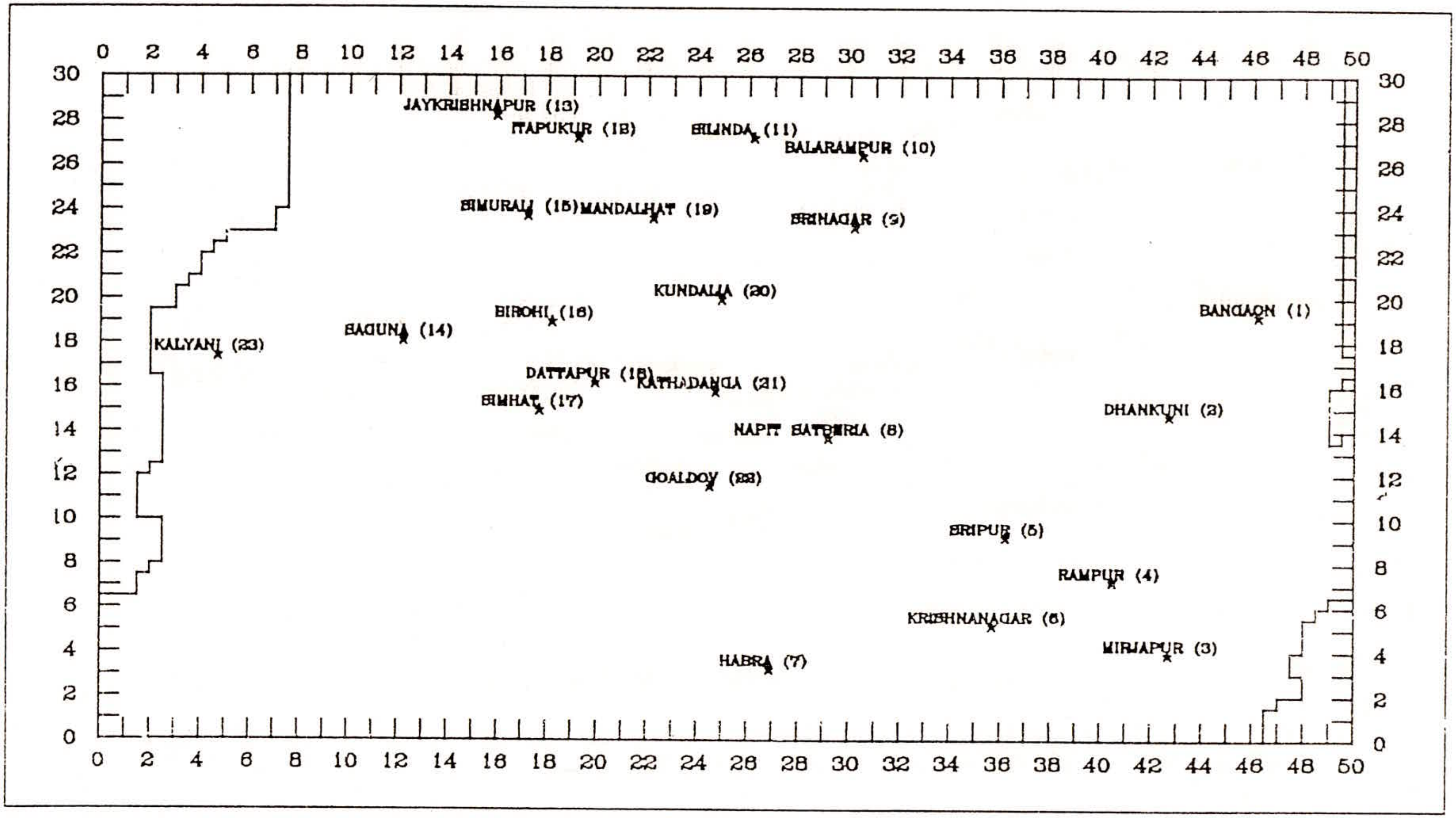


Figure 2: Location of Litholog Points in the Study Area.

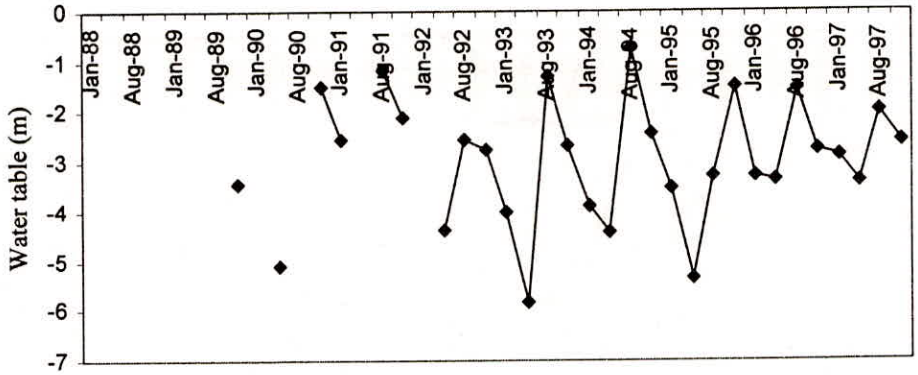


Figure -A.5: Time series plot of water table (b.g.l) at Ashoknagar (Habra-I block)

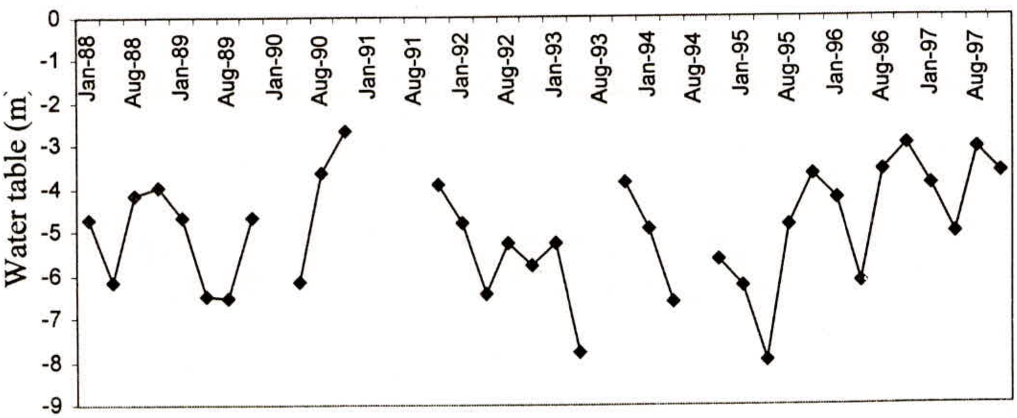


Figure -A.6: Time series plot of water table (b.g.l) near Khusbasi (Chakdah block)

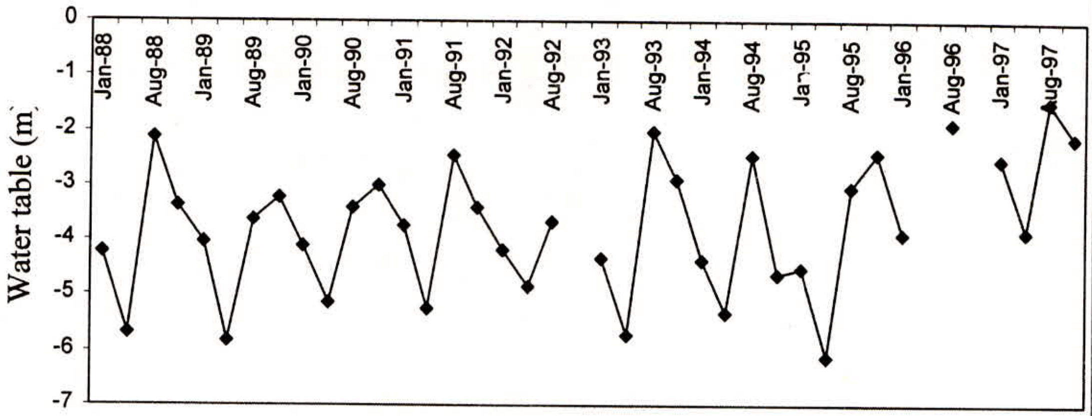


Figure - A.7: Time series of water table (b.g.l) at Maslandpur (Swarupnagar block)

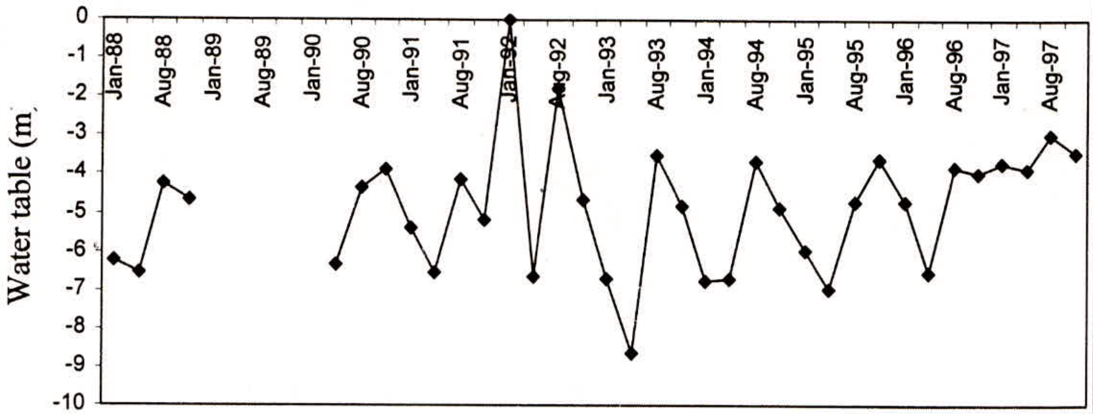


Figure - A.8: Time series of water table (b.g.l) at Gaighata

Table - A.1 : Month-wise observed water level data.

SL	LOCATION	DEPTH	RL OF GL	WL04 97	WL06 97	WL08 97	WL09 97	WL10 97	WL11 97	WL12 97	WL01 98	WL02 98	WL03 98	WL05 98
1	KALIGANG	122.50	8.820	7.830	7.970	5.500	5.580	5.690	6.200	6.430	6.650	6.760	6.850	7.630
2	TARINIPUR	21.34	8.345	3.390	3.520	1.900	1.990	2.250	2.400	2.590	2.720	2.890	2.990	3.030
3	ALAIPUR	24.38	8.945	5.070	5.290	3.750	3.890	4.330	4.690	4.790	4.990	5.050	5.380	5.990
4	JATRAPUR	13.71	9.250	1.820	2.250	0.770	0.900	1.050	1.250	1.380	1.150	1.620	2.350	2.870
5	HARINGHATA	15.24	7.255	4.840	4.930	3.400	3.620	4.010	4.080	4.010	4.390	4.490	4.920	5.370
6	DATTAPARA	15.24	6.430	3.930	4.120	1.280	1.350	1.630	1.700	1.890	2.050	2.230	2.790	3.820
7	KALAYANI	28.95	7.430	3.150	3.350	3.580	2.700	2.810	2.900	2.990	3.180	3.250	3.950	3.990
8	KANCHRAPARA	18.28	7.820	3.980	4.190	3.480	3.600	3.850	3.980	4.070	4.180	4.260	4.790	5.020
9	GAYESHPUR	15.24	7.460	2.620	3.230	2.500	2.620	2.710	2.800	2.870	2.970	3.070	3.990	4.020
10	KATABELI	18.28	6.800	2.160	2.480	1.500	1.680	0.770	0.870	1.050	1.290	1.450	2.090	3.000
11	SAGUNA	18.28	7.655	3.970	4.280	3.520	3.630	3.740	3.800	3.880	3.990	4.060	4.780	4.910
12	BIROHI	21.33	8.460	4.480	4.650	3.600	3.700	3.850	3.950	4.120	4.240	4.360	5.280	5.500
13	HALISAHAR	106.68	7.025	10.740	10.890	6.360	6.480	6.890	6.950	7.150	7.320	7.400	7.550	7.910
14	TUNTULBERIA	36.57	9.475	7.400	7.610	2.630	2.750	3.010	3.230	3.420	3.630	3.850	4.670	5.620
15	MANDALHAT	18.28	8.675	4.160	4.330	1.640	1.740	2.900	3.250	3.390	3.490	3.580	4.180	4.780
16	PANCHPOTA	30.48	8.210	3.020	3.190	1.790	1.890	2.250	2.300	2.480	2.650	2.780	3.780	4.150

SL	LOCATION	DEPTH	RL OF GL	WL04 97	WL06 97	WL08 97	WL09 97	WL10 97	WL11 97	WL12 97	WL01 98	WL02 98	WL03 98	WL05 98
17	KUNDALIA	21.33	7.920	3.520	3.750	1.820	1.980	2.250	2.360	2.510	2.720	2.920	3.290	3.430
18	KHALSI	21.33	7.235	4.050	4.280	2.140	2.250	2.360	2.410	2.530	2.620	2.760	3.790	4.020
19	NIMTALA	12.19	6.345	2.400	2.520	1.870	1.990	2.100	2.160	2.250	2.390	2.150	3.250	3.390
20	PHULBARI	21.33	6.880	3.070	3.280	2.540	2.620	2.740	2.890	3.010	3.140	3.230	4.290	4.630
21	DIGARI	66.00	7.240	3.550	3.750	1.470	1.580	1.780	1.850	1.980	2.100	2.290	3.850	4.010
22	NISCHINTPUR	24.38	8.025	3.450	3.610	1.870	1.650	1.910	1.990	2.120	2.280	2.410	3.210	3.620
23	NAPIT SATBERIA	21.33	6.710	3.850	3.990	2.940	3.060	3.260	3.300	3.410	3.520	3.640	4.180	4.220
24	HANSPUR	18.28	6.565	5.500	5.690	3.350	3.550	3.910	3.990	4.140	4.420	4.600	5.100	5.430
25	NAGABUKRA	18.28	6.420	4.320	4.520	2.130	2.330	2.490	2.550	2.710	2.890	2.980	3.780	4.020
26	BALIDANGA	12.19	6.600	4.020	4.210	1.120	1.320	1.520	1.900	2.100	2.300	2.550	3.120	3.690
27	KASTADANGA	36.57	7.105	5.800	5.930	3.640	3.850	4.100	4.280	4.450	4.580	4.720	4.990	5.700
28	ASHOK NAGAR	51.00	6.240	3.500	4.100	2.100	2.150	2.510	2.680	2.810	2.990	3.210	4.000	4.210
29	HAT THUBA	40.00	7.240	5.950	4.380	1.830	1.960	2.350	2.590	2.760	2.910	3.150	4.000	5.020
30	JANAPHUL	33.52	7.000	3.900	4.620	1.350	1.420	1.620	1.870	1.990	2.130	2.310	3.350	3.890
31	LAKSHMIPUR	30.48	5.960	3.420	4.050	1.080	1.180	1.380	1.420	1.630	1.850	1.990	2.780	3.390
32	MASLANDAPUR	30.00	6.225	3.850	4.170	1.450	1.620	1.920	2.120	2.310	2.520	2.730	3.190	3.670
33	GHOSHPUR	15.00	5.370	2.150	2.650	0.500	0.820	1.050	1.150	1.310	1.540	1.720	2.650	2.780

SL	LOCATION	DEPTH	RL OF GL	WL04 97	WL06 97	WL08 97	WL09 97	WL10 97	WL11 97	WL12 97	WL01 98	WL02 98	WL03 98	WL05 98
34	CHARGHAT	165.00	4.920	3.900	4.300	2.390	2.480	2.750	2.990	3.140	3.300	3.420	4.510	4.610
35	ICHAPUR	30.00	5.770	2.400	3.100	0.200	0.300	0.770	0.990	1.230	1.410	1.620	2.530	2.820
36	BISHNUPUR	52.00	4.865	2.950	3.600	0.990	1.150	1.650	1.780	1.920	2.100	2.310	3.320	3.610
37	SUTIA BARASAT	50.00	4.300	3.250	3.380	0.690	0.820	1.310	1.430	1.510	1.740	1.860	2.550	3.020
38	JAGULI		6.495											
39	GANADI PAYAN	50.00	6.385	2.700	3.150	0.950	1.200	1.620	1.750	1.900	2.090	2.290	3.210	3.450
40	JIKRA	66.00	6.100	5.340	5.950	2.610	2.720	2.910	3.100	3.290	3.430	3.610	4.590	4.970
41	GOPALPUR	65.00	6.035	3.160	3.700	0.990	1.120	1.310	1.500	1.770	1.980	2.170	2.970	3.260
42	JALESWAR	35.00	6.090	3.000	3.500	2.550	2.780	2.910	2.050	3.210	3.350	3.470	4.280	4.620
43	GAIGHATA	50.00	6.430	2.950	3.300	2.070	2.190	2.430	2.510	2.640	2.510	2.890	3.920	4.020
44	DEVIPUR	70.00	5.435	3.150	3.200	0.890	0.950	1.050	1.180	1.380	1.540	1.770	2.670	3.050
45	CHAITAPARA	33.00	5.980	1.800	1.450	0.490	0.650	1.150	1.240	1.360	1.510	1.690	2.590	2.910
46	RAMSANKARPUR	40.00	6.845	2.900	3.180	0.200	0.400	0.920	1.020	1.240	1.470	1.700	2.900	2.970
47	NAHATA	90.00	6.530	2.850	3.300	1.060	1.350	1.620	1.900	2.100	2.420	2.640	3.520	6.710
48	SIMULPUR	30.00	5.235	5.650	5.800	2.150	2.250	2.510	2.680	2.820	2.970	3.150	4.050	4.650
49	JAGADISHPUR	21.33	10.380				2.380	2.610	2.750	2.890	3.040	3.160	3.990	4.670
50	BAGDABA	24.38	10.455				3.100	3.290	3.400	3.520	3.670	3.810	4.280	4.320

SL	LOCATION	DEPTH	RL OF GL	WL04 97	WL06 97	WL08 97	WL09 97	WL10 97	WL11 97	WL12 97	WL01 98	WL02 98	WL03 98	WL05 98
51	BELGARIA	24.38	8.520				2.950	3.160	3.380	3.510	3.720	3.890	4.340	4.650
52	PURBA BISHNUPUR	15.24	11.315				2.550	2.920	3.020	3.250	3.480	3.620	4.210	4.570
53	BELIA	21.33	9.270				3.050	3.510	3.620	3.780	3.910	4.060	4.810	5.020
54	NUTAN SILINDA	15.24	11.045				2.780	3.150	3.310	3.490	3.700	3.860	4.700	4.820
55	KHUSBASI	24.38	10.465				2.890	3.050	3.950	4.210	4.490	4.600	5.010	5.650
56	MASRA	45.72	10.745				3.190	3.650	3.850	4.120	4.390	4.480	4.990	5.720
57	HAKIMPUR	27.43	6.770				2.880	3.150	3.260	3.450	3.660	3.780	4.280	4.810
58	PHULTALA	21.33	6.805				3.060	3.420	3.600	3.760	3.980	4.070	4.520	4.920
59	KALOPUR	24.38	6.620				3.120	3.400	3.570	3.730	3.920	4.040	4.500	4.870
60	KEUTIA	48.76	6.825				3.290	3.500	3.620	3.770	3.990	4.100	4.490	4.950
61	GHAT BAHAR	30.48	7.285				3.180	3.410	3.600	3.780	4.010	4.160	4.560	5.110
62	SIMIUPUR	42.67	6.215				3.290	3.520	3.680	3.840	3.980	4.120	4.490	4.870
63	HAMIDPUR	24.38	6.595				2.970	3.250	3.430	3.640	3.870	3.990	4.350	4.620

DEPTH = Depth of the well from ground
DEPTHRL = Depth of well (RL) from ground = RL OF GL - DEPTH
WL4/97 = Water level for April'97
WT4/97 = Water table elevation for April'97 = RL OF GL - ST.WL4/97
* Blank cells indicate `data not available'

Table -A.2 : Converted data of water level to water table

SL	LOCATION	DEPTH	RL OF GL	WT04 97	WT06 97	WT08 97	WT09 97	WT10 97	WT11 97	WT12 97	WT01 98	WT02 98	WT03 98	WT05 98
1	KALIGANG	122.50	8.820	0.990	0.850	3.320	3.240	3.130	2.620	2.390	2.170	2.060	1.970	1.190
2	TARINIPUR	21.34	8.345	4.955	4.825	6.445	6.355	6.095	5.945	5.755	5.625	5.455	5.355	5.315
3	ALAIPUR	24.38	8.945	3.875	3.655	5.195	5.055	4.615	4.255	4.155	3.955	3.895	3.565	2.955
4	JATRAPUR	13.71	9.250	7.430	7.000	8.480	8.350	8.200	8.000	7.870	7.750	7.630	6.900	6.380
5	HARINGHATA	15.24	7.255	2.415	2.325	4.800	3.635	3.245	3.175	3.020	2.865	2.765	2.335	1.885
6	DATTAPARA	15.24	6.430	2.500	2.310	5.150	5.080	4.800	4.730	4.540	4.380	4.200	3.640	2.610
7	KALAYANI	28.95	7.430	4.280	4.080	5.000	4.730	4.620	4.530	4.440	4.250	4.180	3.480	3.440
8	KANCHRAPARA	18.28	7.820	3.840	3.630	4.340	4.220	3.970	3.840	3.750	3.640	3.560	3.030	2.800
9	GAYESHPUR	15.24	7.460	4.840	4.230	4.960	4.840	4.750	4.660	4.590	4.490	4.390	3.470	3.440
10	KATABELI	18.28	6.800	4.640	4.320	5.300	6.030	6.030	5.930	5.750	5.510	5.350	4.710	3.800
11	SAGUNA	18.28	7.655	3.685	3.375	4.135	4.025	3.915	3.855	3.775	3.665	3.595	2.875	2.745
12	BIROHI	21.33	8.460	3.980	3.810	4.860	4.760	4.610	4.510	4.340	4.220	4.100	3.180	2.960
13	HALISAHAR	106.68	7.025	-3.715	-3.865	0.665	0.545	0.135	0.075	-0.125	-0.295	-0.375	-0.525	-0.885
14	TUNTULBERIA	36.57	9.475	2.075	1.865	6.845	6.725	6.465	6.245	6.055	5.845	5.625	4.805	3.855
15	MANDALHAT	18.28	8.675	4.515	4.345	7.035	6.405	5.775	5.425	5.285	5.185	5.095	4.495	3.895
16	PANCHPOTA	30.48	8.210	5.190	5.020	6.420	6.320	5.960	5.910	5.730	5.560	5.430	4.430	4.060
17	KUNDALIA	21.33	7.920	4.400	4.170	6.100	5.940	5.670	5.560	5.410	5.200	5.000	4.630	4.490
18	KHALSI	21.33	7.235	3.185	2.955	5.095	4.985	4.875	4.825	4.705	4.615	4.475	3.445	3.215

SL	LOCATION	DEPTH	RL OF GL	WT04 97	WT06 97	WT08 97	WT09 97	WT10 97	WT11 97	WT12 97	WT01 98	WT02 98	WT03 98	WT05 98
19	NIMTALA	12.19	6.345	3.945	3.825	4.475	4.355	4.245	4.185	4.095	3.955	3.525	3.095	2.955
20	PHULBARI	21.33	6.880	3.810	3.600	4.340	4.260	4.140	3.990	3.870	3.740	3.650	2.590	2.250
21	DIGARI	66.00	7.240	3.690	3.490	5.770	5.660	5.460	5.390	5.260	5.140	4.950	3.390	3.230
22	NISCHINTPUR	24.38	8.025	4.575	4.415	6.375	6.375	6.115	6.035	5.905	5.745	5.615	4.815	4.405
23	NAPIT SATBERIA	21.33	6.710	2.860	2.720	3.770	3.650	3.450	3.410	3.300	3.190	3.070	2.530	2.490
24	HANSPUR	18.28	6.565	1.065	0.875	3.215	3.015	2.655	2.575	2.425	2.145	1.965	1.465	1.135
25	NAGABUKRA	18.28	6.420	2.100	1.900	4.290	4.090	3.930	3.870	3.710	3.530	3.440	2.640	2.400
26	BALIDANGA	12.19	6.600	2.580	2.390	5.480	5.280	5.080	4.700	4.500	4.300	4.050	3.480	2.910
27	KASTADANGA	36.57	7.105	1.305	1.175	3.465	3.255	3.005	2.825	2.655	2.525	2.385	2.115	1.405
28	ASHOK NAGAR	51.00	6.240	2.740	2.140	4.140	4.090	3.730	3.560	3.430	3.250	3.030	2.240	2.030
29	HAT THUBA	40.00	7.240	1.290	2.860	5.410	5.280	4.890	4.650	4.480	4.330	4.090	3.240	2.220
30	JANAPHUL	33.52	7.000	3.100	2.380	5.650	5.580	5.380	5.130	5.010	4.870	4.690	3.650	3.110
31	LAKSHMIPUR	30.48	5.960	2.540	1.910	4.880	4.780	4.580	4.540	4.330	4.110	3.970	3.180	2.570
32	MASLANDAPUR	30.00	6.225	2.375	2.055	4.775	4.605	4.305	4.105	3.915	3.705	3.495	3.035	2.555
33	GHOSHPUR	15.00	5.370	3.220	2.720	4.870	4.550	4.320	4.220	4.060	3.830	3.650	2.720	2.590
34	CHARGHAT	165.00	4.920	1.020	0.620	2.530	2.440	2.170	1.930	1.780	1.620	1.500	0.410	0.310
35	ICHAPUR	30.00	5.770	3.370	2.670	5.570	5.470	5.000	4.780	4.540	4.360	4.150	3.240	2.950
36	BISHNUPUR	52.00	4.865	1.915	1.265	3.875	3.715	3.215	3.085	2.945	2.765	2.555	1.545	1.255
37	SUTIA BARASAT	50.00	4.300	1.050	0.920	3.610	3.480	2.990	2.870	2.790	2.560	2.440	1.750	1.280

SL	LOCATION	DEPTH	RL OF GL	WT04 97	WT06 97	WT08 97	WT09 97	WT10 97	WT11 97	WT12 97	WT01 98	WT02 98	WT03 98	WT05 98
38	JAGULI		6.495	6.495	6.495	6.495	6.495	6.495	6.495	6.495	6.495	6.495	6.495	6.495
39	GANADI PAYAN	50.00	6.385	3.685	3.235	5.435	5.185	4.765	4.635	4.485	4.295	4.095	3.175	2.935
40	JIKRA	66.00	6.100	0.760	0.150	3.490	3.380	3.190	3.000	2.810	2.670	2.490	1.510	1.130
41	GOPALPUR	65.00	6.035	2.875	2.335	5.045	4.915	4.725	4.535	4.265	4.055	3.865	3.065	2.775
42	JALESWAR	35.00	6.090	3.090	2.590	3.540	3.310	3.180	3.040	2.880	2.740	2.620	1.810	1.470
43	GAIGHATA	50.00	6.430	3.480	3.130	4.360	4.240	4.000	3.920	3.790	3.665	3.540	2.510	2.410
44	DEVIPUR	70.00	5.435	2.285	2.235	4.545	4.485	4.385	4.255	4.055	3.895	3.665	2.765	2.385
45	CHAITAPARA	33.00	5.980	4.180	4.530	5.490	5.330	4.830	4.740	4.620	4.470	4.290	3.390	3.070
46	RAMSANKARPUR	40.00	6.845	3.945	3.665	6.645	6.445	5.925	5.825	5.605	5.375	5.145	3.945	3.875
47	NAHATA	90.00	6.530	3.680	3.230	5.470	5.180	4.910	4.630	4.430	4.110	3.890	3.010	2.830
48	SIMULPUR	30.00	5.235	-0.415	-0.565	3.085	2.985	2.725	2.555	2.415	2.265	2.085	1.185	0.585
49	JAGADISHPUR	21.33	10.380				8.000	7.770	7.630	7.490	7.340	7.220	6.390	5.710
50	BAGDABA	24.38	10.455				7.355	7.165	7.055	6.935	6.785	6.645	6.175	6.135
51	BELGARIA	24.38	8.520				5.570	5.360	5.140	5.010	4.800	4.630	4.180	3.870
52	PURBA BISHNUPUR	15.24	11.315				8.765	8.395	8.295	8.065	7.835	7.695	7.105	6.745
53	BELIA	21.33	9.270				6.220	5.760	5.650	5.490	5.360	5.210	4.460	4.250
54	NUTAN SILINDA	15.24	11.045				8.265	7.895	7.735	7.555	7.345	7.185	6.345	6.225
55	KHUSBASI	24.38	10.465				7.575	7.415	6.515	6.255	5.975	5.865	5.455	4.815
56	MASRA	45.72	10.745				7.555	7.095	6.895	6.625	6.355	6.265	5.755	5.025

SL	LOCATION	DEPTH	RL OF GL	WT04 97	WT06 97	WT08 97	WT09 97	WT10 97	WT11 97	WT12 97	WT01 98	WT02 98	WT03 98	WT05 98
57	HAKIMPUR	27.43	6.770				3.890	3.620	3.510	3.320	3.110	2.990	2.490	1.960
58	PHULTALA	21.33	6.805				3.745	3.385	3.205	3.045	2.825	2.735	2.285	1.885
59	KALOPUR	24.38	6.620				3.500	3.220	3.050	2.890	2.700	2.580	2.120	1.750
60	KEUTIA	48.76	6.825				3.535	3.325	3.205	3.055	2.835	2.725	2.335	1.875
61	GHAT BAHAR	30.48	7.285				4.105	3.875	3.685	3.505	3.275	3.125	2.725	2.175
62	SIMIUPUR	42.67	6.215				2.925	2.695	2.535	2.375	2.235	2.095	1.725	1.345
63	HAMIDPUR	24.38	6.595				3.625	3.345	3.165	2.955	2.725	2.605	2.245	1.975

DEPTH = Depth of the well from ground
DEPTHRL = Depth of well (RL) from ground = RL OF GL - DEPTH
WL4/97 = Water level for April'97
WT4/97 = Water table elevation for April'97 = RL OF GL - ST.WL4/97
* Blank cells indicate `data not available'

Table - A.3: Details of rivers' stresses considered for modelling

A.3(a) : River Bhagirathi

Month/year	Entry (North)		Exit (South)		Remarks
	RL of Water surface (m)	RL of River bed(m)	RL of water surface(m)	RL of river bed(m)	
Aprl'96	104.56	101.20	102.56	100.40	i) Conductance of the river at entry (North) = 3870 m^2/d ii) Conductance of the river at exit (South) = 1457 m^2/day iii) The gradient of water surface is 1: 15000.
May'96	104.68		102.68		
June'96	104.93		102.93		
July'96	106.02		104.02		
Aug'96	107.66		105.66		
Sept'96	107.19		105.19		
Oct'96	105.98		103.98		
Nov.'96	105.22		103.22		
Dec.'96	105.07		103.07		
Jan'97	105.07		103.07		
Feb.'97	104.59		102.59		
March'97	104.06		102.06		
April'97	103.64		101.64		
May'97	104.14		102.14		
June'97	104.66		102.66		
July'97	106.64		104.64		

A.3(b) : River Ichamati

Month/year	Entry (North)		Exit (South)		Remarks
	RL of Water surface (m)	RL of River bed(m)	RL of water surface(m)	RL of river bed(m)	
Aprl'96	103.25		103.05		
May'96	103.38		103.26		i) Conductance of the river at entry (North) = 770 m^2/d
June'96	103.41		103.35		
July'96	104.60		103.50		
Aug'96	106.56		103.71		ii) Conductance of the river at exit (South) = 960 m^2/day
Sept'96	107.08		104.05		
Oct'96	105.19		103.42		
Nov.'96	104.64		103.59		iii) The gradient of water surface is 1: 15000.
Dec.'96	103.59	99.925	102.31	99.43	
Jan'97	103.25		102.29		
Feb.'97	103.09		102.03		
March'97	102.83		102.48		
April'97	102.77		101.85		
May'97	102.98		101.98		
June'97	103.80		102.80		
July'97	104.12		103.12		

A.3(c) : River Yamuna

Month/year	Intake end (West)		Discharge end (East)		Remarks
	RL of Water surface (m)	RL of River bed(m)	RL of water surface(m)	RL of river bed(m)	
Sept'96	106.68	104.082	104.60	101.778	River conductance = 150 m^2/d
Oct'96	105.50		103.70		
Nov.'96	104.75		103.745		
Dec.'96	104.60		102.40		
Jan'97	104.60		102.40		
Feb.'97	104.10		102.20		
March'97	103.62		102.52		
April'97	103.20		102.00		
May'97	103.70		102.13		
June'97	104.20		102.90		
July'97	104.20		104.10		

(* 100 refers arbitrary datum above MSL)

Table A.4: Measured Arsenic concentration (mg/l) at different locations

SL	LOCATION	DEPTH	DEPTHRL	RL OF GL	Apr/97	Jun/97	Aug/97	Sep/97	Oct/97	Nov/97	Jan/98	Mar/98	May/98
1	KALIGANG	122.50	-113.680	8.820	BDL	BDL	0.002	-	-	BDL	BDL	BDL	BDL
2	TARINIPUR	21.34	-12.995	8.345	-	BDL	-	-	-	0.002	-	-	BDL
3	ALAIPUR	24.38	-15.435	8.945	BDL	BDL	BDL	-	BDL	0.002	BDL	BDL	BDL
4	JATRAPUR	13.71	-4.460	9.250	BDL	BDL	0.001	0.003	-	0.001	BDL	BDL	BDL
5	HARINGHATA	15.24	-7.985	7.255	0.004	0.070	0.001	0.002	BDL	0.002	BDL	0.025	0.046
6	DATTAPARA	15.24	-8.810	6.430	0.018	0.090	0.001	-	-	BDL	BDL	BDL	BDL
7	KALAYANI	28.95	-21.520	7.430	0.053	BDL	BDL	0.002	-	BDL	-	0.045	0.050
8	KANCHRAPARA	18.28	-10.460	7.820	BDL	BDL	BDL	-	-	0.002	BDL	BDL	BDL
9	GAYESHPUR	15.24	-7.780	7.460	0.011	BDL	BDL	BDL	-	0.001	BDL	0.023	0.030
10	KATABELI	18.28	-11.480	6.800	BDL	BDL	BDL	0.001	0.003	0.003	BDL	BDL	BDL
11	SAGUNA	18.28	-10.625	7.655	-	BDL	BDL	-	-	-	BDL	BDL	BDL
12	BIROHI	21.33	-12.870	8.460	0.097	0.060	0.001	BDL	0.042	0.021	0.051	0.034	0.040
13	HALISAHAR	106.68	-99.655	7.025	BDL	BDL	BDL	-	-	0.002	BDL	0.002	0.002
14	TUNTULBERIA	36.57	-27.095	9.475	BDL	0.027	0.001	-	-	0.002	0.016	BDL	BDL
15	MANDALHAT	18.28	-9.605	8.675	0.121	0.130	BDL	0.093	0.009	0.068	-	0.048	0.056
16	PANCHPOTA	30.48	-22.270	8.210	0.160	BDL	0.001	-	-	0.001	BDL	0.014	0.010
17	KUNDALIA	21.33	-13.410	7.920	0.130	0.180	-	0.098	0.059	BDL	0.016	0.048	0.056
18	KHALSI	21.33	-14.095	7.235	0.012	BDL	BDL	0.009	0.005	0.002	0.022	0.065	0.040

SL	LOCATION	DEPTH	DEPTHRL	RL OF GL	Apr/97	Jun/97	Aug/97	Sep/97	Oct/97	Nov/97	Jan/98	Mar/98	May/98
19	NIMTALA	12.19	-5.845	6.345	BDL	BDL	0.001	-	BDL	0.002	-	0.005	BDL
20	PHULBARI	21.33	-14.450	6.880	BDL	BDL	0.001	-	-	0.002	0.012	BDL	0.010
21	DIGARI	66.00	-58.760	7.240	0.030	0.050	0.002	0.002	-	BDL	-	0.025	BDL
22	NISCHINTPUR	24.38	-16.355	8.025	-	BDL	-	-	-	BDL	-	BDL	BDL
23	NAPIT SATBERIA	21.33	-14.620	6.710	0.011	BDL	0.002	0.002	-	BDL	0.022	-	BDL
24	HANSPUR	18.28	-11.715	6.565	-	BDL	0.002	-	-	BDL	0.003	-	0.004
25	NAGABUKRA	18.28	-11.860	6.420	0.004	BDL	-	0.002	0.002	BDL	BDL	BDL	BDL
26	BALIDANGA	12.19	-5.590	6.600	0.012	-	BDL	0.017	-	BDL	0.022	-	BDL
27	KASTADANGA	36.57	-29.465	7.105	0.012	BDL	0.002	0.003	0.002	BDL	-	0.014	0.008
28	ASHOK NAGAR	51.00	-44.760	6.240	0.255	-	BDL	0.170	0.006	BDL	0.003	-	0.004
29	HAT THUBA	40.00	-32.760	7.240	0.008	-	0.001	-	0.005	0.002	-	-	0.002
30	JANAPHUL	33.52	-26.520	7.000	0.019	-	BDL	-	-	0.002	-	0.014	0.016
31	LAKSHMIPUR	30.48	-24.520	5.960	0.020	-	0.002	0.066	-	0.001	-	BDL	BDL
32	MASLANDAPUR	30.00	-23.775	6.225	0.018	-	0.002	0.012	-	BDL	-	0.037	0.219
33	GHOSHPUR	15.00	-9.630	5.370	0.011	-	BDL	-	-	0.002	-	-	0.115
34	CHARGHAT	165.00	-160.080	4.920	0.006	-	0.001	-	-	BDL	-	-	BDL
35	ICHAPUR	30.00	-24.230	5.770	0.045	-	-	0.043	0.013	0.002	-	0.014	0.130
36	BISHNUPUR	52.00	-47.135	4.865	0.066	-	0.002	-	-	0.001	-	0.025	BDL
37	SUTIA BARASAT	50.00	-45.700	4.300	0.004	-	-	-	-	BDL	-	-	-
38	JAGULI				-	-	-	-	-	-	-	-	-

SL	LOCATION	DEPTH	DEPTHRL	RL OF GL	Apr/97	Jun/97	Aug/97	Sep/97	Oct/97	Nov/97	Jan/98	Mar/98	May/98
39	GANADI PAYAN	50.00	-43.615	6.385	0.018	-	BDL	0.045	BDL	0.002	0.003	-	-
40	JIKRA	66.00	-59.900	6.100	0.019	-	0.001	-	-	0.003	-	-	0.003
41	GOPALPUR	65.00	-58.965	6.035	0.022	-	0.026	0.066	0.013	BDL	BDL	-	BDL
42	JALESWAR	35.00	-28.910	6.090	0.009	-	0.002	-	-	0.002	-	BDL	-
43	GAIGHATA	50.00	-43.570	6.430	0.060	-	0.002	0.060	0.016	-	-	-	-
44	DEVIPUR	70.00	-64.565	5.435	0.011	-	0.002	-	-	0.002	0.019	BDL	0.246
45	CHAITAPARA	33.00	-27.020	5.980	0.001	-	0.007	-	-	BDL	-	0.014	0.012
46	RAMSANKARPUR	40.00	-33.155	6.845	0.019	-	BDL	-	0.012	BDL	-	BDL	BDL
47	NAHATA	90.00	-83.470	6.530	0.005	-	BDL	-	-	BDL	0.003	0.014	0.016
48	SIMULPUR	30.00	-24.765	5.235	-	-	-	-	-	0.003	-	-	-
49	JAGADISHPUR	21.33	-10.950	10.380	-	-	-	-	-	BDL	-	BDL	0.010
50	BAGDABA	24.38	-13.925	10.455	-	-	-	-	-	0.003	-	BDL	0.123
51	BELGARIA	24.38	-15.860	8.520	-	-	-	-	-	-	0.022	-	0.010
52	PURBA BISHNUPUR	15.24	-3.925	11.315	-	-	-	-	-	0.002	-	0.008	BDL
53	BELIA	21.33	-12.060	9.270	-	-	-	-	-	BDL	-	BDL	BDL
54	NUTAN SILINDA	15.24	-4.195	11.045	-	-	-	-	-	0.003	-	BDL	BDL
55	KHUSBASI	24.38	-13.915	10.465	-	-	-	-	-	BDL	-	0.014	0.260
56	MASRA	45.72	-34.975	10.745	-	-	-	-	-	0.001	-	-	BDL
57	HAKIMPUR	27.43	-20.660	6.770	-	-	-	-	-	0.002	-	BDL	BDL

SL	LOCATION	DEPTH	DEPTHRL	RL OF GL	Apr/97	Jun/97	Aug/97	Sep/97	Oct/97	Nov/97	Jan/98	Mar/98	May/98
58	PHULTALA	21.33	-14.525	6.805	-	-	-	-	-	0.003	-	-	BDL
59	KALOPUR	24.38	-17.760	6.620	-	-	-	-	-	BDL	-	-	BDL
60	KEUTIA	48.76	-41.935	6.825	-	-	BDL	BDL	-	BDL	-	0.017	0.015
61	GHAT BAHAR	30.48	-23.195	7.285	-	-	-	-	-	-	-	-	-
62	SIMIUPUR	42.67	-36.455	6.215	-	-	-	-	-	0.003	-	-	-
63	HAMIDPUR	24.38	-17.785	6.595	-	-	-	-	-	0.001	BDL	0.008	-

(-) = Not determined; BDL = Below detection limit; DEPTH = Depth of the well from ground
DEPTHRL = Depth of well (RL) from ground = RL OF GL - DEPTH

Table - A.5 :Geological formations of different bore hole logs in the study area.

Sl.	Classification	Depth Range (m)		Thickness (m)
		From	To	
1. BANGAON				
1	Clay (Grey)	0.00	31.10	31.10
2	Sand (Fine to Medium)	31.10	35.10	4.00
3	Clay (Grey with Fine Sand)	35.10	56.10	21.00
4	Sand (Medium to Coarse with Gravel)	56.10	73.10	17.00
5	Clay with Fine Sand	73.10	80.20	7.10
6	Sand (with Gravel)	80.20	94.20	14.00
7	Clay (Grey)	94.20	122.20	28.00
8	Sand (Coarse) with Gravel	122.20	192.30	70.10
9	Clay (Grey)	192.30	306.90	114.60
2. DHANKUNI				
1	Surface Soil	0.00	3.05	3.05
2	Clay (Plastic)	3.05	9.15	6.10
3	Sand (Fine)	9.15	51.81	42.66
4	Clay	51.81	54.86	3.05
5	Sand (Fine to Coarse)	54.86	94.48	39.62
6	Clay	94.48	128.10	33.62
3. MIRJAPUR				
1	Sand (Fine and Silt)	0.00	16.15	16.15
2	Clay (Sticky Silt)	16.15	19.20	3.05
3	Sand (Medium to Fine)	19.20	34.44	15.24
4	Clay (Silty)	34.44	37.48	3.04
5	Sand (Fine to Medium)	37.48	80.46	42.98
6	Clay (Silty)	80.46	98.45	15.24
7	Sand (Medium to Fine)	98.45	113.69	15.24
8	Sand(Medium) & Fine Gravel	113.69	116.74	3.05

Sl.	Classification	Depth Range (m)		Thickness (m)
		From	To	
9	Sand (Coarse) and Gravel	116.74	138.07	21.33
10	Sand (Medium to Fine)	138.07	146.00	7.93
6. KRISHNANAGAR				
1	Clay (Silty)	0.00	12.00	12.00
2	Sand (Fine)	12.00	61.00	49.00
3	Clay	61.00	67.00	6.00
4	Sand (Fine to Coarse)	67.00	149.00	82.00
7. HABRA				
1	CLAY	0.00	4.57	4.57
2	Sand (Very Fine)	4.57	10.66	6.09
3	Clay (Black to Yellow)	10.66	54.86	44.20
4	Sand (Fine)	54.86	82.29	27.43
5	Sand (Medium to Coarse)	82.29	121.01	38.72
8. SATBERIA				
1	Top Soil	0.00	3.09	3.09
2	Very Fine Sand	3.09	12.26	9.17
3	Medium Fine Sand	12.26	18.36	6.10
4	Grey Medium Fine Sand	18.36	42.74	24.38
5	Medium Sand	42.74	48.84	6.10
6	Grey Medium Coarse Sand	48.84	85.42	36.58
7	Medium Fine Sand	85.42	93.56	8.14
8	Grey Medium Sand	93.56	102.83	9.27
9	Medium Sand with Clay	102.83	105.75	2.92
10	Medium Sand	105.75	117.94	12.19
11	Very Coarse Sand with Gravel	117.94	146.36	28.42
12	Grey Coarse Sand	146.36	155.62	9.26
10. BALARAMPUR				
1	Light brown Silty Clay	0.00	3.96	3.96

Sl.	Classification	Depth Range (m)		Thickness (m)
		From	To	
2	Grey Fine Sand	3.96	16.15	12.19
3	Grey Medium and Fine Sand	16.15	19.20	3.05
4	Grey Fine and Uniform Sand	19.20	22.25	3.05
5	Dark Grey Fine Sand and Mica	22.25	28.34	6.09
6	Dark Grey Fine Uniform Sand & Silty Clay	28.34	31.39	3.05
7	Grey Fine Sand	31.39	37.49	5.10
8	Grey Fine Sand and Sandstone	37.49	40.53	3.04
9	Grey Fine Sand	40.53	43.58	3.05
10	Grey Fine Sand and Clay mixed	43.58	46.63	3.05
11	Grey Medium Uniform Sand	46.63	49.68	3.05
12	Dark Grey Silty Clay and Sand	49.68	52.73	3.05
13	Grey Fine Sand	52.73	56.38	3.65
14	Grey Coarse and Medium Sand	56.38	67.97	11.59
15	Grey Very Fine Dirty Sand	67.97	75.89	7.92
16	Grey Coarse Sand	75.89	80.16	4.27
17	Grey Fine to Coarse Sand	80.16	83.21	3.05
18	Grey Fine Sand	83.21	86.25	3.04
19	Grey Fine Dirty Sand and Mica	86.25	89.30	3.05
20	Grey Sand and Sandstone	89.30	93.87	4.57
21	Grey Fine Sand	93.87	106.37	12.50
22	Dark Grey Silty Clay	106.37	109.11	2.74
23	Dark Grey Silty Sand	109.11	110.64	1.53
24	Grey Coarse Sand and Gravel	110.64	116.73	6.11
25	Grey Medium & Fine Sand & Gravel	116.73	119.78	3.05
26	Grey Coarse Sand	119.78	122.83	3.05
27	Grey Well Geaded Sand & Gravel	122.83	132.58	9.75
28	Grey Medium and Uniform Sand	132.58	135.02	2.44
11. SILINDA				

Sl.	Classification	Depth Range (m)		Thickness (m)
		From	To	
1	Clay	0.00	1.52	1.52
2	Very Fine Sand	1.52	18.28	16.76
3	Fine Sand with Mica	18.28	39.62	21.34
4	Medium Sand	39.62	42.67	3.05
5	Coarse Sand	42.67	81.38	38.71
6	Black Sand	81.38	109.11	27.73
12. ITAPUKUR				
1	Brown Clay	0.00	1.52	1.52
2	Black Clay	1.52	8.53	7.01
3	Very Fine Sand	8.53	9.75	1.22
4	Black Hard Clay	9.75	16.15	6.40
5	Very Fine Sand	16.15	19.81	3.66
6	Hard Clay	19.81	34.44	14.63
7	Yellowish Sand	34.44	38.10	3.65
8	Grey Medium Sand with Light Yellow Clay	38.10	63.39	25.29
9	Grey Medium Sand	63.39	70.10	6.71
10	White Coarse Sand	70.10	81.88	11.28
11	Clay mixed with Gravel	81.88	89.00	7.62
12	Black Sticky Clay	89.00	98.14	9.14
13	Black Clay mixed with Fine Sand	98.14	114.91	16.77
13. JAYKRISHNAPUR				
1	Brown Clay	0.00	11.27	11.27
2	Medium Sand	11.27	30.48	19.21
3	Grey Coarse Sand	30.48	48.15	17.67
4	Sandstone	48.15	48.76	0.61
5	Coarse Sand with Gravel	48.76	74.67	25.01
6	Black Clay	74.67	99.06	24.39
7	Fine Sand with Clay	99.06	106.08	7.62

Sl.	Classification	Depth Range (m)		Thickness (m)
		From	To	
14. SAGUNA				
1	Grey Brown Silty Clay	0.00	3.96	3.96
2	Sand (Fine to Medium)	3.96	13.10	9.14
3	Sand (Fine)	13.10	16.15	3.05
4	Sand (Fine to Medium)	16.15	19.20	3.05
5	Sand (Fine)	19.20	25.29	6.09
6	Clay (Silty Yellow)	25.29	34.44	9.15
7	Clay (Silty Grey)	34.44	40.53	6.09
8	Clay (Silty Dark Grey)	40.53	78.03	37.50
9	Sand (Fine Grey)	78.03	81.69	3.66
10	Medium Sand	81.69	108.81	27.12
11	Silty Clay with Sand	108.81	115.22	6.41
12	Sand (Medium)	115.22	117.96	2.74
13	Sand and Gravel	117.96	123.44	5.48
14	Coarse Sand	123.44	125.88	2.44
15	Grey Yellow Clay with Sand	125.88	129.54	3.66
15. SIMURALI				
1	Yellowish Hard Clay	0.00	3.96	3.96
2	Light Brown Soft Clay	3.96	7.01	3.05
3	Light Grey Silty Clay and traces of Fine Sand	7.01	10.05	3.04
4	Grey Fine Sand	10.05	13.10	3.05
5	Dark Grey Hard Clay	13.10	24.68	11.58
6	Brown Hard Clay	24.68	31.39	6.71
7	Light Brown Medium Coarse Sand	31.39	33.22	1.83
8	Grey Fine Sand	33.22	37.49	4.27
9	Brown Very Fine Sand with Clay	37.49	39.62	2.13
10	Yellowish Medium Coarse Sand with Clay	39.62	52.73	13.11

Sl.	Classification	Depth Range (m)		Thickness (m)
		From	To	
11	Dark Grey Hard Clay	52.73	63.09	10.36
12	Grey & Brown Clay with Fine Sand	63.09	67.97	4.88
13	Grey Fine Sand	67.97	79.24	11.27
14	Grey Medium Coarse Sand	79.24	88.08	8.86
15	Dark Grey Hard Clay	88.08	91.44	3.36
16	Grey Medium to Fine Sand	91.44	95.40	3.96
17	Grey Medium to Coarse Sand with Clay	95.40	96.31	0.91
18	Grey Hard Clay	96.31	100.58	4.27
19	Grey Medium Coarse Sand	100.58	104.54	3.96
20	Grey Medium to Fine Sand with Clay	104.54	109.72	5 18
21	Grey Medium Coarse Sand	109.72	112.16	2.44
22	Well Graded Sand with Fine Gravel	112.16	124.66	12.50
23	Dark Grey Hard Clay	124.66	131.97	7.31
24	Grey Clayish Fine Sand	131.97	135.02	3.05
25	Grey Medium Coarse Sand with Little Clay	135.02	137.16	2.14
26	Grey Hard Clay mixed with Coarse Sand	137.16	138.98	1.82
27	Grey Coarse Sand with little Gravel	138.98	142.34	3.36
28	Dark Grey Hard Clay	142.34	146.60	4.26
16. BIROHI				
1	Clay	0.00	12.19	12.19
2	Sand, Fine Grained	12.19	21.34	9.15
3	Sand Medium Grained	21.34	33.53	12.19
4	Sand, Coarse Grained	33.53	65.53	32.00
5	Clay, Black mixed with Fine Sand	65.53	72.95	7.42
6	Clay, Black	72.95	85.34	12.39
7	Sand, Fine, Black	85.34	88.89	3.05
8	Clay, Black, Sticky	88.89	109.12	20.73
17. SIMHAT				

Sl.	Classification	Depth Range (m)		Thickness (m)
		From	To	
1	Yellow Clay	0.00	3.96	3.96
2	Black Clay	3.96	13.10	9.14
3	Black Clay with Sand	13.10	19.20	6.10
4	Black Clay with Stone	19.20	28.34	9.14
5	Yellow Hard Clay	28.34	34.44	6.10
6	Yellow Medium to Fine Sand	34.44	46.63	12.19
7	Yellow Coarse Sand with Fine Sand Stone	46.63	55.77	9.14
8	Grey Coarse Sand	55.77	58.82	3.05
9	Grey Medium to Coarse Sand	58.82	61.87	3.05
10	Grey Medium Coarse Sand	61.87	67.06	5.19
11	Black Hard Clay	67.06	71.01	3.95
12	Grey Fine Sand with traces of Clay	71.01	74.06	3.05
13	Grey Coarse Sand with traces of Clay	74.06	77.11	3.05
14	Grey Medium to Fine Sand	77.11	91.44	14.33
15	Black Hard Clay	91.44	103.02	11.58
16	Grey Fine Sand	103.02	107.59	4.57
17	Grey Medium Coarse Sand	107.59	110.64	3.05
19. GHATUGACHI				
1	Surface Clay	0.00	3.04	3.04
2	Dark Grey Clay	3.04	14.32	11.28
3	Very Fine Sand mixed with Clay	14.32	16.15	1.83
4	Medium Coarse Sand	16.15	25.29	9.14
5	Very Fine Sand excess of Mica & Clay	25.29	28.34	3.05
6	Grey Fine Sand	28.34	35.96	7.62
7	Hard Grey Clay with Sand particles	35.96	37.49	1.53
8	Very Fine Grey Sand	37.49	43.58	6.09
9	Grey Medium Sand	43.58	46.63	3.05

Sl.	Classification	Depth Range (m)		Thickness (m)
		From	To	
10	Coarse Sand and Medium Fine Sand with Fine Gravel	46.63	49.68	3.05
11	Coarse Sand and Gravel	49.68	52.73	3.05
12	Grey Fine Sand	52.73	58.82	6.09
13	Coarse Sand Graded and Gravels	58.82	64.92	6.10
14	Coarse & Medium Fine Sand & Gravels	64.92	71.01	6.09
15	Grey Coarse Sand	71.01	72.84	1.83
16	Grey Hard Clay	72.84	95.40	22.56
17	Grey Medium Fine Sand	95.40	98.45	3.05
18	Grey Medium Coarse & Sand Fine Sand	98.45	104.54	6.09
19	Grey Coarse Medium Sand	104.54	110.64	6.10
20	Grey Graded Coarse Sand	110.64	113.69	3.05
21	Grey Medium Coarse Sand	113.69	116.73	3.04
22	Well Graded Coarse Sand and Gravel	116.73	125.88	9.15
23	Grey Medium Coarse Sand and Gravels	125.88	128.01	2.13
24	Grey Clay with Gravels	128.01	128.93	0.92
25	Dark Grey Silty Clay	128.93	131.97	3.04
21. KASTODANGA				
1	Yellow Clay	0.00	3.96	3.96
2	Yellow Fine Sand	3.96	7.01	3.05
3	Grey Fine Sand with traces of Clay	7.01	13.11	6.10
4	Grey Medium to fine Sand	13.11	20.12	7.01
5	Grey Coarse Sand	20.12	25.29	5.17
6	Grey Coarse Sand with small Gravel and little Hard Clay	25.29	28.34	3.05
7	Grey Medium to Fine Sand with black very Hard Clay	28.34	31.39	3.05
8	Grey Medium Coarse Sand	31.39	37.49	6.10
9	Dark Black Hard Clay	37.49	40.54	3.05

Sl.	Classification	Depth Range (m)		Thickness (m)
		From	To	
10	Coarse Sand with Gravel	40.54	46.63	6.11
11	Grey Medium Coarse Sand	46.63	49.68	3.05
12	Yellow Coarse Sand with small Sand Stone	49.68	55.78	6.10
13	Grey Medium to Fine Sand	55.78	67.97	12.19
14	Small Gravel with Yellow Coarse Sand	67.97	73.15	5.18
15	Black Hard Clay	73.15	80.16	7.01
16	Grey Fine Sand with traces of Clay	80.16	104.54	24.38
17	Grey Medium Coarse Sand	104.54	107.59	3.05
18	Grey Coarse Sand with Gravel	107.59	113.69	6.10
19	Graded Gravel with Coarse Sand	113.69	128.93	15.24
20	Coarse Sand with well graded Gravel	128.93	138.07	9.14
21	Black Hard Clay with Gravel	138.07	141.12	3.05
22. GOALDOV				
1	Top Brown Silty Clay	0.00	3.96	3.96
2	Silty Clay	3.96	12.10	8.14
3	Medium to Fine Sand	12.10	15.15	3.05
4	Fine Sand with Mica	15.15	21.25	6.10
5	Medium to Fine Sand	21.25	24.30	3.05
6	Grey Fine Sand with Mica	24.30	27.35	3.05
7	Medium to Fine Sand	27.35	39.54	12.10
8	Black Clay	39.54	42.59	3.05
9	Grey Fine Sand	42.59	45.64	3.05
10	Coarse Sand with Graded Gravel	45.64	48.69	3.05
11	Medium Coarse Sand	48.79	54.79	6.10
12	Fine Sand	54.79	57.84	3.05
13	Coarse Sand with well graded Gravel	57.84	60.89	3.05
14	Grey Fine Sand with Sand Stone	60.89	63.94	3.05
15	Grey Fine Sand	63.94	70.04	6.10

Sl.	Classification	Depth Range (m)		Thickness (m)
		From	To	
16	Dark Grey Fine Sand with Mica	70.04	76.14	6.10
17	Hard Clay	76.14	85.34	9.20
18	Grey Sticky Soil with Fine Sand	85.34	91.35	6.01
19	Grey Fine Sand	91.35	103.54	12.19
20	Medium to Coarse Sand	103.54	106.59	3.05
21	Hard Clay	106.59	108.72	2.13
22	Coarse Sand with Gravel	108.72	134.01	25.29
23	Coarse Sand	134.01	136.06	2.05
24	Coarse Sand with well graded Gravel	136.06	145.37	9.31

Table - A.6 : Reclassified formations of lithologs

SL.	CLASSIFICATION	FROM	TO	RL
1. BANGAON (RL=5.00)				
1	CLAY	0.00	31.10	-26.10
2	FINE SAND	31.10	56.10	-51.10
3	SAND	56.10	73.10	-68.10
4	FINE SAND	73.10	80.20	-75.20
5	SAND	80.20	94.20	-89.20
6	CLAY	94.20	122.20	-117.20
7	SAND	122.20	192.30	-187.30
8	CLAY	192.30	306.90	-301.90
2. DHANKUNI (RL=5.00)				
1	SURFACE SOIL	0.00	3.05	1.95
2	CLAY	3.05	9.15	-4.15
3	FINE SAND	9.15	51.81	-46.81
4	CLAY	51.81	54.86	-49.86
5	SAND	54.86	94.48	-89.48

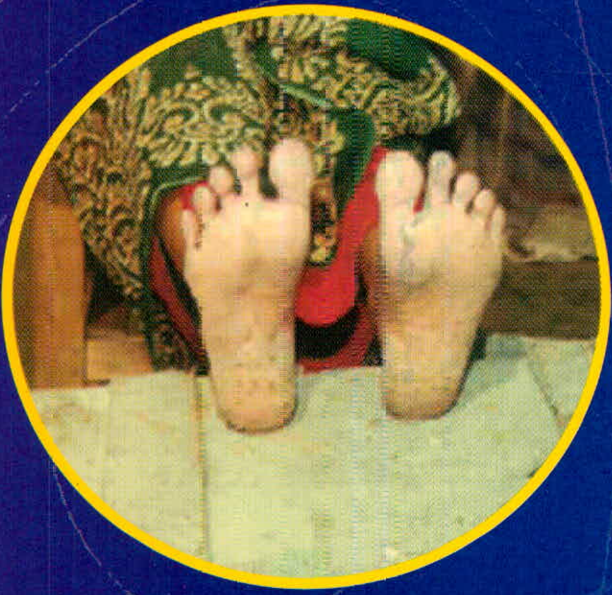
SL.	CLASSIFICATION	FROM	TO	RL
6	CLAY	94.48	128.10	-123.10
3. MIRJAPUR (RL=5.00)				
1	FINE SAND	0.00	16.15	-11.15
2	CLAY	16.15	19.20	-14.20
3	SAND	19.20	34.44	-29.44
4	CLAY	34.44	37.48	-32.48
5	SAND	37.48	80.46	-75.46
6	CLAY	80.46	98.45	-93.45
7	SAND	98.45	146.00	-141.00
6. KRISHNANAGAR (RL=6.05)				
1	CLAY	0.00	12.00	-5.95
2	FINE SAND	12.00	61.00	-54.95
3	CLAY	61.00	67.00	-60.95
4	SAND	67.00	149.00	-142.95
7. HABRA (RL=6.62)				
1	CLAY	0.00	4.57	2.05
2	FINE SAND	4.57	10.66	-4.04
3	CLAY	10.66	54.86	-48.24
4	FINE SAND	54.86	82.29	-75.67
5	SAND	82.29	121.01	-114.39
8. SATBERIA (RL=6.90)				
1	TOP SOIL	0.00	3.09	3.81
2	FINE SAND	3.09	42.74	-35.84
3	SAND	42.74	155.62	-148.72
10. BALARAMPUR (RL=9.75)				
1	CLAY	0.00	3.96	5.79
2	FINE SAND	3.96	46.63	-36.88
3	SAND	46.63	49.68	-39.93
4	CLAY	49.68	52.73	-42.98

SL.	CLASSIFICATION	FROM	TO	RL
5	FINE SAND	52.73	56.38	-46.63
6	SAND	56.38	67.97	-58.22
7	FINE SAND	67.97	75.89	-66.14
8	SAND	75.89	83.21	-73.46
9	FINE SAND	83.21	106.37	-96.62
10	CLAY	106.37	109.11	-99.36
11	FINE SAND	109.11	110.64	-100.89
12	SAND	110.64	135.02	-125.27
11. SILINDA (RL=10.00)				
1	CLAY	0.00	1.52	8.48
2	FINE SAND	1.52	39.62	-29.62
3	SAND	39.62	109.11	-99.11
12. ITAPUKUR (RL=9.75)				
1	CLAY	0.00	8.53	1.22
2	FINE SAND	8.53	9.75	0.00
3	CLAY	9.75	16.15	-6.40
4	FINE SAND	16.15	19.81	-10.06
5	CLAY	19.81	34.44	-24.69
6	SAND	34.44	81.88	-72.13
7	CLAY	81.88	114.91	-105.16
13. JAYKRISHNAPUR (RL=9.50)				
1	CLAY	0.00	11.27	-1.77
2	SAND	11.27	48.15	-38.65
3	SANDSTONE	48.15	48.76	-39.26
4	SAND	48.76	74.67	-65.17
5	CLAY	74.67	99.06	-89.56
6	FINE SAND	99.06	106.08	-96.58
14. SAGUNA (RL=7.655)				
1	CLAY	0.00	3.96	3.70

SL.	CLASSIFICATION	FROM	TO	RL
2	FINE SAND	3.96	25.29	-17.63
3	CLAY	25.29	78.03	-70.37
4	FINE SAND	78.03	81.69	-74.03
5	SAND	81.69	108.81	-101.15
6	CLAY	108.81	115.22	-107.56
7	SAND	115.22	125.88	-118.22
8	CLAY	125.88	129.54	-121.88
15. SIMURALI (RL=9.475)				
1	CLAY	0.00	10.05	-0.58
2	FINE SAND	10.05	13.10	-3.63
3	CLAY	13.10	31.39	-21.92
4	SAND	31.39	33.22	-23.75
5	FINE SAND	33.22	39.62	-30.15
6	SAND	39.62	52.73	-43.26
7	CLAY	52.73	67.97	-58.50
8	FINE SAND	67.97	79.24	-69.77
9	SAND	79.24	88.08	-78.61
10	CLAY	88.08	91.44	-81.97
11	SAND	91.44	96.31	-86.84
12	CLAY	96.31	100.58	-91.11
13	SAND	100.58	124.66	-115.19
14	CLAY	124.66	135.02	-125.55
15	SAND	135.02	137.16	-127.69
16	CLAY	137.16	138.98	-129.51
17	SAND	138.98	142.34	-132.87
18	CLAY	142.34	146.60	-137.13
16. BIROHI (RL=8.46)				
1	CLAY	0.00	12.19	-3.73
2	FINE SAND	12.19	21.34	-12.88

SL.	CLASSIFICATION	FROM	TO	RL
3	SAND	21.34	65.53	-57.07
4	CLAY	65.53	85.34	-76.88
5	FINE SAND	85.34	88.89	-80.43
6	CLAY	88.89	109.12	-100.66
17. SIMHAT (RL=7.255)				
1	CLAY	0.00	34.44	-27.19
2	SAND	34.44	67.06	-59.81
3	CLAY	67.06	71.01	-63.76
4	FINE SAND	71.01	74.06	-66.81
5	SAND	74.06	91.44	-84.19
6	CLAY	91.44	103.02	-95.77
7	FINE SAND	103.02	107.59	-100.34
8	SAND	107.59	110.64	-103.39
19. GHATUGACHI (RL=8.40)				
1	CLAY	0.00	14.32	-5.92
2	FINE SAND	14.32	16.15	-7.75
3	SAND	16.15	25.29	-16.89
4	FINE SAND	25.29	35.96	-27.56
5	CLAY	35.96	37.49	-29.09
6	FINE SAND	37.49	43.58	-35.18
7	SAND	43.58	52.73	-44.33
8	FINE SAND	52.73	58.82	-50.42
9	SAND	58.82	72.84	-64.44
10	CLAY	72.84	95.40	-87.00
11	FINE SAND	95.40	98.45	-90.05
12	SAND	98.45	128.93	-120.53
13	CLAY	128.93	131.97	-123.57
21. KASTODANGA (RL=7.105)				
1	CLAY	0.00	3.96	3.15

SL.	CLASSIFICATION	FROM	TO	RL
2	FINE SAND	3.96	13.11	-6.01
3	SAND	13.11	28.34	-21.24
4	FINE SAND+CLAY	28.34	31.39	-24.29
5	SAND	31.39	37.49	-30.39
6	CLAY	37.49	40.54	-33.44
7	SAND	40.54	73.15	-66.05
8	CLAY	73.15	80.16	-73.06
9	FINE SAND	80.16	104.54	-97.44
10	SAND	104.54	138.07	-130.97
11	CLAY	138.07	141.12	-134.02
22. GOALDOV (RL=6.50)				
1	CLAY	0.00	12.10	-5.60
2	FINE SAND	12.10	39.54	-33.04
3	CLAY	39.54	42.59	-36.09
4	FINE SAND	42.59	45.64	-39.14
5	SAND	45.64	54.79	-48.29
6	FINE SAND	54.79	57.84	-51.34
7	SAND	57.84	60.89	-54.39
8	FINE SAND	60.89	76.14	-69.64
9	CLAY	76.14	91.35	-84.85
10	FINE SAND	91.35	103.54	-97.04
11	SAND	103.54	106.59	-100.09
12	CLAY	106.59	108.72	-102.22
13	SAND	108.72	145.37	-138.87



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