HYDROGEOLOGICAL AND SIMULATION STUDIES OF AQUIFER AROUND UCIL, BHOPAL

Introduction:

UCIL (Union Carbide India Ltd.) had been producing pesticides and insecticides since the inception of its factory in 1969 in Bhopal (M.P.), India. After the MIC gas leakage in December 1984, the production had stopped and subsequently the factory has been closed. Some of the structures are lying in the premises, many buildings are demolished. The industrial raw materials, produces and wastes are dumped at different places. As rainwater infiltrates during the monsoon, it is likely that some of the toxic elements may infiltrate and pollute groundwater in the area. In order to assess the groundwater regime around the area following investigations were carried out:

* Hydrogeological investigations
* Drilling of test bores,
* Aquifer characterization
* Monitoring of water levels
* Reduction of water levels to Mean Sea Level (msl), and
* Simulation of groundwater regime.

The investigations have been financed by MP State Govt. namely BGTR&RD (Bhopal Gas Tragedy Relief & Rehabilitation Directorate) and Ministry of Chemical and Fertilizer (Govt. of India).

Study area:

UCIL was established to produce pesticides at Bhopal and the factory is located in the north of Bhopal Railway Station, along the railway track towards Ujjain as shown in

Fig. 1. The production of pesticides continued till December 1984 when MIC (methylisocyanate) gas leaked and the factory was subsequently closed. There are some remains of plant and building still lying in the factory premises. There are heaps of industrial raw materials, produces and wastes lying at different places that can be easily seen at the ground surface. Many of these dumps give very pungent smell of pesticides even today, as one visit the dump sites. Although these heaps of dumps are seen at many places, the groundwater regime underneath is not well defined. It is this objective that hydrogeological investigations have been carried out.

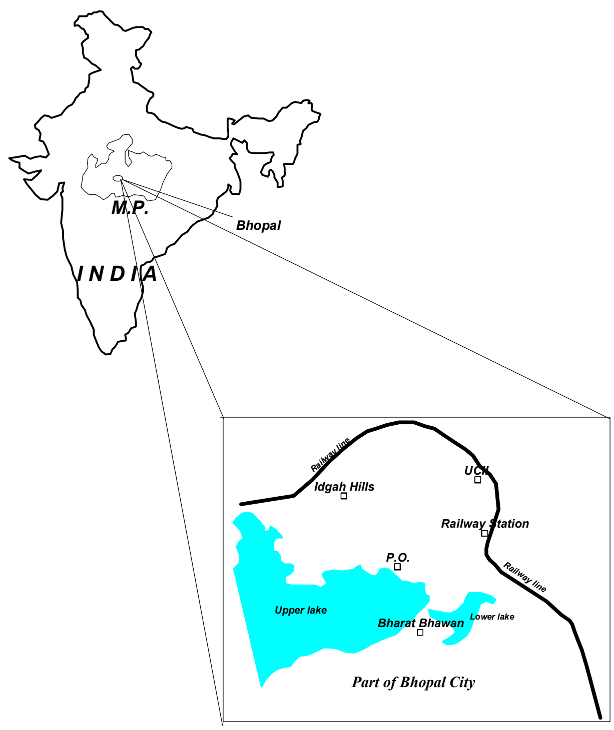

Fig. 1 Location map of study area

Hydrogeological Settings:

A broad framework of hydrogeological setting of the area around Bhopal city is described by Hussain and Gupta (1999). In general the topography around the city of Bhopal is undulating with hills formed by Vindhyan formations and valleys occupied by alluvium and basalts. Similarly, the water resources assessment is described by Gupta and Bharadwaj (2006). A detailed geological map of city of Bhopal is presented by Hussain and Gupta (1999). A geological profile across the study area is also presented by Burmeier et al (2005). Basaltic formation is reported to be pinching out in the study area and is underlained by Vindhyans. The Vindhyan sandstones occur with intercalation of shale and conglomerates at deeper depths. The quartzitic and ferruginous sandstone is reported to be compact with poor permeability. The upper part of Vindhyan is weathered sandy alluvium with pebbles. The geomorphological map described by Gupta and Bharadwaj (2006) indicates that the study area lies in the pediplain. The weathered basalt overlying the Vindhyans is reported to be thin, shallow and poor in groundwater potential.

In order to explore more details about the subsurface geology, initially geophysical imagings have been carried out (Singh et al 2009). A typical 2D profile carried out in the southern part of the area is shown in Fig. 2.

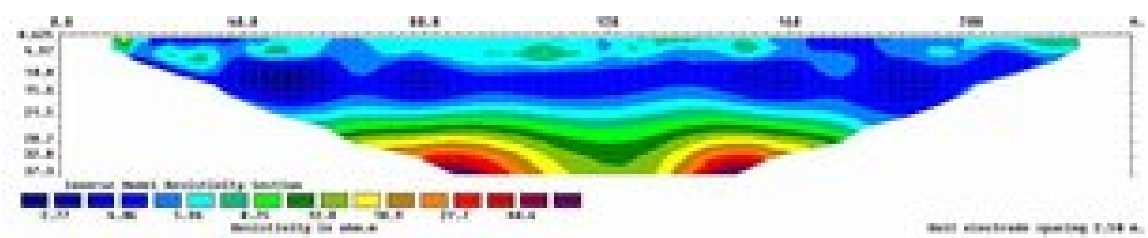

Fig. 2: 2D geo-electrical Profile

It can be seen that the area is covered with low resistivity as deep as about 25-30m indicating occurrence of clay/alluvium sandy clay or weathered basalt. It is followed by increase in resistivity indicating saturated weathered basalt or weathered Vindhyans.

The ground elevation of the study area is shown in Fig. 3. It indicates that the general slope of the area is towards southeast.

In order to understand the groundwater regime around the premises, well inventory has been carried out in and around the area in the month of November 2008 (Table 1). There is only one bore well in the study area. The bore well exists at the entrance of the area in the southern part. Seven other existing wells were selected at the periphery of the area to monitor water level as shown in Fig 4. Although there exists numerous wells at the periphery of the area, however monitoring of these wells are difficult as these are continuously being pumped for domestic use. Further, it is difficult to make measurement of water level on many of existing wells. Well no. 4 & 5 are close to each other, hence only one was monitored. The depth of these wells varies from 55 to 68m except for well no. 2 which is shallow (9.5m deep) dug well. The diameter of these bore wells is 0.085m (except for well no. 2 which has 3.2m dia). The water level below ground level measured during November 2008 is depicted in Fig. 5. It can be seen that shallow groundwater exist in the south western part where as deep water level is recorded in the eastern part. These water levels are immediately after the monsoon and can be treated as post monsoon level. The electrical conductivity (EC) value of the groundwater which is indication of major cation and anion varies from 800 to 1600 micromhos. It is maximum in the south eastern part which is also in the vicinity of populated as well as industrial area. The variation of EC is shown in Fig. 6.

The well hydrograph is shown in Fig. 7 depicting variation in the water level. It can be observed that water level variation ranges from 3.4m to 23.37m due to monsoon of 2008-09.

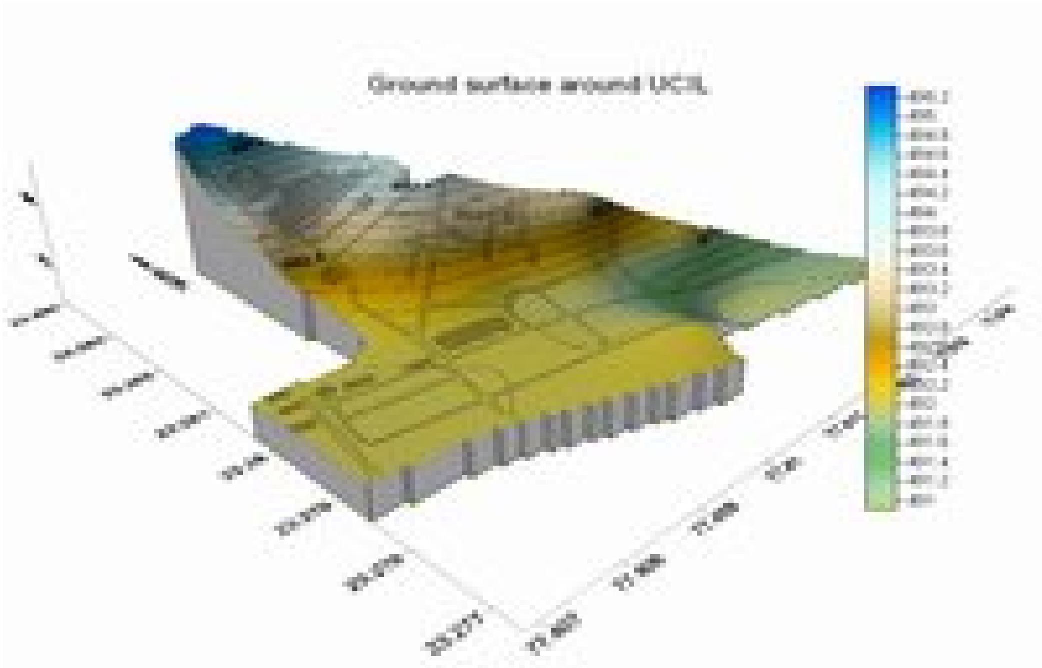

Fig. 3 Ground elevation map of area

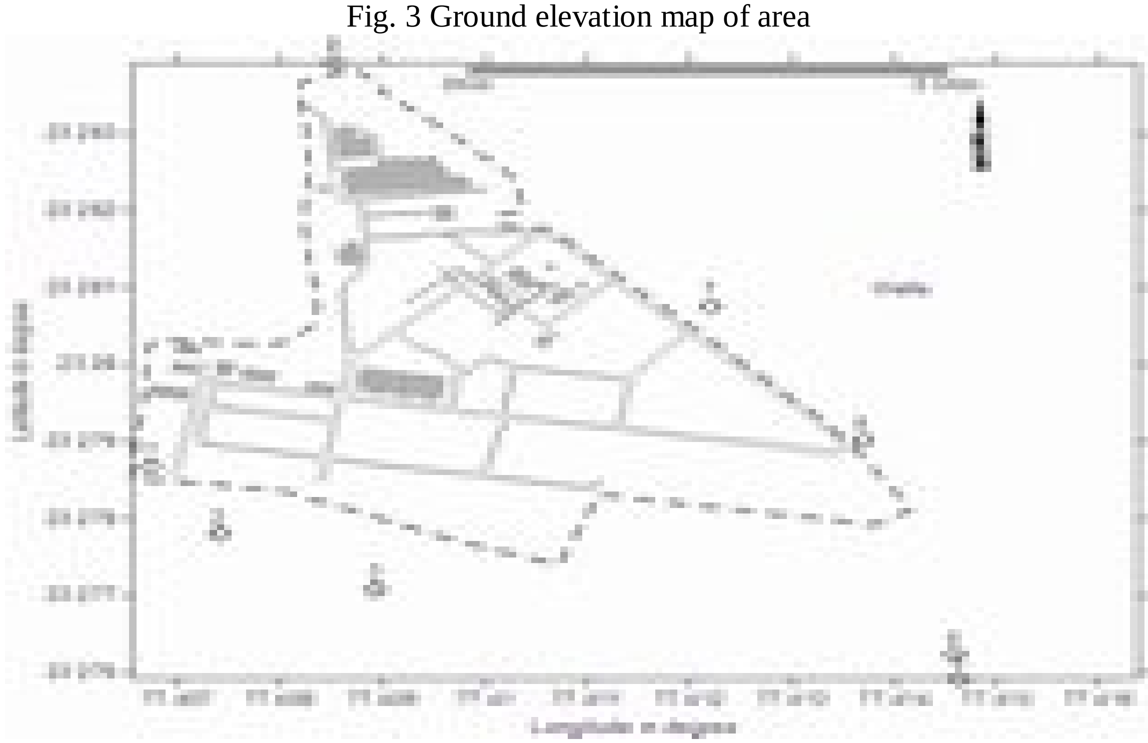

Fig. 4 Well Location map

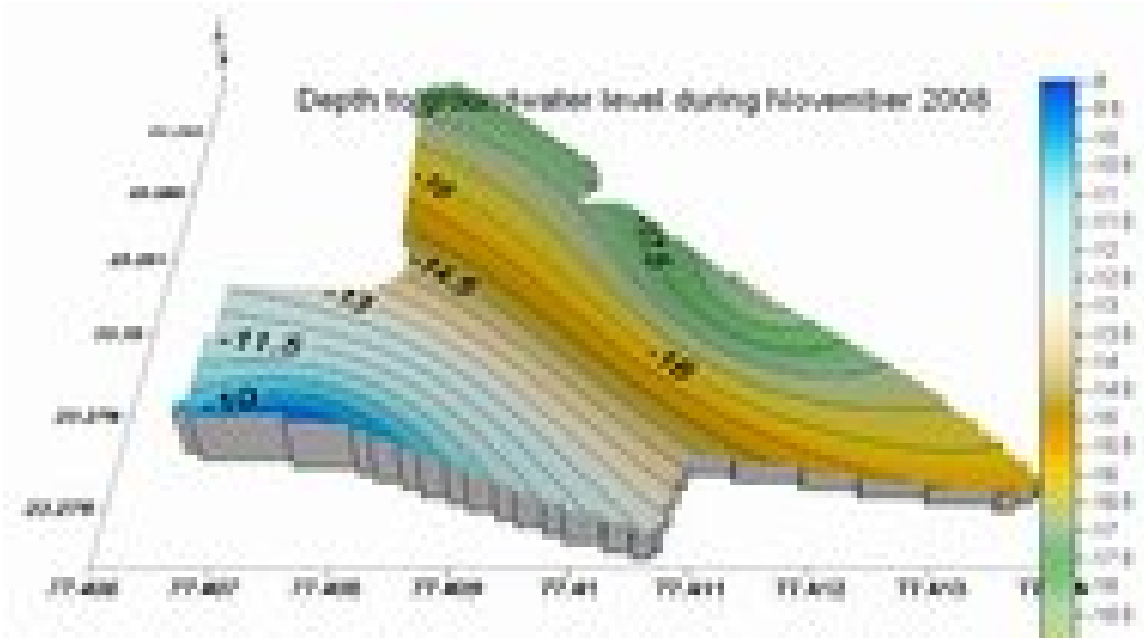

Fig. 5 Depth to water level during November 2008

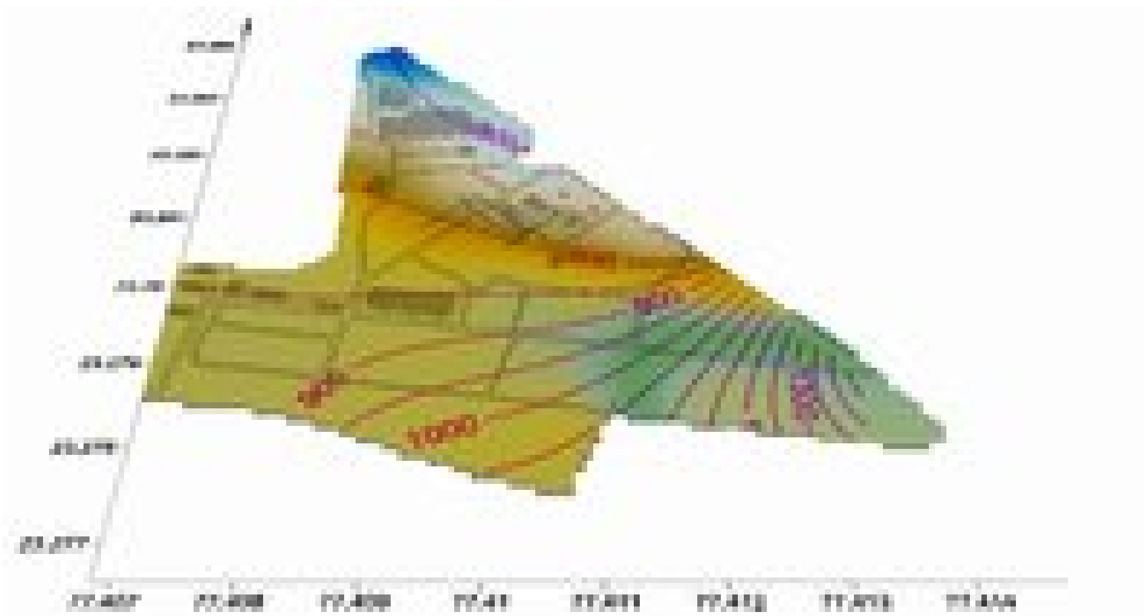

Fig. 6 EC value during November 2008

Table 1: Well inventory

Well No.	Location	Diameter (in m)	Depth (in m)	Water level (below measuring point) (in m)	Measuring Point above ground (in m)	Well type	Well use	Electrical Conductivity in µmhos
1	At the entrance of UCIL	0.085	≈60	10.66	0.4	Bore Well	unused	900
2	Electricity office opp. UCIL	3.2	9.5	7.3	0.6	Dugwell	unused	800
3	Opp. Rajeev Bal Kendra	0.085	≈60	12.0	0.5	Bore Well	domestic	1100
4	Near Railway crossing	0.085	≈55	14.62	0.25	Bore Well	unused	1200
5	Near Ganesh Temple at Railway crossing	0.085	≈55	13.76	0.4	Bore Well	domestic	1000
6	Along Railway line, Ayubnagar	0.085	≈60	17.1	0.6	Bore Well	domestic	1600
7	Near Railway cabin, Ayubnagar	0.085	≈68	19.95	0.5	Bore Well	domestic	700
8	At northern end of UCIL near Rly line	0.085	≈65	18.2	0.5	Bore Well	domestic	800

The lowest variation of 3.4m is observed in the shallow dug well outside the area and it may be a localized shallow aquifer. The remaining all the bore wells have shown similar behavior with a variation of about 9-10m, except for a well in the eastern part (23.37m) which has very high abstraction (almost running for 24hrs).

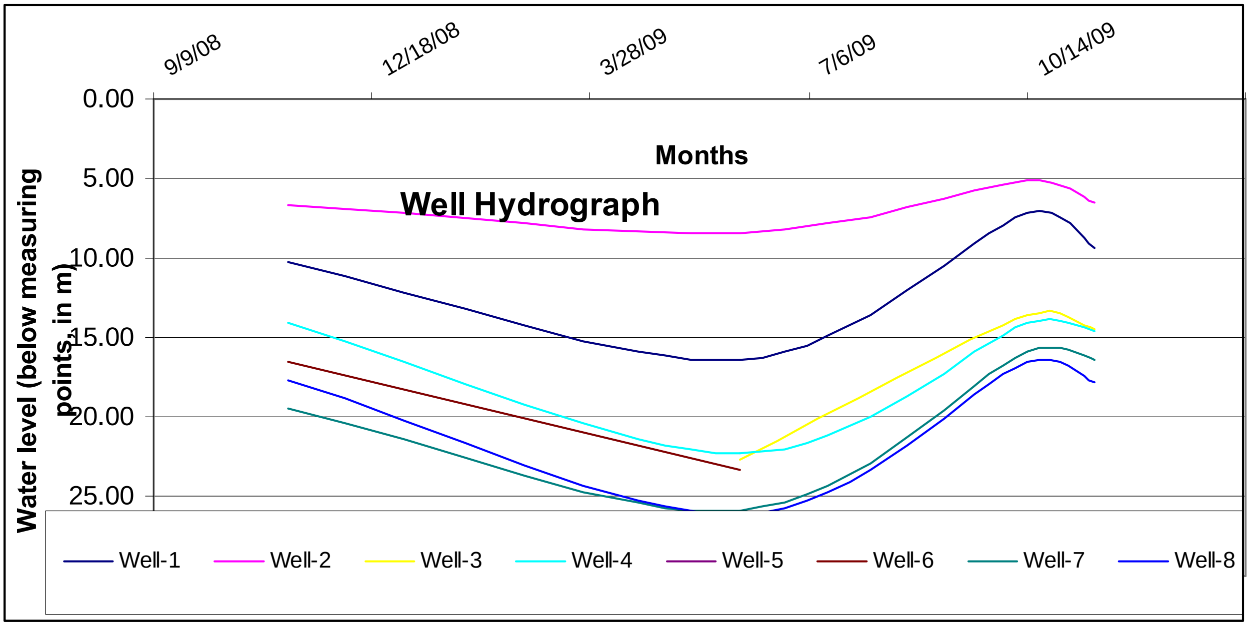

Fig. 7 Well Hydrograph of wells at the periphery of area

Drilling of test bore wells:

As there were no wells in the vicinity of plant, neither any lithological information was available; five sites were selected to carry out drilling for exploration of aquifer zone in the area. The selected sites for drilling are shown in Fig. 8. Lithologs were collected at different intervals during drilling. The lithological description of each site is given below.

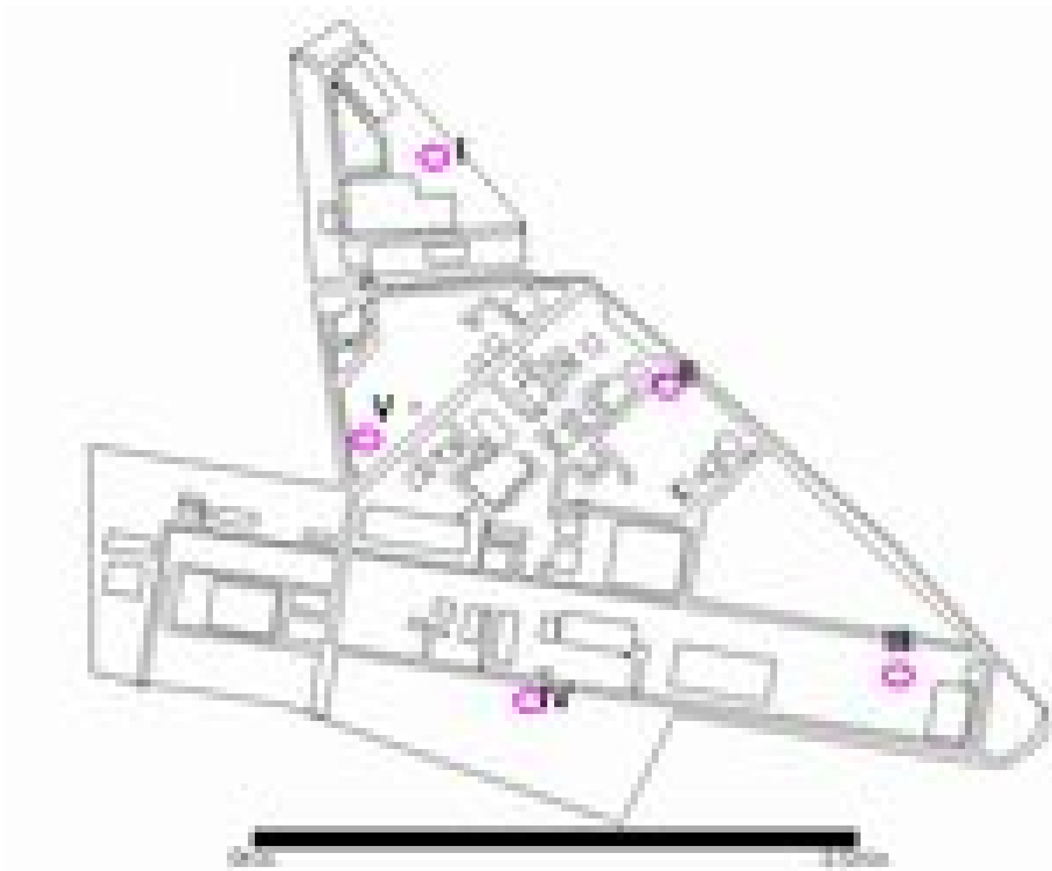

Fig. 8 Location of Drilling sites

Site I : Drilling has been carried out in the northern part of the area in the front of formulation plant as shown in Fig. 8. The drill litholog is shown in Fig. 9.

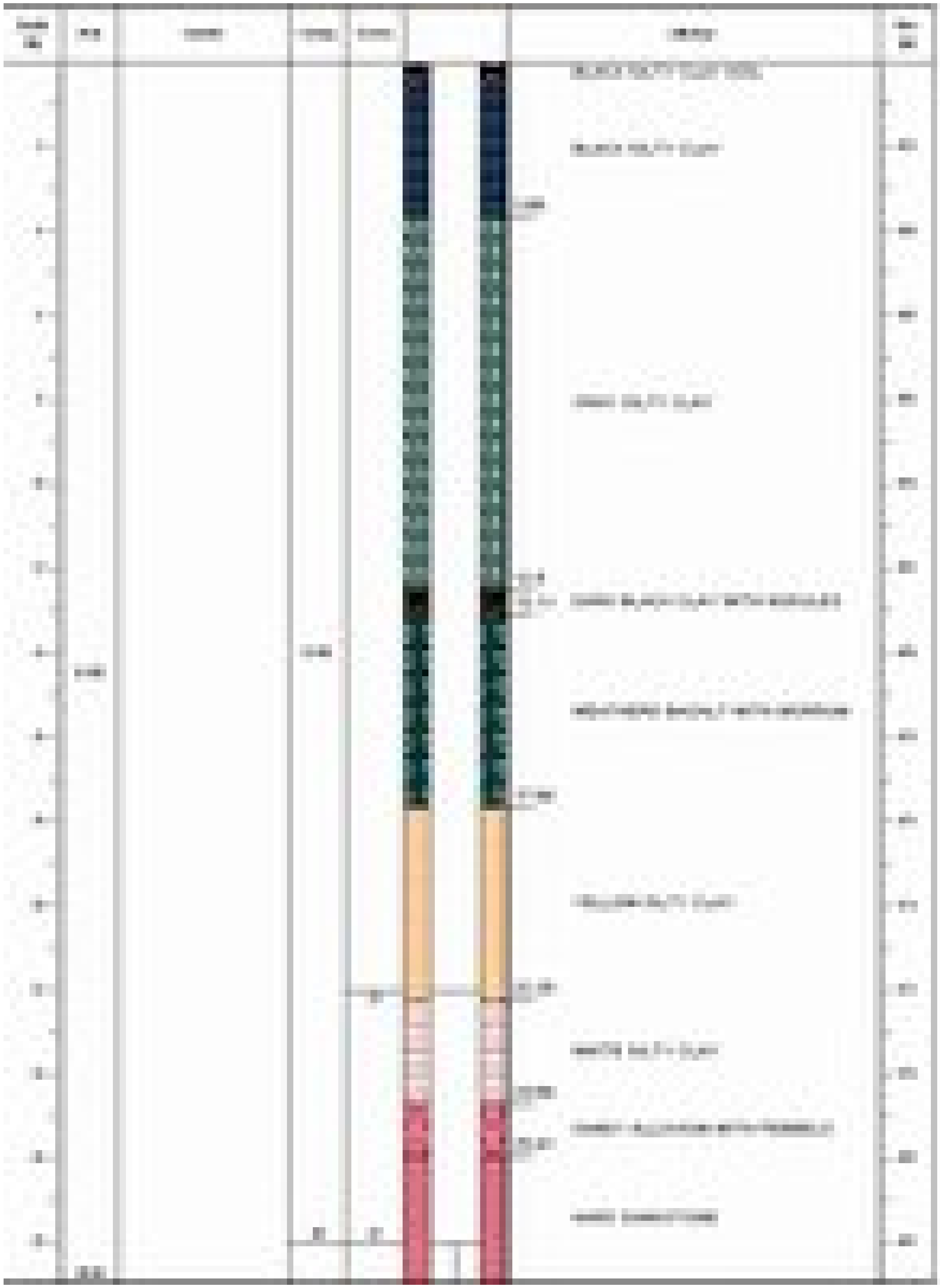

Fig. 9 : Litholog and drill time log.

The litholog (Fig. 9) shows top is covered with black cotton soil followed by gray to black silty clay. It is underlained by weathered basalt of about 4.5m thick which is devoid of water. Further it is followed by yellow and white silty clay up to 24m. The sandy alluvium with pebbles has encountered at about 24m with 1.5m thickness. This zone is saturated with water and it is further followed by hard sandstone where drilling was terminated. The water was struck at 24m. The water level measured after 24hr was 9.14m below ground level (bgl).

Site II: The site was selected considering geophysical investigations. The drilling was carried out in the vicinity of plant and on the east of road (Fig. 8). Initially black cotton soil was encountered which was followed by silty clay formation. The litholog is shown in Fig. 10. The silty clay continued upto about 13m followed by weathered basalt of about 2.7m thick. It was further followed by silty clay upto 22m. The alluvium with pebbles is underlained with a thickness of 2.5m followed by hard sandstone. The water was struck at 22m. The water level measured after 24hr was 9.10m bgl.

Site III : The site was selected in the southeastern part of the area, near solar evaporation pond as shown in Fig. 8. The litholog obtained during drilling is shown in Fig. 11. The top layer of gray silty clay is overlained by black cotton soil. The weathered basalt of about 5.2m is followed by again silty clay up to the depth of 23m. The alluvium with pebbles is encountered with a thickness of 4.6m which is underlained by hard sandstone and drilling was terminated thereafter. The water was stuck at 22.85m. The water level measured after 24hr was 8.5m bgl.

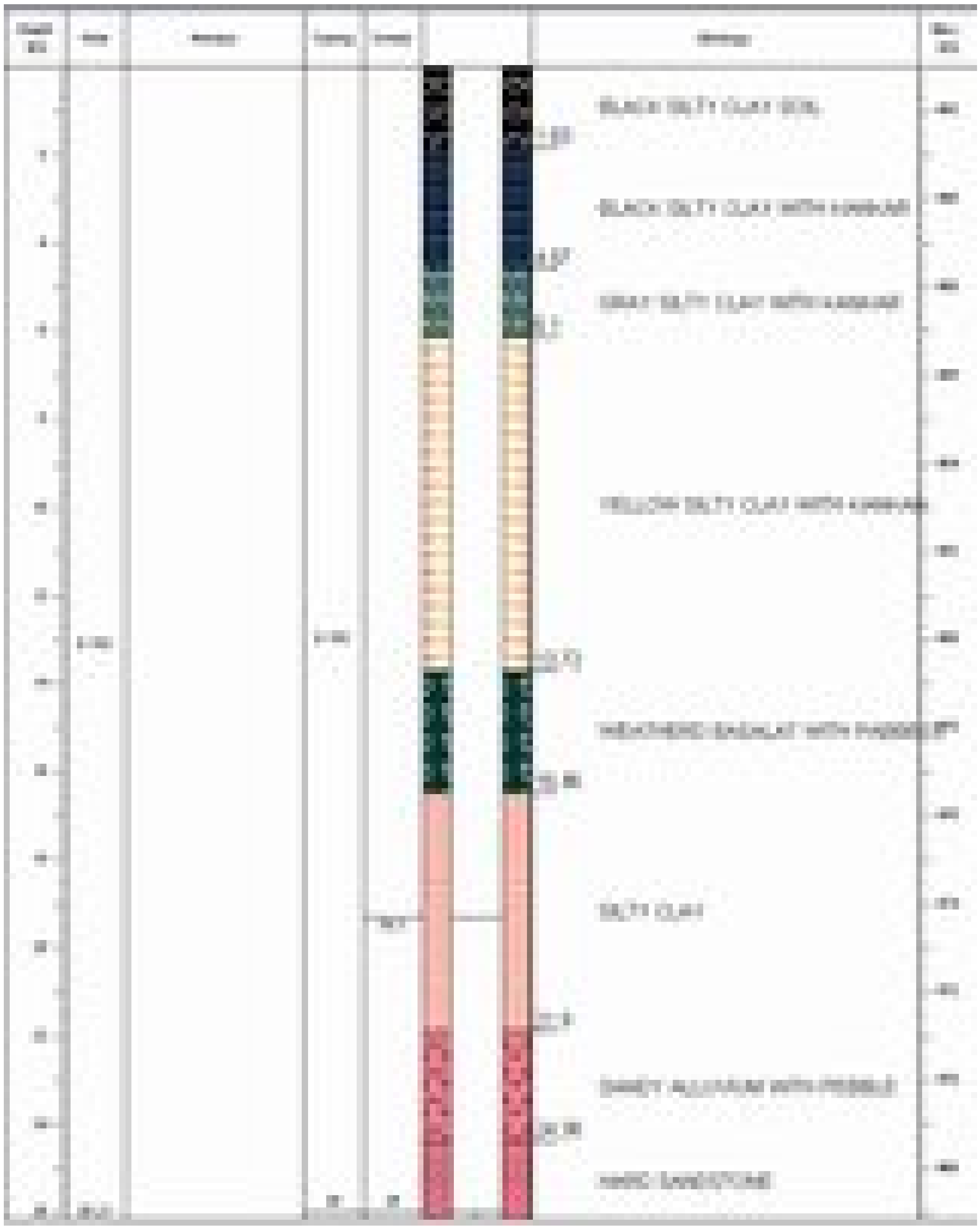

Fig. 10 Litholog and drill-time log at site II

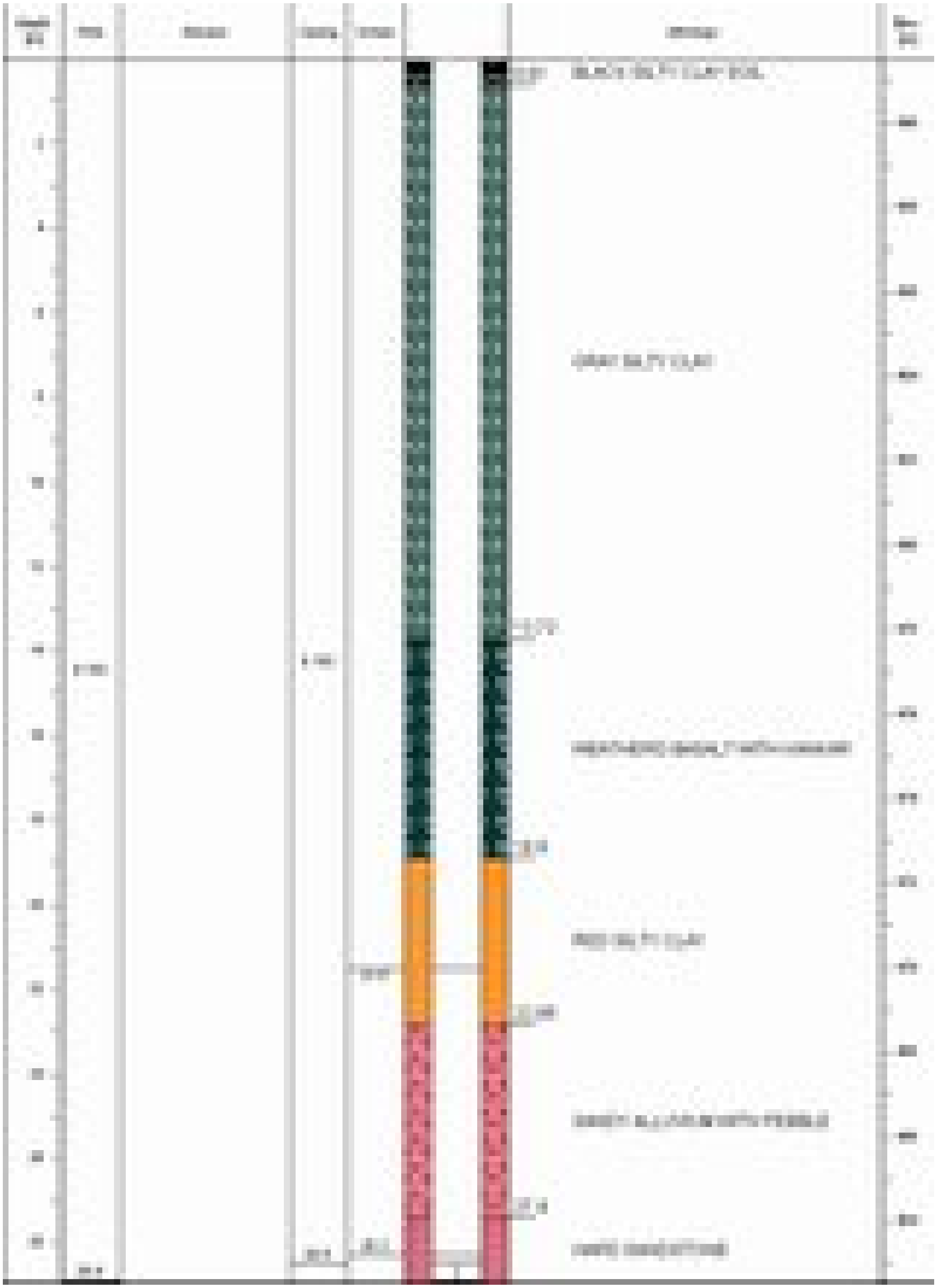

Fig. 11 Litholog and drill-time log at site III

Site IV:

The site was selected in the southern part of area as shown in Fig. 8. The black cotton soil is found at the surface underlained by silty clay up to a depth of 14m. Weathered basalt has been encountered below it with a thickness of 2.4m. Further, it is underlained by silty clay up to 25m. The alluvium with pebbles has been encountered with a thickness of 0.7m, followed by hard sandstone. Litholog is shown in Fig. 12. Water was stuck at 25m. The water level measured after 24hr was 8.94m bgl.

Site V

The site was selected in the western part of the area. The near surface black cotton soil is underlained by black clay up to the depth of 10.3m. It is followed by weathered basalt of 6m thickness. Further, silty clay has been found up to a depth of 23m. Alluvium with pebbles has been encountered with a thickness of 1.4m underlained by hard sandstone. The litholog is shown in Fig. 13. Water was struck at 23m. The water level measured after 24hr was 14.2 m bgl.

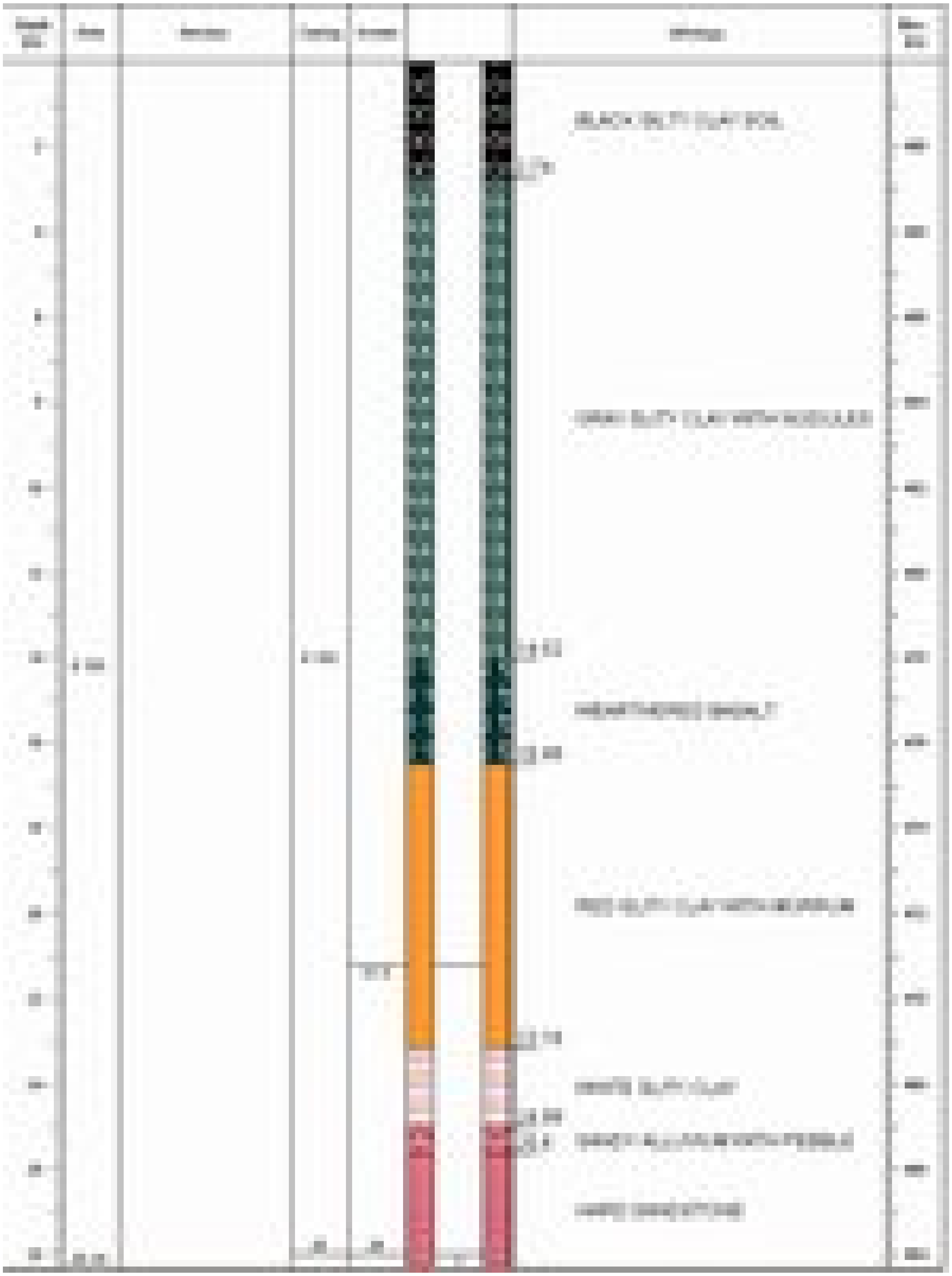

Fig. 12 Litholog at site IV

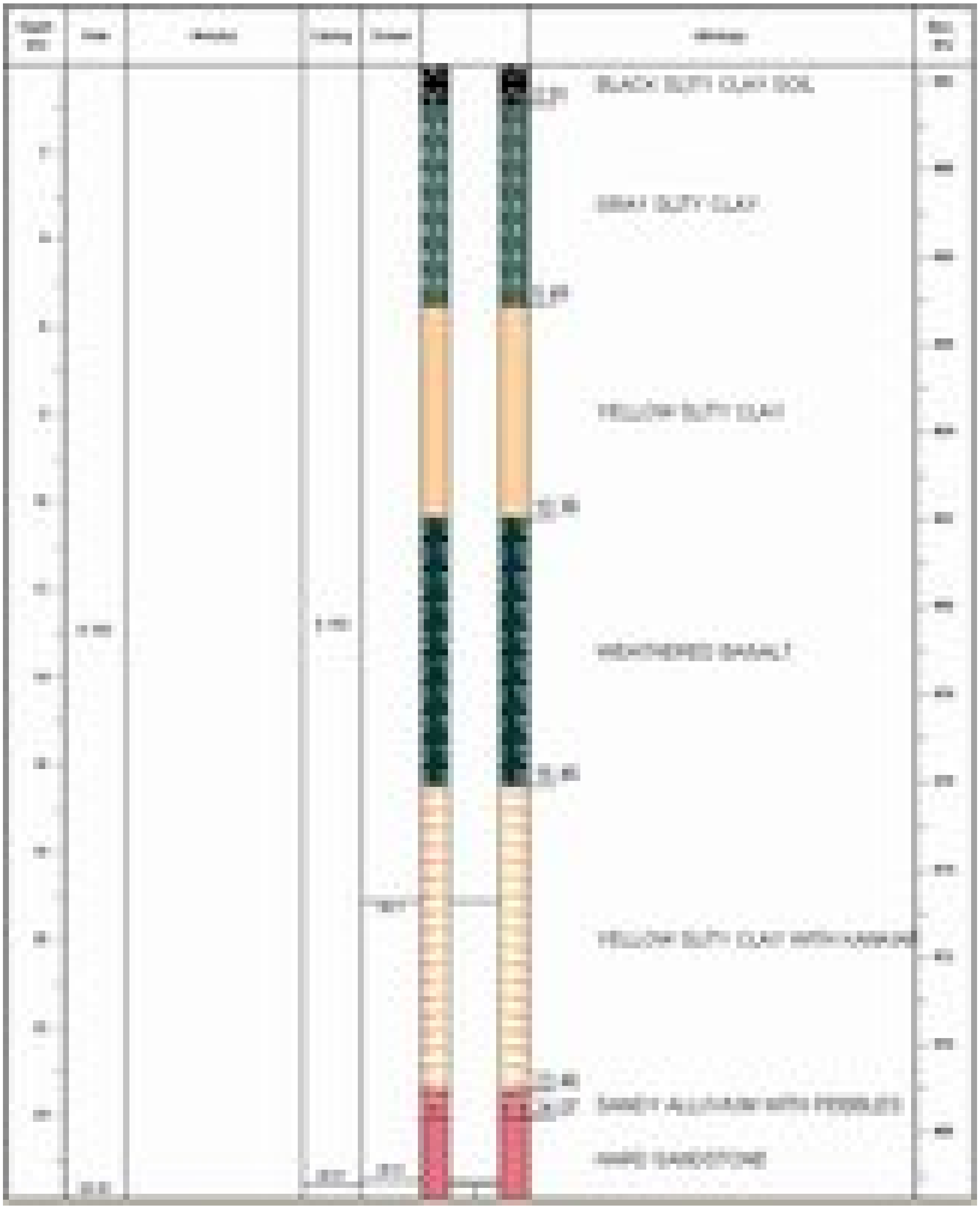

Fig. 13 Litholog at site V

A fence diagram based on the lithologs is shown in Fig. 14. The weathered basalt is found to be overlained by black silty clay of 10 to 17m below ground surface. Its thickness varies from 2.7 to 6m being thick in western part. The basalt is further underlained by yellow silty clay and its depth varies from 22 to 25m. The underneath formation is sandy alluvium with pebbles which is saturated with water forming aquifer. The thickness of this aquifer varies from 0.7 to 4.6m being thickest in eastern part as shown in Fig. 15. Water has been struck at about 22 to 25m below ground surface and risen to about 8.5 -14m indicating aquifer may be in confined condition. All the bore wells are screened only in the lower part against aquifer and remaining portion is sealed with iron casing.

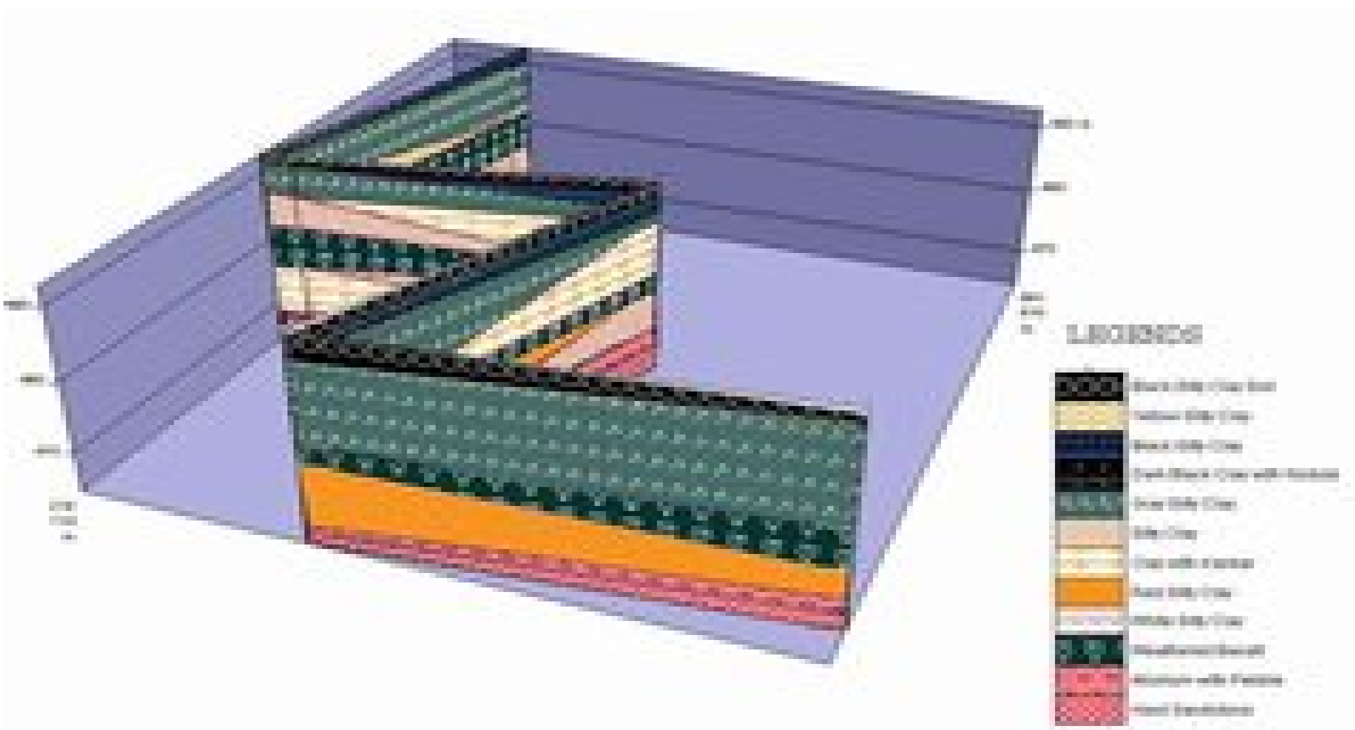

Fig 14 Fence diagram showing geological strata

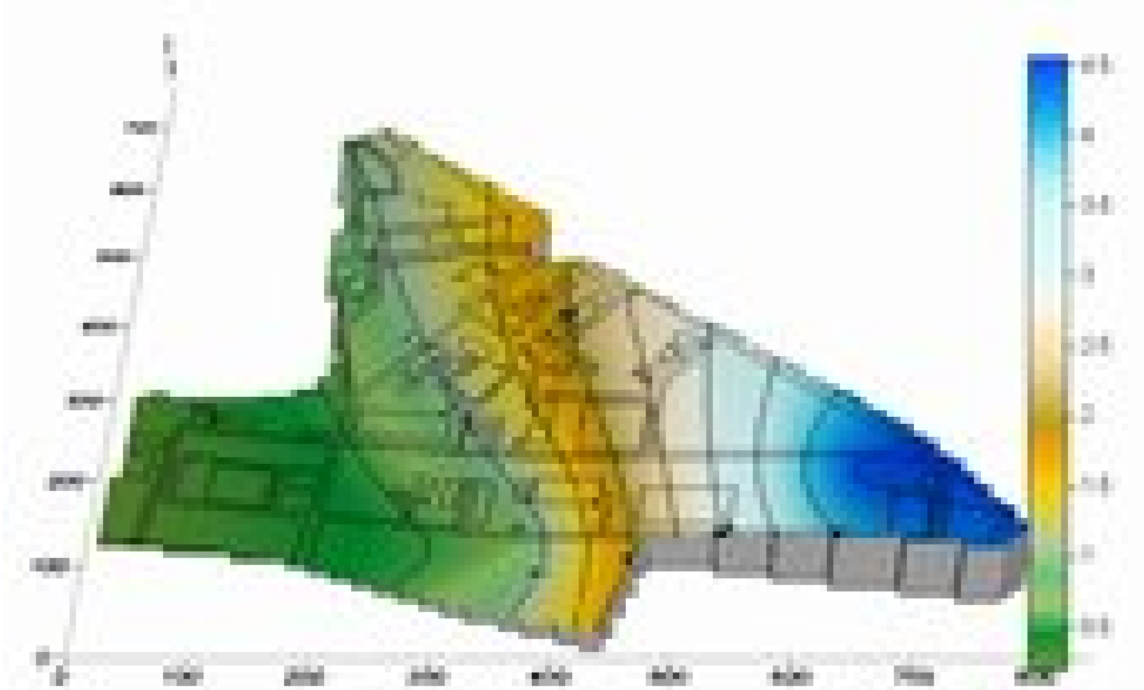

Fig. 15 Aquifer thickness distribution

Characterization of Aquifer :

In order to determine aquifer characteristics, experiments were carried out at each bore wells. In many situations the bore wells water are not desired to be pumped or there exists only one well or the well is poor yielding. In such cases slug tests are carried out to get aquifer parameters. The procedure involves either instantaneously adding or removing a measured quantity of water from a well, followed by making a rapid series of water-level measurements to assess the rate of water-level recovery (either rising-head or falling-head). These evaluations have advantages and disadvantages when compared with other methods.

Advantages of the slug test method include:

- Relatively low cost.

- Requires little time to conduct slug test(s).
- Involves removal of little or no water from the aquifer.

More accurate results are generally obtained when using a data logger to collect water-level versus time measurements during the test. The transducer is placed in the well below the pre-test water-level at sufficient depth to permit testing (adding and/or removing a "slug" of water). An instrument (data-logger) records water-depth above the transducer before, during, and after the "slug" is introduced. The "slug" is introduced instantaneously (either raising or lowering the water-level) and a series of water-level versus time measurements are made as the water-level changes toward an equilibrium situation. The measurements are collected automatically by the transducer and data-logger, usually at pre-programmed time intervals.

For the data-logger/transducer method of conducting slug tests we have found that the rapid addition of a solid metallic cylinder displaces a known quantity of water in the well bore. Adding the cylinder causes an abrupt rise of water-level and rapid removal of the cylinder causes an abrupt drop in water-level in the well. Typically the cylinder is constructed of MS tubing capped at each end. We have used 0.95m long cylinder of 3.5 inches diameter in slug tests.

Slug tests were conducted at all the drilled bore wells. These data were used for deriving aquifer transmissivity using method described by Cooper et al (1967) and using software AquiferTest Pro (2007).

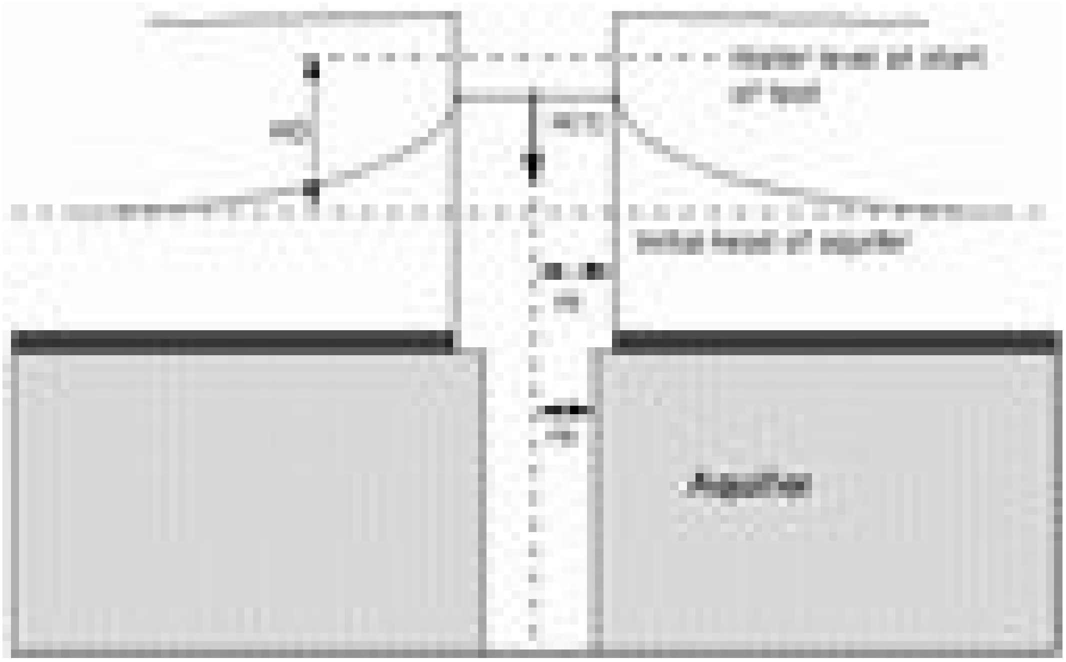

Fig.16 Slug Test (after Cooper et al 1967)

The following considerations are made for slug tests:

- The aquifer is isotropic, homogeneous, elastic and compressible,
- The aquifer is confined,
- The aquifer is infinite in areal extent and horizontal,
- The Darcyȏs law is applicable to the flow domain,
- The aquifer is fully penetrating, and
- The change in the water level is instantaneously at t=0 .

A detailed picture of slug test is shown in Fig. 16. It is assumed that a volume of slug V is added to the well and this causes sudden rise of water level in the well. Considering water level H_t observed above static water level at any time t after the slug was introduced, and H_0 the instantaneous rise in water level at time t =0**,** the following expression is derived by Cooper et al (1967) :

$$H_t = \frac{2H_0}{\pi}\int_0^\infty \exp(-\frac{\beta u^2}{\alpha})(J_0(\frac{ur}{r_c})[uY_0(u) - 2\alpha Y_1(u)] - Y_0$$
$$(\frac{ur}{r_c})[uJ_0(u) - 2\alpha J_1(u)])(\frac{1}{\Delta(u)})du$$

Where $\Delta u = [uJ_0(u) - 2\alpha J_1(u)]^2 + [uY_0(u) - 2\alpha Y_1(u)]^2$ and

$$\alpha = (r_w^2 S)/r_c^2 \qquad \beta = \frac{Tt}{r_c^2}$$

The type curves are given by Copper et al (1967) for the estimation of T. H_t/H_0 is plotted against time t. This plot is matched with the type curve given by Cooper et al (1967). After getting a close match, the value of time t is noted for which $\frac{Tt}{r_c^{\,2}} = 1$, where T is transmissivity and r_c is radius of well casing where water level fluctuates.

The software Aquifer Test (2007) utilizes optimization as well as forward technique to get best fit. The slug test data obtained during test with interpreted curves are shown in Fig. 17 to 21. The transmissivity values obtained are shown in Table 4. These values are representative of aquifer in the vicinity of bore wells. These values are found to vary from 4.29 to 24m^2/d. Considering the aquifer thickness the permeability in the vicinity of the well is found to vary from 5.31 to 7.55 m/d. It can be seen that the permeability of aquifer is slightly higher in the south western part and minimum in the north eastern part of the area.

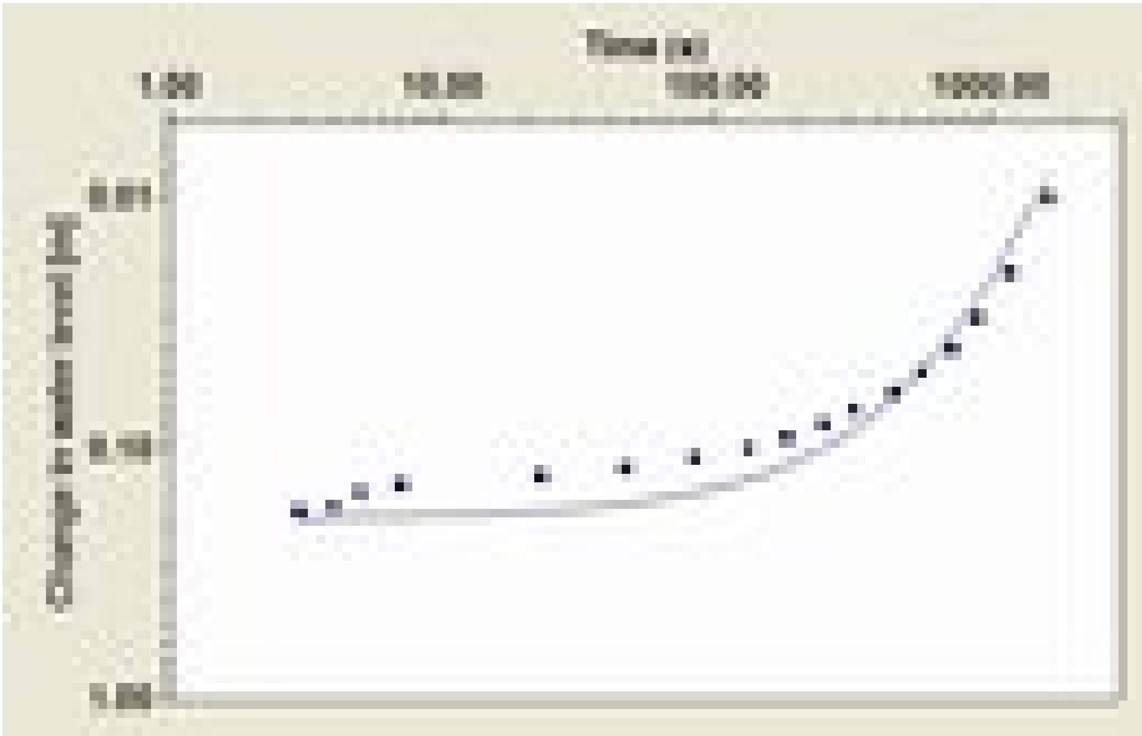

Fig. 17 Match with type curve at Well 1

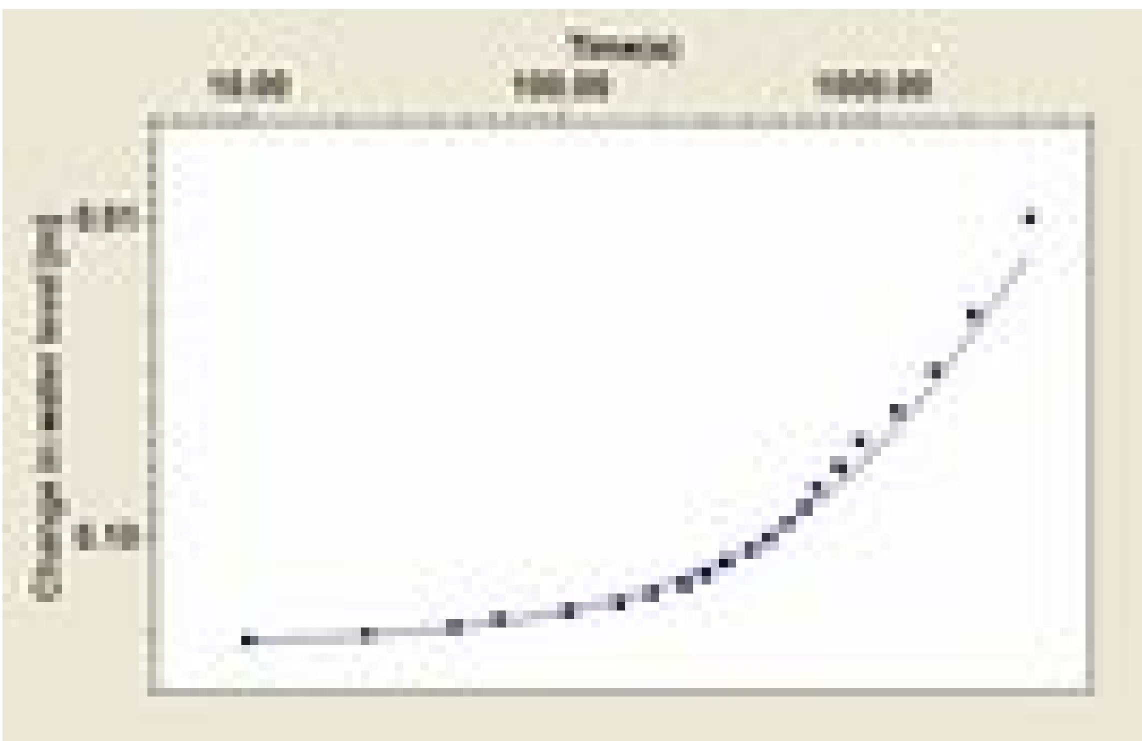

Fig. 18 Match with type curve at Well 2

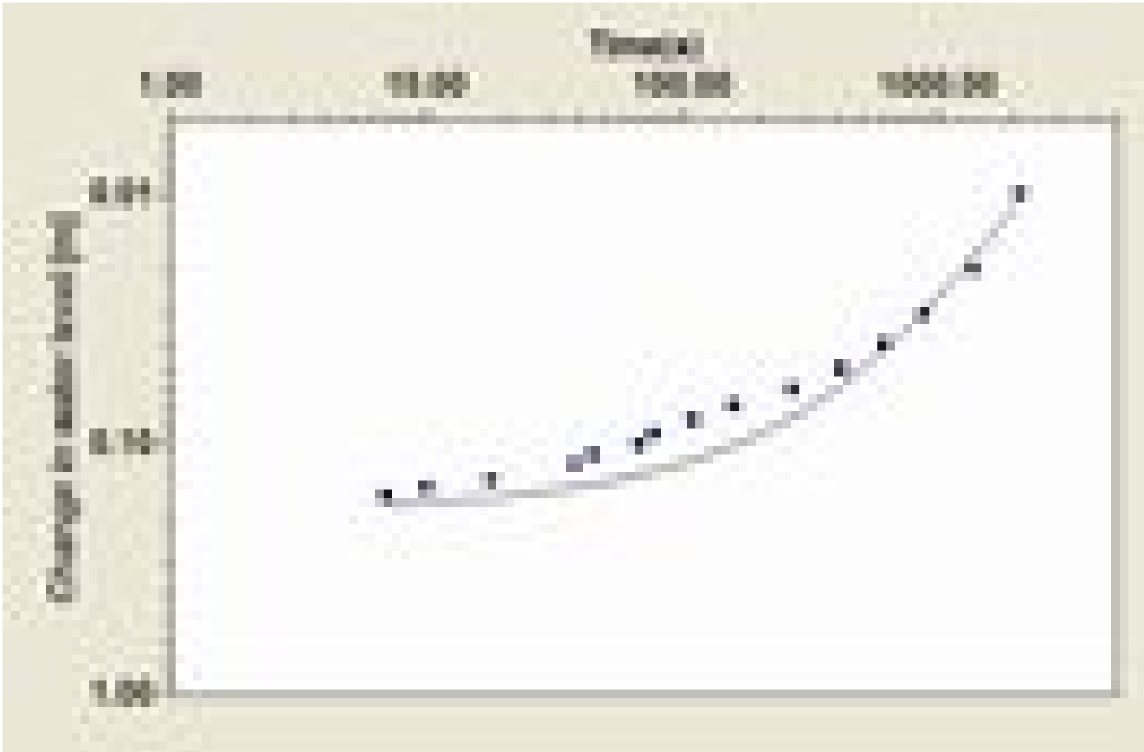

Fig. 19 Match with type curve at Well 3

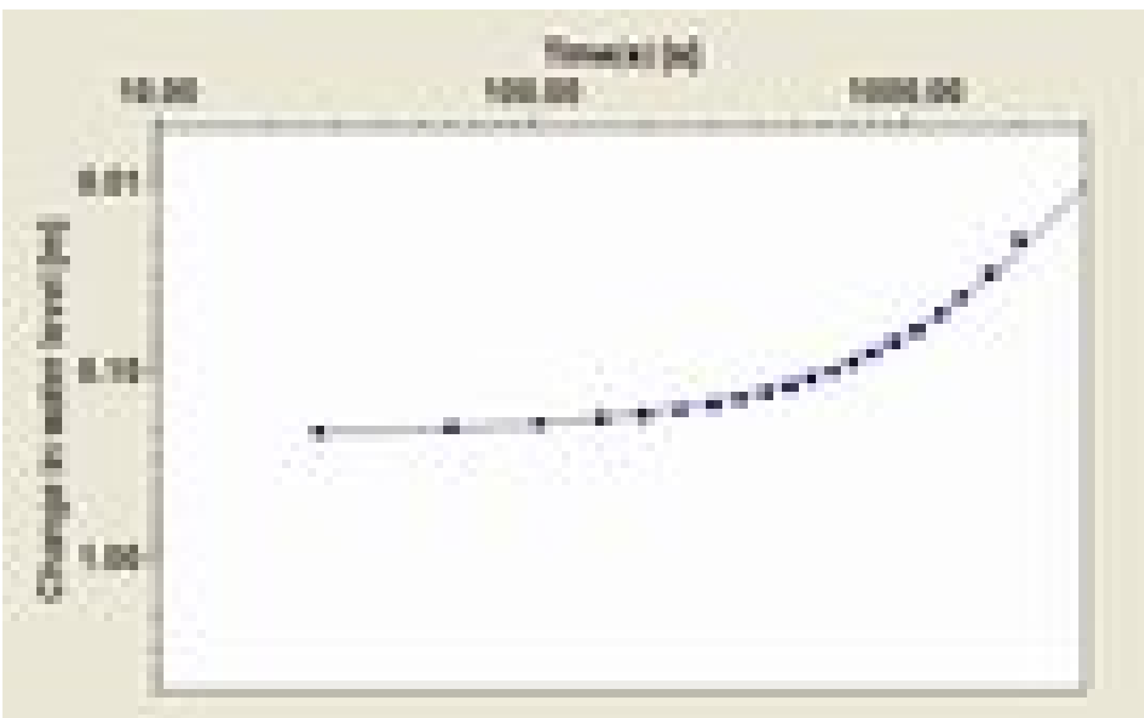

Fig. 20: Match with type curve at Well 4

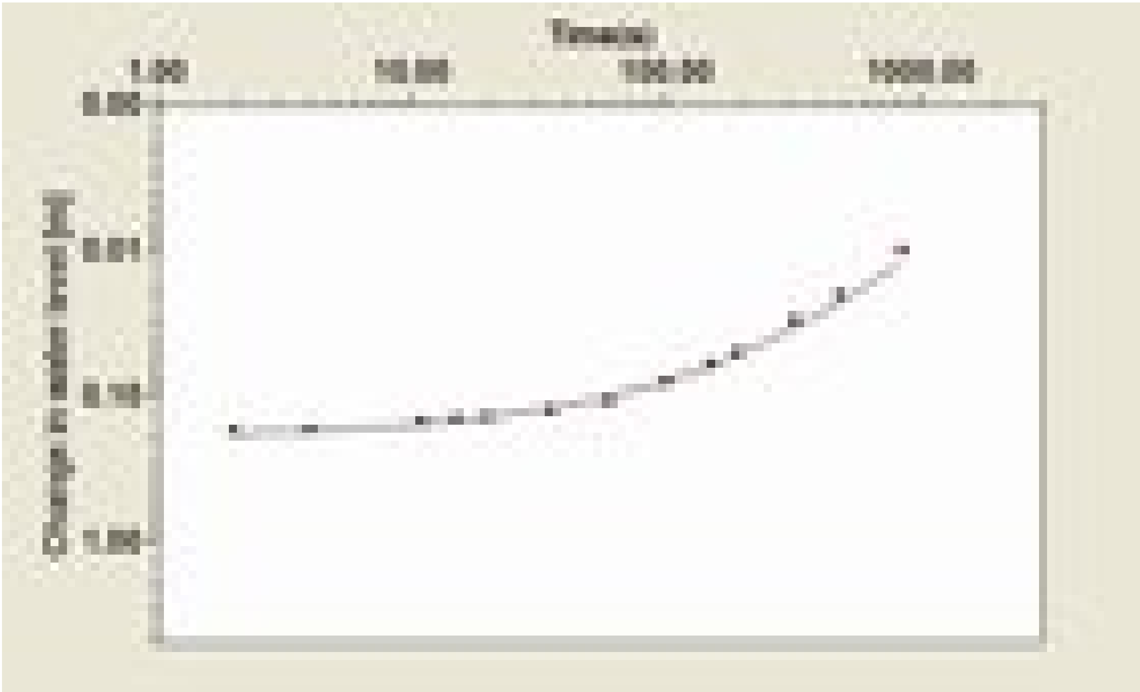

Fig. 21: Match with type curve at Well 5

Table 4: Transmissivity derived from Slug Test

Well No.	T (m^2/d)	K (m/d)
1	7.0	5.73
2	24.2	5.31
3	4.29	7.0
4	18.1	7.29
5	4.61	7.55

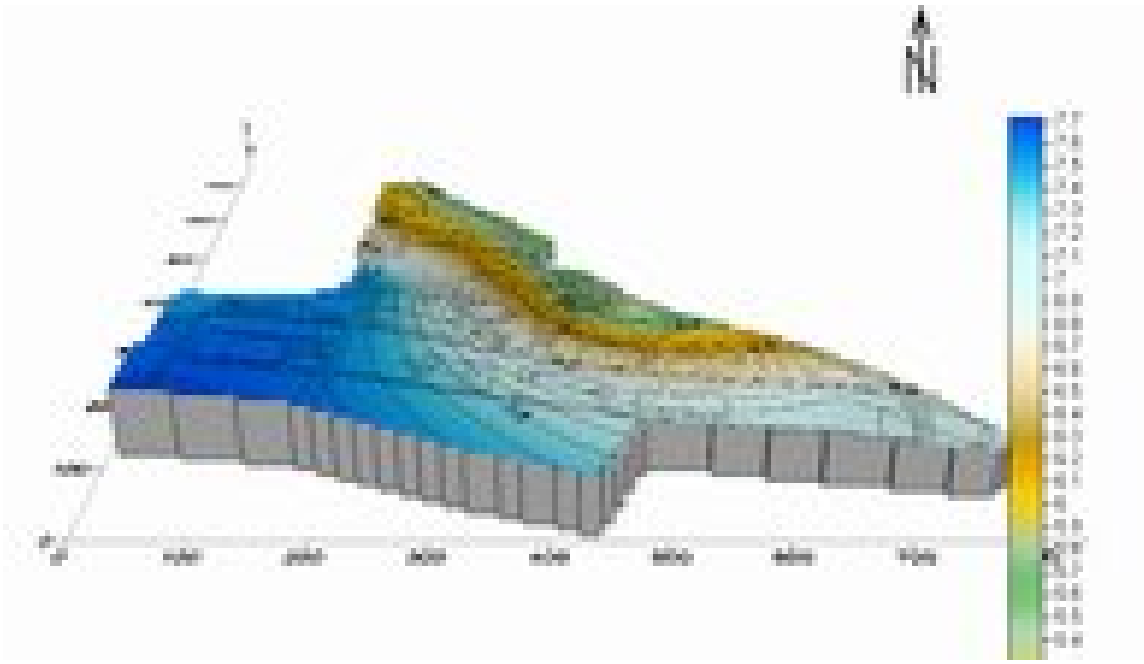

Fig.22: Permeability distribution map

Groundwater flow :

In order to obtain groundwater flow in and around the study area, water levels in all the wells have been monitored. The location of these wells is shown in Fig. 23. The existing wells are denoted by numbers where as the new bore well numbers are preceded with BH.

The water levels in all the wells have been recorded on February 18, 2010. The measuring point of each well has been connected to mean see level through surveying. The Bench Mark value obtained from Survey of India, Dehradun, was used for this purpose.

All the water levels have been considered to prepare water level map for the month of February, 2010. It is shown in Fig. 23. The groundwater elevation varies from 475 to 487m above mean sea level (amsl). The maximum elevation lies in the southern part whereas the lowest level lies in the southeast corner of the area.

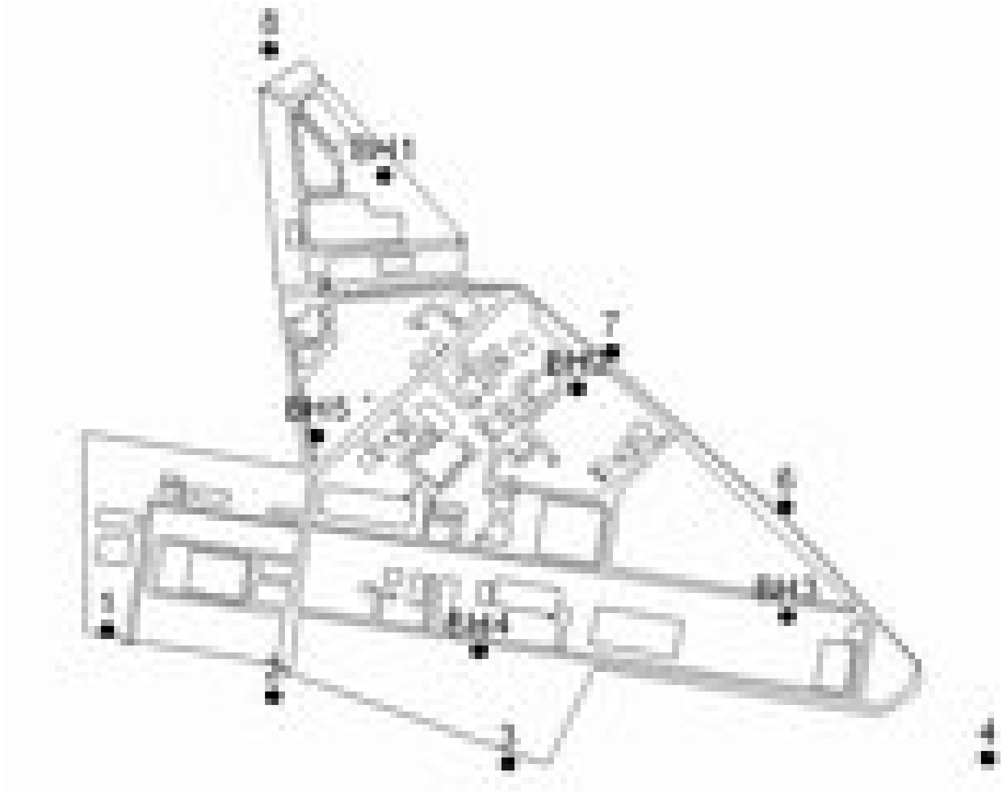

Fig. 23 Location of monitoring wells during Feb. 2010

Fig. 24: Groundwater flow map for February 2010

The hydraulic gradient for the month of February 2010 is depicted in Fig. 25. The hydraulic gradient varies from minimum of 0.001 in the southeastern part to a maximum of 0.1699 in the southern part as shown in Fig. 25. The vectors indicate the groundwater flow direction which in general in south east except in the western part which is due to low water level in well no. 5. These characteristics are variable and may change with time.

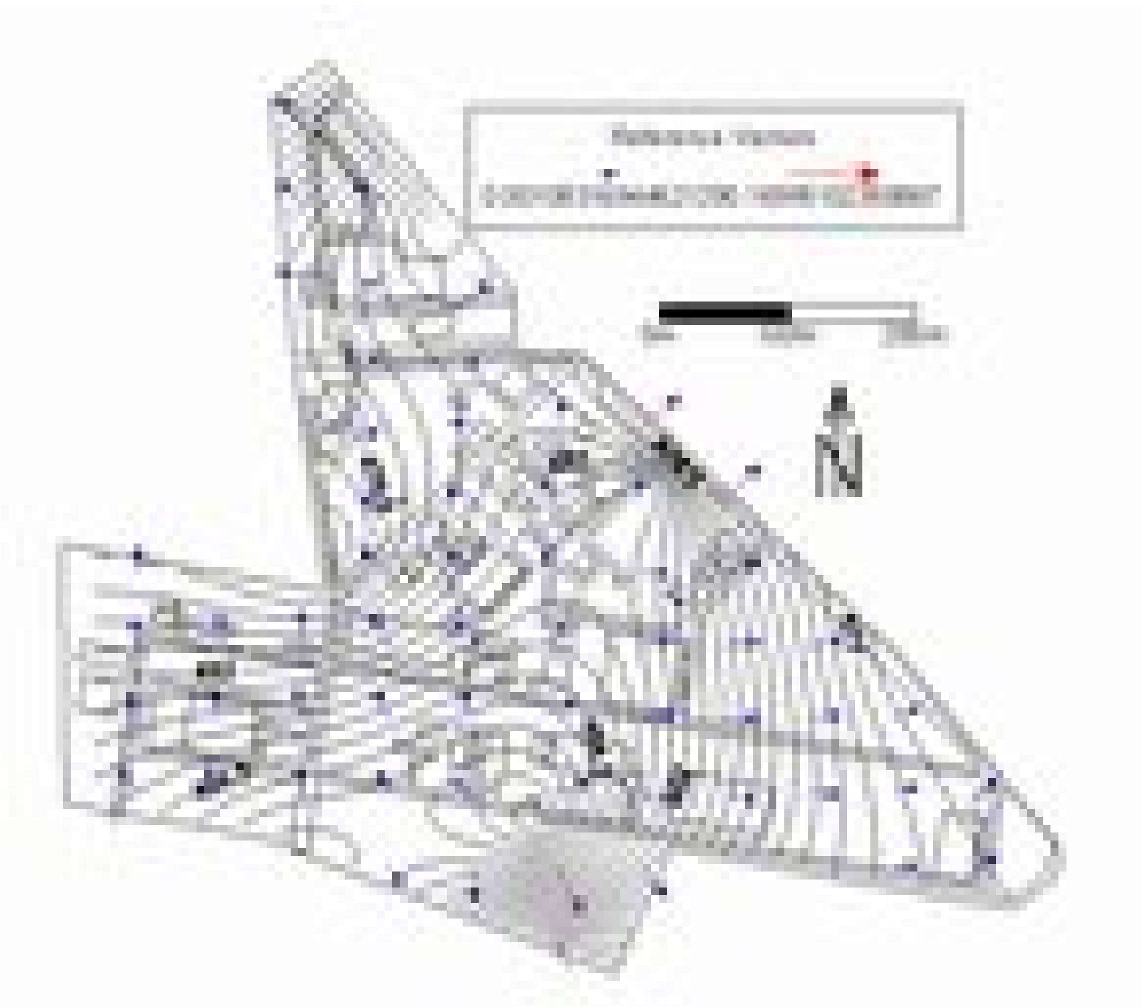

Fig. 25: Hydraulic gradient map for February 2010

SIMULATION OF GROUNDWAT ER REGIME

In order to understand the groundwater regime in the area and its behavior to various stresses in terms of water level variation, an attempt has been made to construct a mathematical model of the area. A physical frame work of the area has been prepared and the aquifer characteristics have been assigned. The boundary conditions as observed in the field have also been assigned. The various inputs to the model have been arrived from the available data. The model was then calibrated against the observed water level. The model was then used as a tool to visualize the long term effect on groundwater.

Mathematical Formulation:

Essentially, mathematical modeling of a system implies obtaining solutions to one or more partial differential equations describing groundwater regime. In the present case, it was assumed that the groundwater system is a two dimensional one wherein the Dupit-Forcheimer condition is valid. The partial differential equation describing two dimensional groundwater flow may be written in a homogeneous aquifer as

$$\frac{\partial}{\partial y}\left(T_x \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial y}\left(T_y \frac{\partial h}{\partial y}\right) = S\frac{\partial h}{\partial t} \pm W \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where

T_x, T_y = The transmissivity values along x and y directions respectively.

h = The hydraulic head

S = Storativity

W = The groundwater volume flux per unit area (+ve for outflow and ï ve for inflow

x, y = The Cartesian co-ordinates.

Usually, it is difficult to find exact solution of equation (1) and one has to resort to numerical techniques for obtaining their approximate solutions. In the present study, finite difference method was used to solve the above equation. Herein, first a continuous system is discritized (both in space and time) into 780x720 number of node points in a grid pattern. The size of each grid is considered as 10m. The partial differential equation is then replaced by a set of simultaneous algebraic equations valid at different node points. Thereafter, using standard methods of matrix inversion these equations are solved for the water level. Computer software, Visual Modflow vs. 4.2 (2006), was used for this work.

Conceptual Model:

The available data for aquifer was analyzed to evolve a groundwater flow regime in area. The study area was divided into 780x720 cells. Those cells, which fall outside the study area, are made inactive cells (colored), and final cells are shown in Fig 26. These cells are square having cell length as 10m.

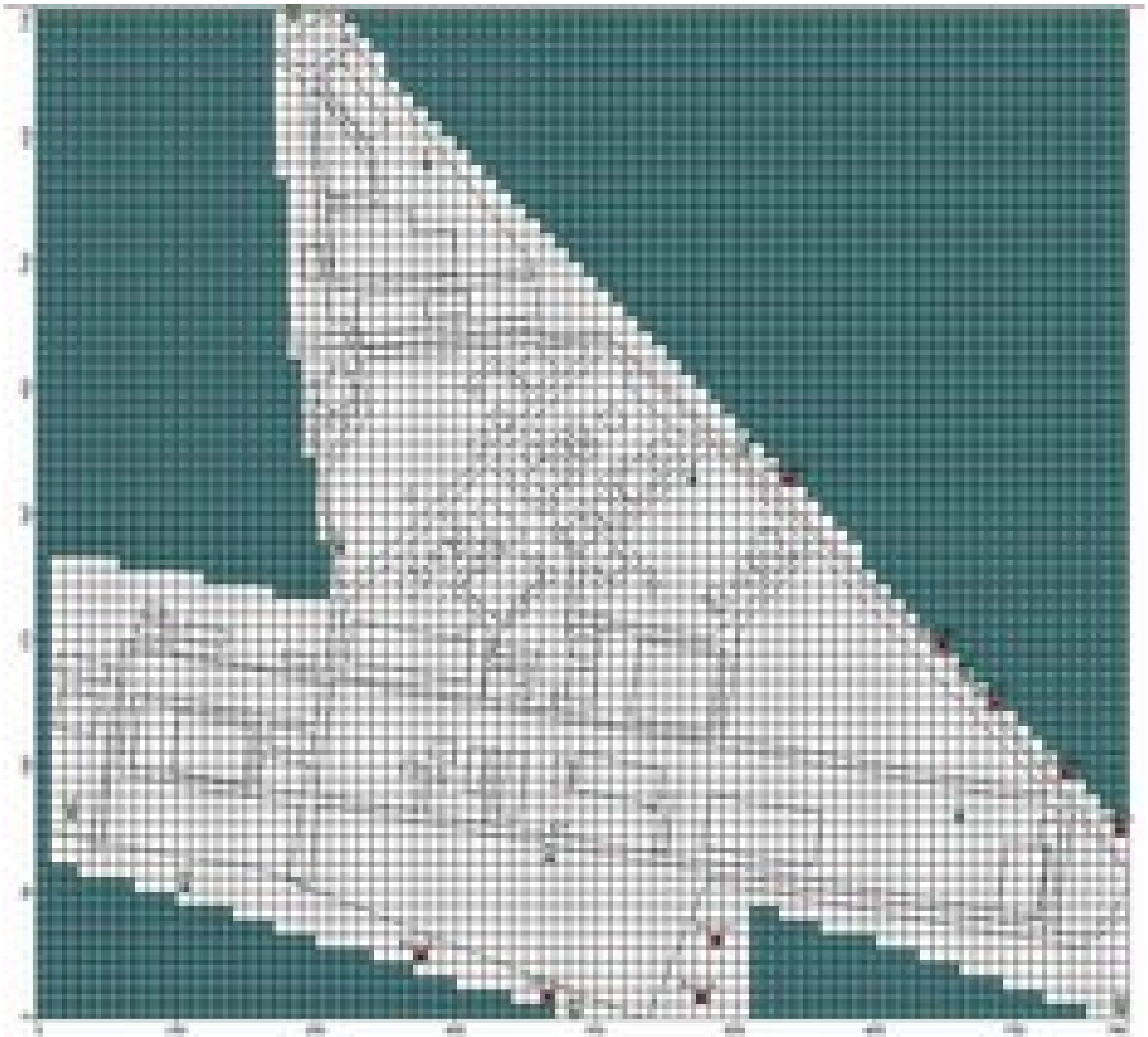

Fig. 26 : Discritization of study area.

Various inputs such as transmissivity, storage coefficient, recharge etc were assigned into different zones considering the hydrogeology as described in the above section.

Inputs:

Physical Frame work : In order to define the physical framework of the aquifer system in the study area, the various inputs such as aquifer characteristics, boundaries etc were assigned to the cells of model.

Permeability Distribution : Considering the estimated aquifer parameters and the hydrogeological conditions, initially the permeability values were assigned as shown in Fig. 22, which were subsequently modified during the model calibration.

Storativity : In order to arrive at the initial distribution of storativity in the region, the values arrived from the hydrogeological conditions have been carefully considered.

Recharge:

Based on recharge experiments carried out by Rangarajan et al (2010), and considering the hydrogeological and climatic conditions prevailing into the area, the initial values of recharge has been divided into different zones varying from 40 to 170mm/yr as shown in Fig.27. These values were subsequently modified during the model calibration.

Groundwater draft :

The groundwater is exploited at the southeastern periphery for domestic, purposes. An estimated groundwater draft based on the field estimate of abstraction from bore wells and hand pumps, which are the main source for groundwater exploitation, the groundwater draft in the study area is assigned at various cells (by red dots) as shown in Fig.28. In order to get the aquifer response in terms of water level, various observation wells are also assigned (by blue dots) as shown in Fig. 28.

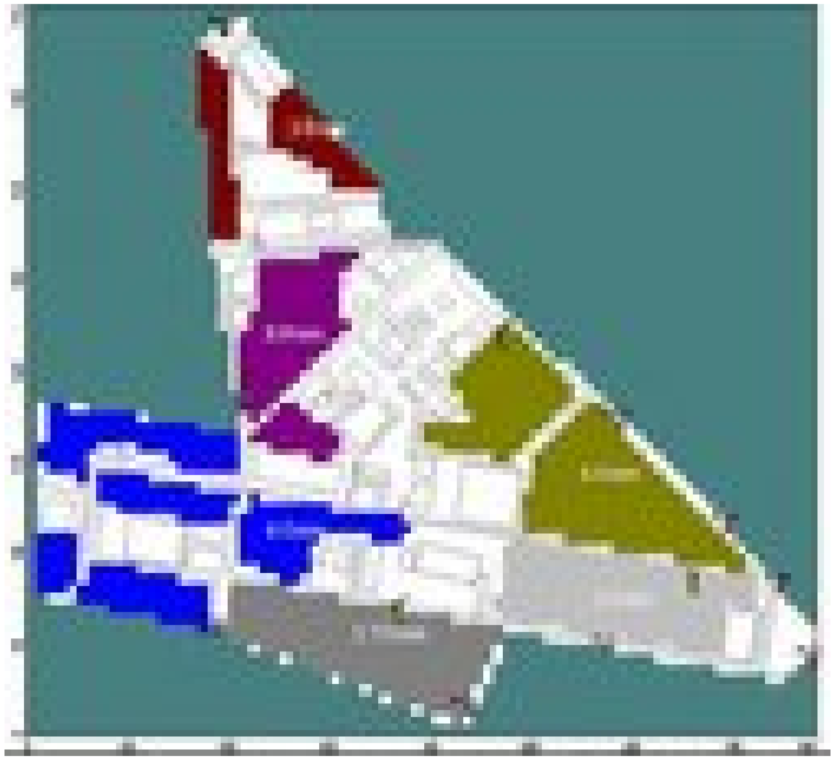

Fig 27: Initial recharge distribution

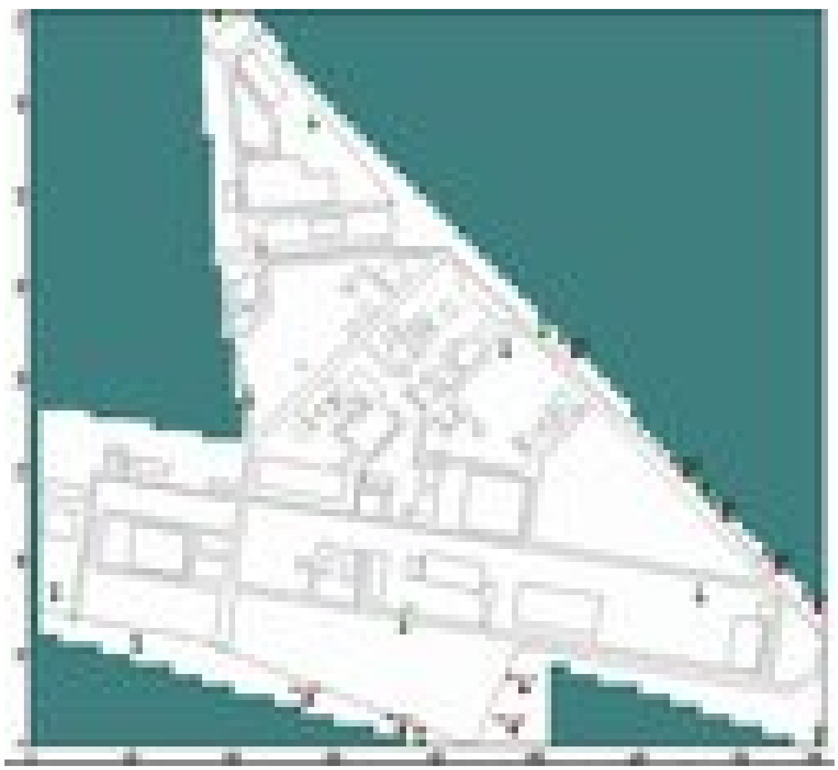

Fig. 28 Observation and Abstraction wells

Boundary Condition:

As the area of study is small and not enough subsurface hydrogeological information is available, the groundwater flow map is considered as basis for boundary conditions. There exists water body at the distance of about 250m east from the northern most part of the area. Similarly there is drainage with water body at the western boundary of the area. It is considered that these water bodies may be influencing the groundwater regime. A General Head Boundary condition is therefore considered at these sides as also indicated by the groundwater flow map. All the other sides are considered as open boundary.

Model Calibration:

The initial water level of February 2010 was taken as initial steady state for model calibration. The model had been run for 365 days. The estimated abstraction for these months were added and divided by 365 to get an average constant daily rate. Similarly the rainfall during the wet month was added and divided by 365 to get an average constant daily value for this period.

During the steady state calibration the model was calibrated against the observed water level, through a sequence of sensitivity analysis runs, starting with the parameters for which the least data were known, i.e. the boundaries. The values of permeability, and recharge were adjusted during a series of trial runs till a better match of computed and observed water levels were obtained. The computed versus the observed heads are illustrated in Fig. 29 for the month of February 2010.

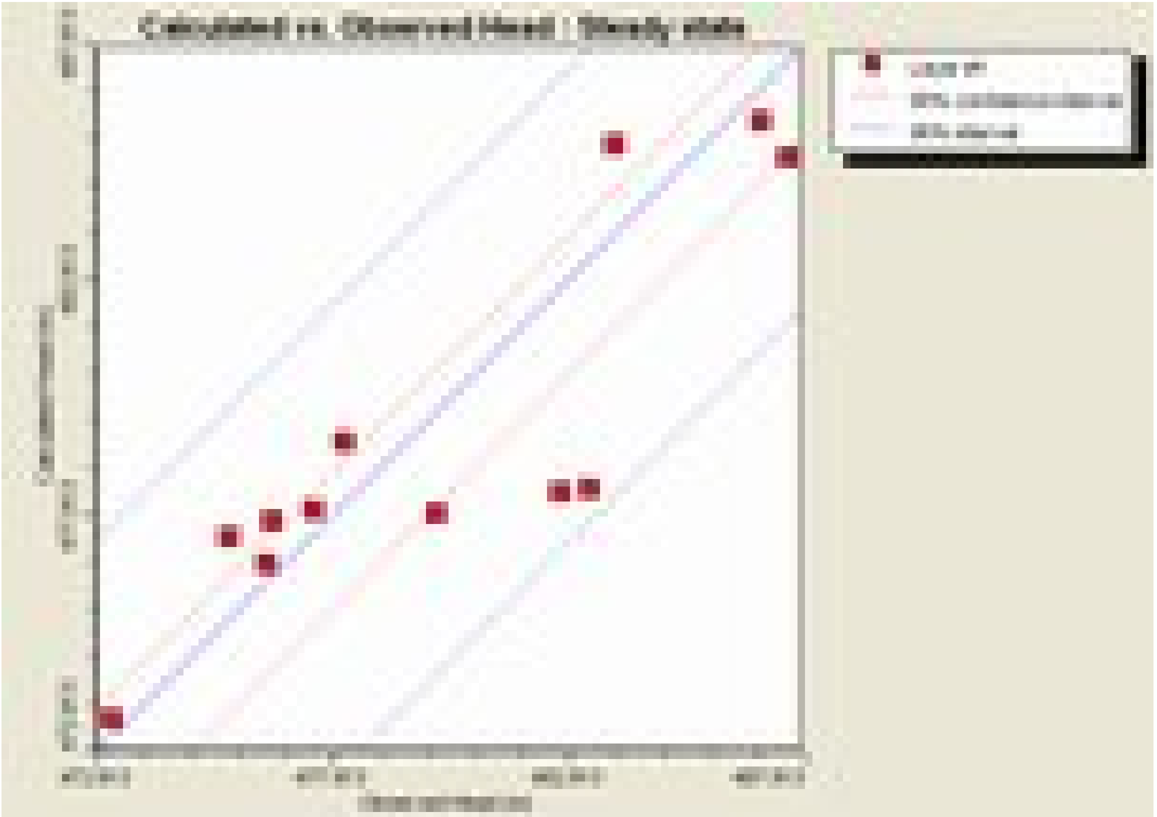

Fig. 29: Comparison between the computed and observed water levels

The values of water level measured at different wells are compared with the values calculated by the numerical model. The blue line at 45^0 (x=y) represents an ideal calibration scenario; however it hardly happens as the occurrence of aquifer in nature is complex and a simplified version is simulated. Most of the data on water level falls within 95% confidence interval indicating that the simulation results can be accepted for a given data. However a couple of wells fall closer to 95% confidence interval but with 95% interval of total data points which is expected for a good simulation.

The other statistics about simulation is given below:

Max. Residual -4.585(m) at BH2

Minimum residual 0.196(m) at 4

Residual mean -0.629(m)

Abs. Residual mean 1.827(m)

Standard Error of Estimate 0.648(m)

Root Mean Square 2.24(m)

Normalized RMS 15.62%

Correlation Coefficient 0.875

The higher correlation coefficient is indicative of a satisfactory simulation with the given data set.

The calculated potential lines are shown in Fig. 30 which is more or less close to observed data. The total inflow and outflow is shown in Fig. 31. The picture depicts the inflow and outflow in terms of m^3/d and details of which are given below.

VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME
RATES FOR THIS TIME STEP L**3/T
IN:
STORAGE = 0.0000
CONSTANT HEAD = 0.0000
WELLS = 0.0000
HEAD DEP BOUNDS = 1.2557
RECHARGE = 106.1218

TOTAL IN = 107.3775

OUT:
STORAGE = 0.0000
CONSTANT HEAD = 0.0000
WELLS = 74.0000
HEAD DEP BOUNDS = 33.4273
RECHARGE = 0.0000
TOTAL OUT = 107.4273

IN - OUT = -4.9812E-02
PERCENT DISCREPANCY = -0.05

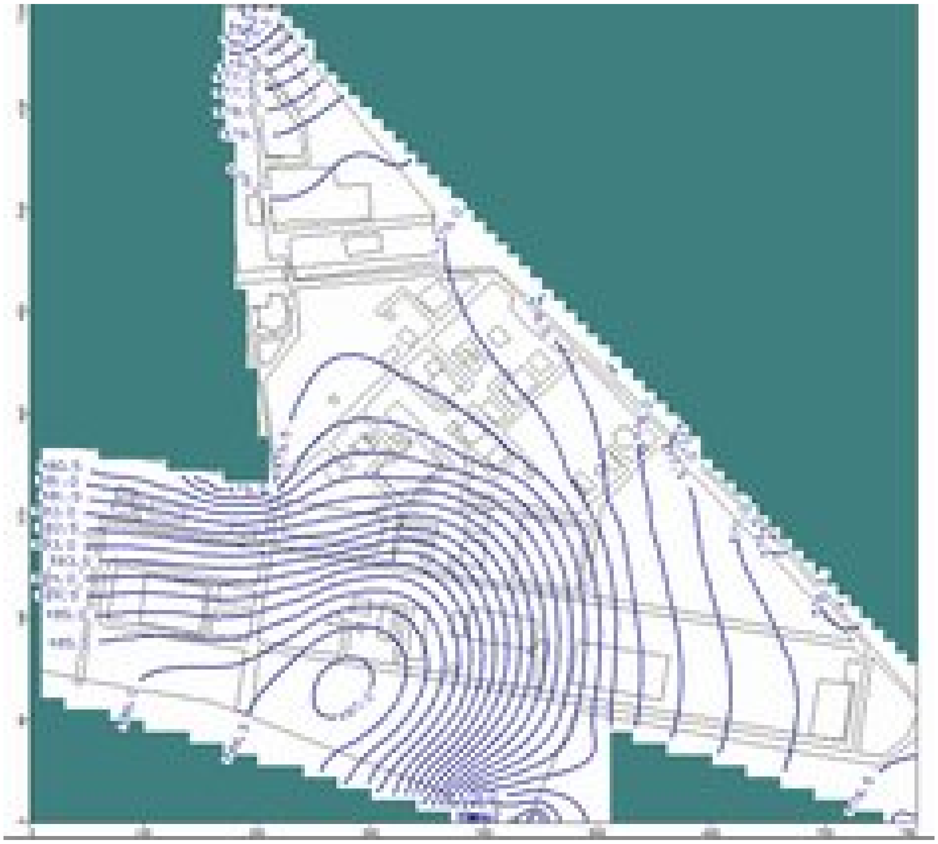

Fig. 30 Simulated potential lines

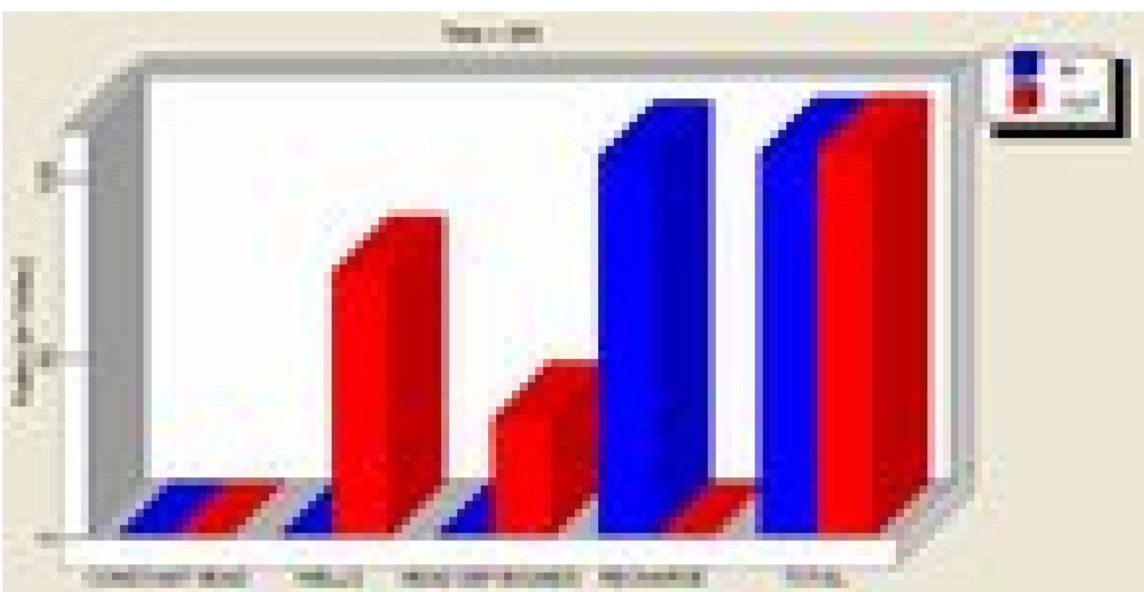

Fig. 31 Mass budget for the model

Groundwater Velocity : The model was used to obtain groundwater velocity in the area considering the groundwater head during the month of February 2010. It is shown in Fig. 32. It can be seen that the velocity varies from 0.03 to about 1m/d. It is 0.08m/d in the northern area opposite formulation plant, 0.2 to 0.3m/d in the central part and higher in the western margin. The groundwater velocity is a function of groundwater potential which varies with time, hence the velocity may also change with time.

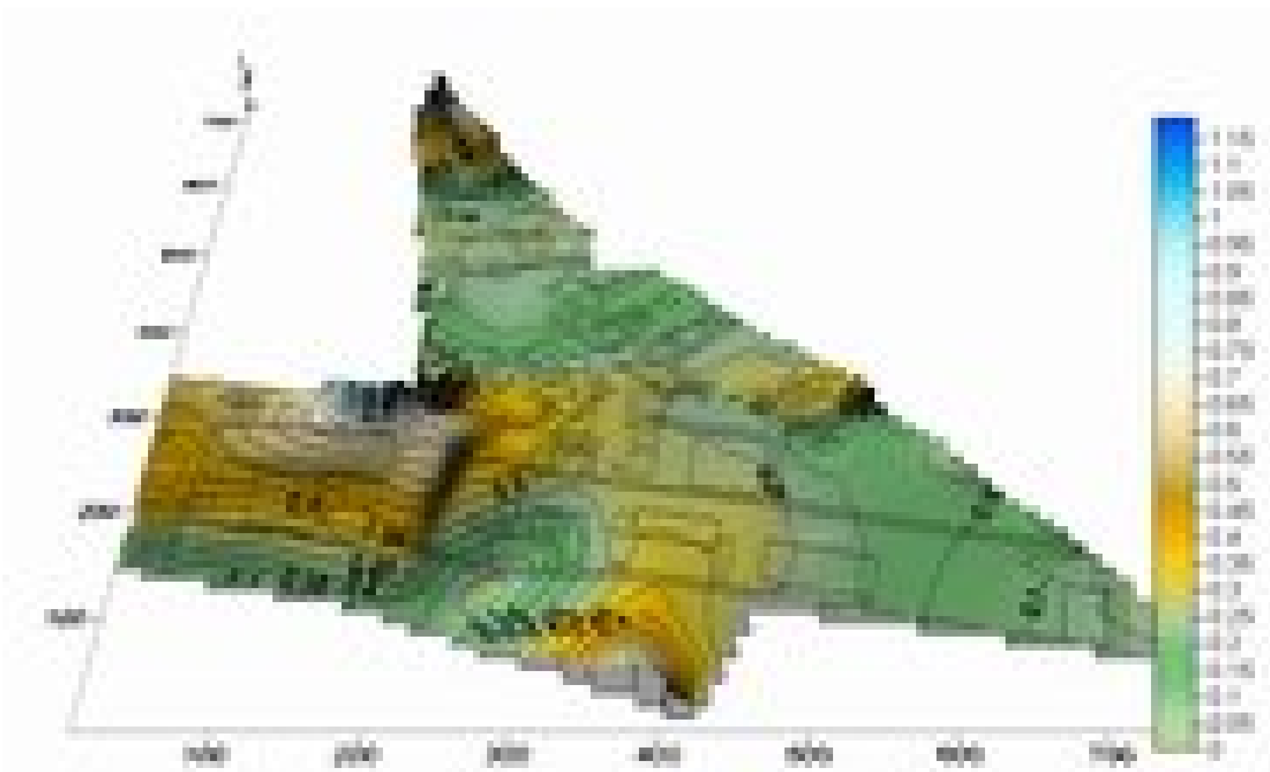

Fig. 32: Groundwater velocity for the month of February 2010.

Prognosis: The model was used for projecting the particle tracking using the software MODPATH. The program was developed by Pollock (1994) for particle tracking using the output from the MODFLOW model. It is semi-analytical particle tracking scheme that allows an analytical expression of the particle flowpath to be obtained within each finite difference grid cell. It is computed by tracking particles from one cell to the next until the particles reaches a boundary. The boundary could be an internal source/sink (recharge or abstraction point) or some other termination criterion defined by the modeler.

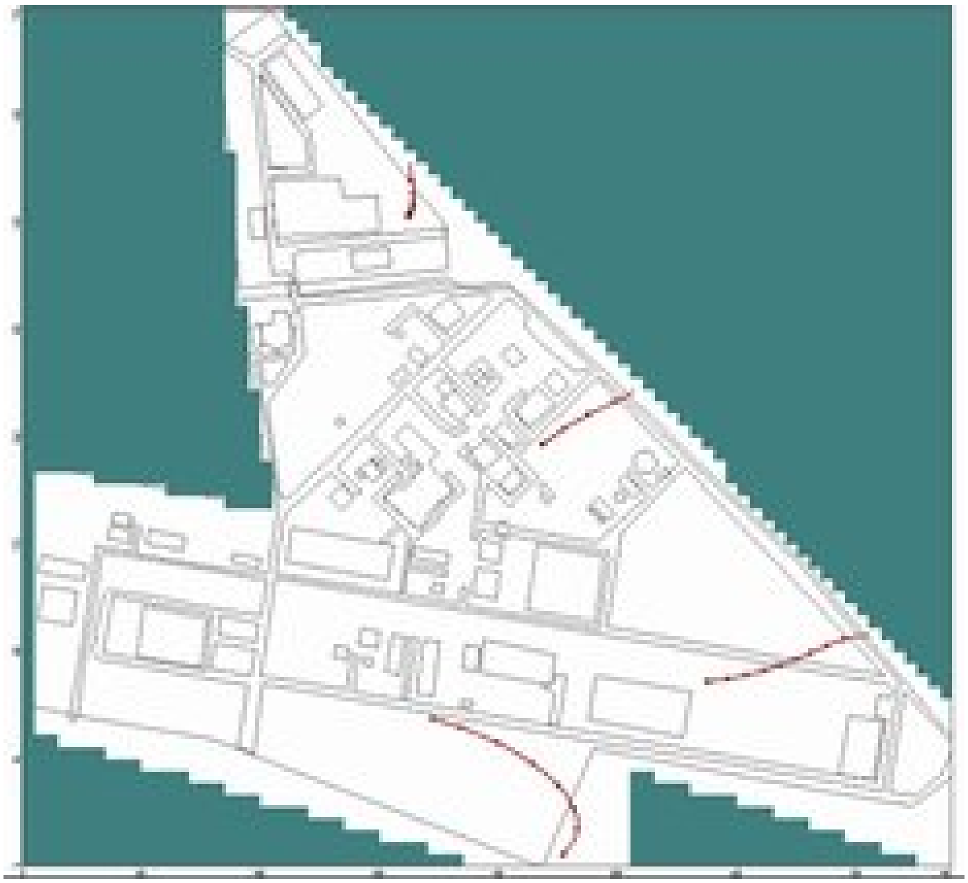

Fig. 33 Particle tracking in different zones

Two applications of MODPATH have been made. In one case we have calculated the path of particle to reach the source well as the particles are dropped at desired locations. We have selected four such locations considering dumps in the area as described below and shown in Fig. 33.

1. In the dump area in front of formulation plant (northern part of area)

2. In the east of main plant

3 In the dump area consisting of SEP

4. In the southern part of area.

The particle tracking was carried out and the resultant path is shown in Fig. 33. It takes minimum of 351 days to reach the well for the point close to plant where as the maximum time of 867 days is taken by point in southeastern part to reach the well. The average tracking time is calculated as 642days.

Further model has been used to track well head by selecting two wells at the eastern boundary and one well each at northern and at the southern boundary. The well head capture area is calculated and shown in Fig. 34. Any pollution infiltrating in the well head capture area will be affecting water withdrawal from these wells.

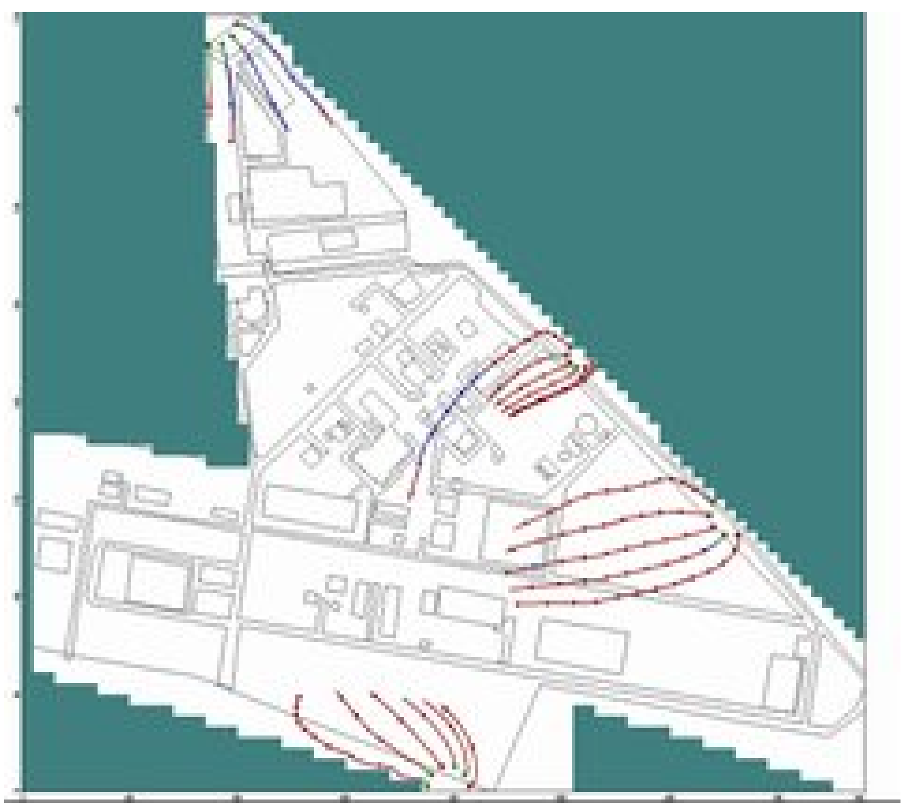

Fig. 34 Well head capture zone at 4 locations

Summary: Groundwater investigations carried out in and around UCIL, Bhopal includes:

* Hydrogeological investigations
* Drilling of test bores,
* Aquifer characterization
* Monitoring of water levels
* Reduction of water levels to Mean Sea Level (msl), and
* Simulation of groundwater regime.

The study area has gentle slope towards southeast. Initially well inventory has been carried out in the study area and the wells have been monitored for the change in water level. The depth to water level below ground surface was found to vary between 10 to 18m during the month of November 2009. It has been found that the water level fluctuates in the range of 9 to 10m during the hydrological cycle of 2008-09 except for a well at the eastern periphery where it was 23m which has very high abstraction rate (almost running for 24hrs). Another unused shallow well at the southern periphery has small fluctuation and it could be a localized shallow aquifer.

There was no information available on the lithology of subsurface formation in and around UCIL. Based on geophysical investigations, five sites have been selected for drilling test wells. The lithologs at all sites has been obtained. It helped in getting data on the aquifer in the area which consists of alluvium with pebbles underlain by the hard sandstone. The water level in the aquifer was monitored. The water level was reduced to mean sea level using the bench mark values from the Survey of India. Finally the groundwater potential map has been prepared.

In order to characterize aquifer system, slug test at each site has been carried out using digital data loggers. The inversion software were used to calculate aquifer transmissibility and hence aquifer permeability which varies from 5 to 7m/d.

All the hydrogeological and geophysical data were used to conceptualize aquifer system in the area. A numerical code MODFLOW was used to simulate aquifer system. The model was calibrated against the water level observed. During the process of calibration, the input parameters such as permeability, recharge, abstraction and boundary condition were changed considering the hydrogeological situation in the area.

The calibrated model was used to predict groundwater velocity in the area and a groundwater velocity map for the month of February, 2010 was prepared. The model has further been used to predict particle track in different parts of study area and the time to reach the abstraction well were calculated. Further, the model was also used to predict well head capture zone considering four locations in different parts of area. These results clearly define the zones likely to be affecting the water supply wells in case any pollutant infiltrates the aquifer.

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