Final Report

Assessment and Remediation of Hazardous Waste Contaminated Areas in and around M/s Union Carbide India Ltd., Bhopal

Sponsor

Bhopal Gas Tragedy Relief and Rehabilitation Department
Govt. of Madhya Pradesh, Bhopal

By

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1.0 Background of the Study

1.0 Preamble

M/s. Union Carbide India Ltd. (UCIL), manufactured carbamate pesticides and the associated intermediate chemicals at their Bhopal unit from 1969 to 1984. The solid, semi-solid, liquid and tarry wastes generated during the manufacture of pesticides and associated chemicals were dumped by UCIL within their premises from 1969 to 1984.

The unit was closed down in December 1984 as a result of the infamous accident of leakage of methyl iso-cyanate gas (MIC).

The unscientific disposal of these wastes could have resulted in contamination of land and water environment in and around plant premises of UCIL and may require remediation, in case the contamination levels exceed the permissible limits delineated by national/international regulations.

During the study it appeared that there is a general misunderstanding among the public as well as various agencies and organizations that, MIC gas tragedy in 1984 also resulted in contamination of soil and groundwater in and around UCIL premises. However, it may be made clear that, contamination of soil and groundwater in and around UCIL premises is solely due to dumping of abovementioned wastes during 1969 to 1984, and MIC gas tragedy has no relevance to it.

Since a considerable time has elapsed and no programmed remedial action (other than natural attenuation) might have been taken place in the past, the present status of soil and groundwater contamination in and around UCIL premises needs to be assessed so as to delineate suitable strategies for remediation. Based on the directives of the Task Force constituted by Hon'ble High Court of Madhya Pradesh, the Bhopal Gas Tragedy Relief and Rehabilitation Department (BGTRRD), Govt. of Madhya Pradesh requested National Environmental Engineering Research Institute (NEERI), Nagpur and National Geophysical Research Institute (NGRI), Hyderabad to undertake a study on fresh assessment of the extent of contamination and delineate suitable strategies for the remediation of contaminated areas in and around the UCIL site. The study was awarded by BGTRRD in March 2009.

1.2 Background data/information for the study

Several studies were carried out by various agencies in the past pertaining to waste disposal and contamination of soil and groundwater in and around the plant premises of UCIL, Bhopal.

The data and information generated by these studies were reviewed by NEERI prior to initiating this study. The salient findings of various studies are presented in the following sections:

1.2.1 Past Studies carried out by NEERI and NGRI

i) Manufacturing processes at UCIL

Between 1977 and 1984, Union Carbide India Limited (UCIL), Bhopal was licensed by the Madhya Pradesh Government to manufacture phosgene, monomethylamine (MMA), methylisocyanate (MIC) and the pesticide carbaryl (also known as Sevin).

Phosgene was manufactured by reacting chlorine gas (brought to the plant by tanker) and carbon monoxide, which was produced from petroleum coke by passing air over red hot coke in a controlled manner in a production facility within the plant.

The MMA was also brought in by tanker. MIC manufacturing process was carried out with equimolar ratios of phosgene to amine or even with an excess of phosgene in a solution of chloroform. The reaction of phosgene with monomethylamine in vapour phase leads to the formation of methyl carbamoyl chloride (MCC).

The reaction products were quenched in chloroform and then fed to phosgene stripping still to remove the un-reacted phosgene for recycle. The bottoms from the stripper were fed to a pyrolyser where MCC is broken to MIC and HCL, which were further separated. The pyrolyser condenser fed the MIC refining still (MRS) where MIC was separated from the chloroform in the upper part and was led directly into a storage tank. The bottoms of MRS containing residues of MCC, chloroform, and other unwanted by-products (e.g. carbon tetrachloride, MMA, dimethylallophanoyl chloride, ammonium chloride, dimethyl urea, trimethylbiuret and cyanuric acid) were collected and recycled back to the process. The HCL formed was scrubbed with chloroform and extracted with water to produce aqueous HCL, which was disposed off by neutralization.

MIC was manufactured primarily to make the pesticide carbaryl (Sevin) as well as smaller quantities of aldicarb (Temik) and butylphenyl methylcarbamate.

Carbaryl was manufactured by the reaction of slight excess of α-naphthol with MIC. Methyl Isocyanate was gradually added upon stirring to an excess of alpha naphthol in carbon tetrachloride solvent at 60-80^{o}C in presence of a catalyst. The reaction is exothermic. The yield of product was more than 95%. Data on the production of Sevin and MIC during 1977-84 are presented in the **Table 1**.

Table 1: Production of Sevin and MIC at UCIL, Bhopal

Year	Sevin (MT/year)	MIC (MT/year)
1977	321	--
1978	367	--
1979	1468	--
1980	1534	374
1981	2658	864
1982	2271	623
1983	1727	535
1984	1101	313
Total	**11447**	**2709**

ii) Geology and hydrogeology of the study area

The National Geophysical Research Institute (NGRI), Hyderabad had carried out geophysical investigation within the premises of UCIL, Bhopal in 1996. The geoelectrical investigations carried out by NGRI revealed that the soil strata are dominated with black cotton soil and the absence of any fault and fissures. The geophysical studies also indicated anomalies in soil resistivity in waste disposal areas suggesting possibility of contamination. Although a broad knowledge of aquifer system in the region existed a specific knowledge of aquifer system in the vicinity of UCIL was not available. Further, the hydrogeological data (aquifers, their characteristics, hydraulic gradient etc.) which provides basis for the development of site specific plan for the remedial measures, could not be studied by NGRI.

iii) Dump materials

NEERI submitted a report in November 1996, on “Assessment of contaminated areas due to past waste disposal practices at EIIL (erstwhile UCIL), Bhopal”. The report documented that UCIL had dumped their solid/hazardous wastes in open areas within the plant premises, which could be a potential source for contamination of groundwater.

The report submitted by NEERI in 1996, indicated that disposal area was divided into three zones covering about 7 hectares. The maximum sevin content in dump was recorded as high as 520003 mg/kg. The concentrations of temik in dump materials varied widely from below detectable limit (BDL) to 7876 mg/kg. α-naphthol was recorded between 500 and 10000 mg/kg in few samples only. However, presence of other organics was not ruled out as the chromatographs had recorded certain peaks which could not be identified then. The naphthalene residues, which were buried in an underground pit, had naphthalene content of 33%.

iv) Soil quality

As per studies carried out by NEERI in 1996, in Disposal Area I (DA I), the maximum concentration of sevin and temik in soil were 356 mg/kg and 74 mg/kg respectively. α-naphthol was not detected in any sample in DA I. However, lindane (γ-HCH) was present almost in all samples recording between 0.5 mg/kg and 2014 mg/kg.

In Disposal Area II (DA II), sevin concentration in soil was 7218 mg/kg. α-naphthol concentration in soil varied between 19.83 mg/kg and 1194 mg/kg in nearly 50% of the samples. The concentration of lindane varied between 0.34 mg/kg and 2.8 mg/kg in some samples.

In the remaining area (rest of area), in general, the semi volatiles were below detection limits. However, in two sites, temik was recorded as 78.36 mg/kg and 102.4 mg/kg. Lindane, α-naphthol and naphthalene were not detected in any sample.

Samples collected near target and spill areas did not show the presence of contaminants except in traces in a few sites. Thus the impact due to material handling in target/spill areas was minimum.

v) Ground water quality

As per the studies carried out by NEERI in 1996, seventeen ground water samples were collected in and around UCIL, Bhopal. None of the groundwater samples indicated the presence of semi volatiles, organics, heavy metals and inorganics beyond the limits of drinking water standards (IS:10500).

vi) Extent of contamination reported by NEERI in the 1996 report

Based on the risk based quality criteria for soil and ground water delineated by US EPA, it was concluded that the entire Disposal Area I (0.3 ha to a depth of 60 cm) and a few identified contaminated zone in Disposal Area II (0.32 ha to a depth of 30 cm) and at two sites in rest of area (0.08 ha to a depth of 30 cm) were contaminated and required remediation.

1.2.2 GTZ Project Proposal

A technical proposal titled “Final and Complete Remediation of the Abandoned Factory site of the Union Carbide” Submitted by GTZ-ASEM-HAWA to Madhya Pradesh Pollution Control Board (MPPCB), Bhopal indicated the following:

- Approximately 25000 tonnes of contaminated solid material may exist at the site
- The water and soil in and around UCIL are likely to be contaminated with pesticides sevin, BHC, aldrine, heptachlor, methoxychlor, endosulfan, dieldrin and endrin, mercury and chemical intermediates such as di-and tri-chlorobenzene isomers, residues of organic solvents and heavy metals.

1.2.3 Greenpeace Report

In 1999, Greenpeace submitted a report titled “Toxic contaminants at the former Union Carbide factory site, Bhopal, India: 15 years after the Bhopal accident“ authored by Labunska, I., Stephenson, A., Brigden, K., Stringer, R., Santillo, D. & Johnston, P.A.(Technical Note 04/99). The survey conducted by Greenpeace International reported contamination of land and drinking water supplies with heavy metals and persistent organic contaminants both within and surrounding the UCIL plant premises.

1.2.4 Sambhavna Trust Clinic’s input

Sambhavna Trust Clinic of Bhopal, an NGO, forwarded a Report titled “Morbidity Survey Related to Water Contamination” prepared in August 2006 by Dr.Sushil Singh and Mrs. Moina Sharma of the Centre For Rehabilitation Studies, Kamala Nehru Hospital of Bhopal. The report concluded that the soil and water contamination has resulted in increase in the morbidity pattern among the population staying near UCIL Factory and surrounding area of solar evaporation pond. The report also quoted a study carried out by the National Institute of Occupational Health, Ahmedabad. The study revealed that soil and water of these locations are contaminated with DDT, HCH, mercury and volatile organic compounds like xylene, benzene, toluene and chlorobenzene.

1.2.5 Srishti’s Report

“Srishti”, a Delhi based NGO prepared a report in January 2002 titled “Surviving Bhopal 2002 Toxic Present - Toxic Future“ which is on human and environmental chemical contamination around the Bhopal disaster site. The report quotes an affidavit, submitted to the New York District Court, by ex-UCIL employee Mr. T.R. Chauhan, which reads as “*from December 1969 to December 1984 a massive amount of chemical substances formulated in the factory - including pesticides, solvents used in production, catalysts, and other* *substances as well as by- products - were routinely dumped in and around the factory grounds. These were in the form of solid, liquid and gas and caused pollution in the soil, water and air*". Chemicals reported to be dumped by UCIL from 1969-84 are listed in **Table 2.**

Table 2: Chemicals reported to be dumped by UCIL from 1969-84.

S. No.	Chemicals	Quantity (MT)	Use in factory	Nature of pollution
1.	Aldicarb	2.0	Product	Air, water & soil
2.	Alpha-napthol	50.0	Ingredient	Air & Soil
3.	Benzene Hexachloride	5.0	Ingredient	Air, water & soil
4.	Carbaryl	50.00	Product	Air, water & soil
5.	Carbon tetrachloride	500.00	Solvent	Air & water
6.	Chemical waste tar	50.00	Waste	Water & soil
7.	Chlorobenzoyl chloride	10.00	Ingredient	Air, water & soil
8.	Chloroform	300.00	Solvent	Air & water
9.	Chlorine	20.00	Ingredient	Air
10.	Chlorosulphonic acid	50.00	Ingredient	Air & soil
11.	Hydrochlroic acid	50.00	Ingredient	Air & soil
12.	Methanol	50.00	Solvent	Air & water
13.	Methylene chloride	100.00	Solvent	Air & water
14.	Methyl Isocyanate	5.0	Ingredient	Air, water and soil
15.	Mercury	1.0	Sealant pan filter	Water and soil
16.	Monochloro toluene	10.00	Ingredient	Air, water and soil
17.	Monomethyl amine	25.00	Ingredient	Air
18.	Naphthalene	50.00	Ingredient	Air
19.	Ortho dichlorobenzene	500.00	Solvent	Air
20.	Phosgene	5.0	Ingredient	Air
21.	Tri methylamine	50.00	Catalyst	Air
22.	Toluene	20.00	Ingredient	Air, water & soil

1.2.6 MPPCB Report

The analysis of the ground water samples collected by MPPCB around the M/s Union Carbide premises reveled that some of the wells investigated had pesticide (BHC, Aldrin, Endosulfan I, & II diendrien, methoxichloro and endrin) in µg/L levels. The water samples also contained heavy metals such as chromium, zinc, nickel and Iron. Other chlorinated organics such as dichloro and trichloro benzene could not be detected. The emergence of these pesticides and heavy metals is highly varying and are subjected to seasonal variations.

1.2.7 Study by Dr. V. Birke and Dr. H. Burmeier

The study by Dr. Birke and Dr. Burmeier, University of Lueneburg, Suderburg, Germany, estimated about 27,600 MT of contaminated solids and soil within the premises of UCIL Bhopal. The contaminants identified were pesticides and intermediate used/manufactured at the site, chlorinated and non-chlorinated solvents, process residues/wastes, polychlorinated biphenyl, polyaromatic hydrocarbons, mercury, chromium and inorganic compounds.

The study concluded that the major threat at the site is not only posed by significant amounts of production (pesticide) residues dumped on site and adjacent to the site but also due to release of Dense Non-Aqueous Phase Liquids (DNAPL) from the site. Based on the review of secondary data, the authors suspected the possibility of large scale groundwater contamination with DNAPL (chlorinated solvents) originating from the site. DNAPLs were used in significant amounts as solvents and were partly dumped/spilled on-site as well as off-site during 1970s and 1980s.

1.2.8 Site cleaning activity carried out by the MPPCB

MPPCB, through M/s Ramkey Ltd., Mumbai had arranged to collect the wastes disposed off within the premises of UCIL, and placed them under a shed as the first measure of remediation (year 2005). The quantities of wastes recovered and stored by the MPPCB are listed in **Table 3**.

Table 3: Quantities of waste recovered and stored by MPPCB

Name of waste	Quantity (MT)*
Contaminated Soil	165.00
Sevin Residue	11.00
Semi-processed pesticides	142.80
Lime sludge	39.60

* as reported by MPPCB

1.3 Objectives and scope of work for the present study

Considering the past studies carried out by NEERI as well as apprehensions/issues raised by various above mentioned studies, the present study was expected to delineate the current status of contamination in and around UCIL plant premises. The main objective of the present study was, therefore, to reassess the extent of contamination and delineate strategies for the remediation of the contaminated areas, if any, especially after the preliminary site cleaning activities carried out by MPPCB with M/s Ramkey Ltd. accordingly, the following scope of work was finalized for the present study.

Phase I: Detailed geophysical and hydrogeologic assessment of the UCIL site and the surrounding area:

a) Collection of available data, well inventory, and identification of data gap,
b) Selection of observation wells, monitoring of water level and quality
c) Geophysical & hydrogeological investigation to identify and characterize aquifer system,
d) Drilling of test wells and performing geophysical logs & aquifer test,
e) Preparation of various maps such as groundwater flow, groundwater quality,
f) Conceptualization of aquifer system and contaminant, and mass transport modeling
g) Simulation of aquifer system and mass transport
h) Validation of model and prognosis
i) Finalization of report

Phase II: Detailed sampling and analysis of dumpsite and groundwater:

a) Review of data/information generated by NGRI with respect hot spots (if any), characteristics of subsurface, groundwater flow direction, groundwater quality, groundwater modelling results etc.
b) Sampling and analysis of dumped materials from the hotspots, if any, identified by NGRI through geophysical and hydrogeological investigations
c) Sampling and analysis of existing groundwater sources (dugwells, borewells) up to a distance of 5 km from the UCIL site (the location and no. of samples will be decided based on the findings of the NGRI

study. In case the contamination is expected beyond 5 km distance, additional samples will be collected)

d) Establishment of lateral and vertical extent of contaminated area
e) Quantification of contaminated soil and groundwater

Phase III: Developing risk based remediation strategies for the contaminated area

a) Study, review and recommendation of risk based remediation standards for contaminated soil and groundwater in and around the UCIL site
b) Identification and evaluation of various full scale remediation options for contaminated soil and groundwater to achieve the risk based remediation goals
c) Recommendation of most feasible full-scale remediation options with cost estimates

1.4 Approach and methodology adopted for the present study

As stated in Section 1.2.1, an exhaustive study was carried out by NEERI during 1994-1996 with respect to the wastes generated, waste disposed and nature and extent of contamination. The exhaustive study was possible due to availability of primary data/information from the industry officials. Hence, the findings of the previsous study by NEERI forms the basis for the present study.

The studies carried out by NEERI had identified three zones viz. disposal area I, disposal area II and disposal area III. Major contaminants detected at these disposal areas were sevin, temik, α-naphthol, naphthalene, and lindane. The disposal areas and the hot-spots identified by NEERI in 1994-1996 were revisited during the present study. In addition to these hot-spots, apprehensions raised by various studies on possibility of existence of other contaminants were also considered for the present study.

The approach followed in the present study involved reconnaissance survey of the UCIL plant premises and the surrounding area, geophysical investigations by NGRI to identify and confirm possible contaminated area (as reported by NEERI in 1996), drilling of bore holes for generating hydrogeological data, sampling and analysis of soil and groundwater from the boreholes, and sampling and analysis of soil and groundwater around UCIL premises.

Based on the data/information available from the previous studies on possible groundwater flow directions, control samples of soil and groundwater were collected and analyzed from the upstream areas.

The sampling and analysis of soil and groundwater were carried out as per widely accepted standard national/international protocols referred in the report.

Based on the hydrogeological investigations carried out by NGRI, Hyderabad and analysis of soil, groundwater and dump materials by NEERI, present status of contamination in and around UCIL premises has been delineated.

Based on the review of available remediation technology options and considering the present site conditions, strategy for remediation of contaminated areas has been delineated.

A detailed account of all these aspects is presented in the present report.

2.0 Site Reconnaissance

2.1 Preamble:

M/s Union Carbide India Ltd (UCIL), is situated within the city of Bhopal, Madhya Pradesh and bound by Latitudes 23.277^0 and 23.283^0 N and Longitudes 77.404^0 and 77.414^0 E as shown in **Figure 1.** **Figure 2** depicts plant layout. The factory area is surrounded by working class settlements. The Bhopal-Indore railway line passes close to the UCIL premises in the northern direction. The area is characterized by nearly flat topography with the topographic elevation of about 492 m above mean sea level (amsl).

Fig. 1: Location of Union Carbide India Ltd.

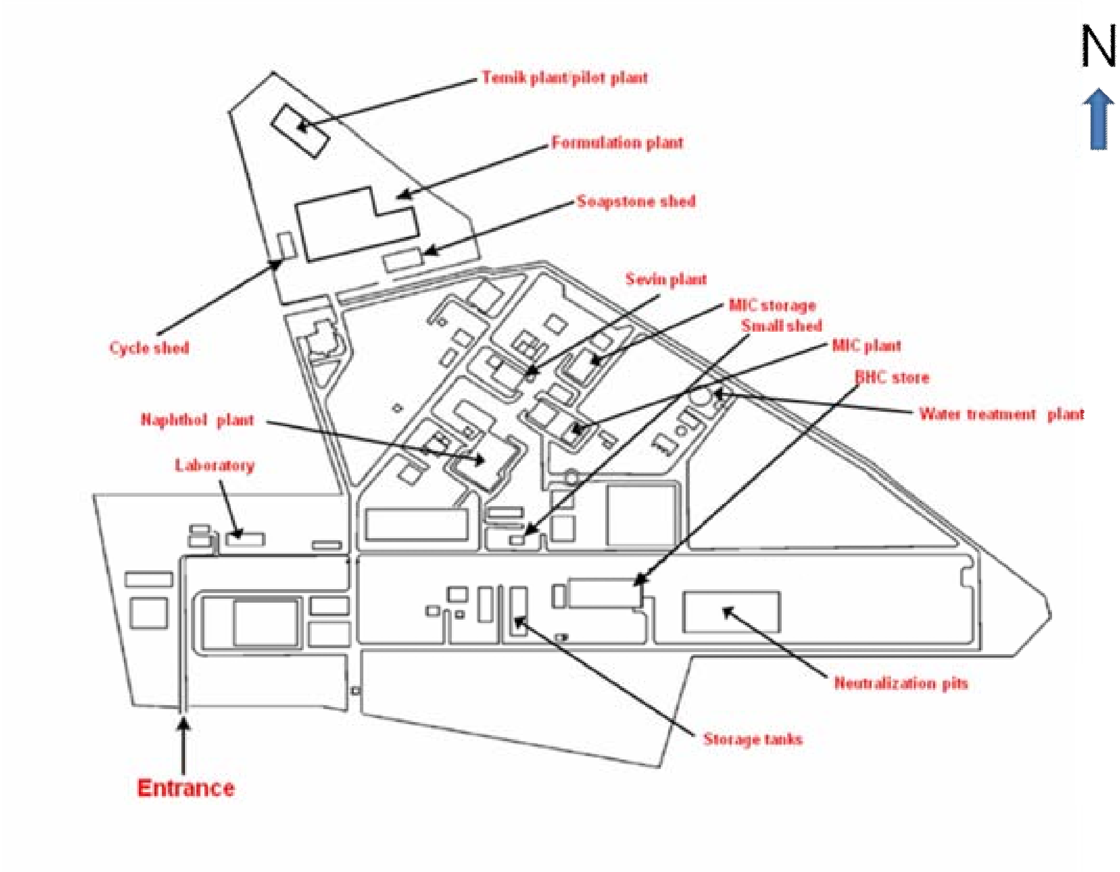

Fig. 2: Plant Layout of UCIL, Bhopal

A detailed reconnaissance survey of the UCIL premises and the surrounding area was carried by NGRI and NEERI during the study. During the reconnaissance survey, the NGRI-NEERI teams collected background information on products, processes, raw materials used and the wastes generated/disposed off by UCIL during its operation. Teams also surveyed the existing dumps located within the UCIL premises as well as waste disposal facilities located outside UCIL premises (solar evaporation ponds and secured landfill). **Plate 1** depicts the general view of UCIL Plant.

Plate 1: General view of UCIL plant

2.2 Past waste disposal activities

During the manufacturing of various intermediates and products at UCIL, Bhopal from 1969 to 1984 various solid, semi-solid and liquid wastes were generated. These include:

- treated wastewater from various process unit
- tarry residues from the distillation units of Sevin and Naphthol units
- off-specification products
- burnt and un-burnt residues from past fire accident

While the most of liquid wastes (treated wastewater) were disposed off in solar evaporation ponds (SEP) located outside UCIL premises, some of the treated wastewater from temik plant was disposed in two solar evaporation ponds constructed within the plant premises. The solid/semi-solid wastes were either stored in drums and other containers or disposed off on open land within plant premises.

As delineated by NEERI in its 1996 Report, the solid/semi-solid wastes were dumped mainly in three areas inside the UCIL premises. These were designated as Disposal Areas I, Disposal area II and Disposal area III.

In addition to these three disposal areas, spillage materials from various units/sections could have been disposed off in other open areas of the plant. The total area of waste disposal was estimated to be 6.9 hectares.

As mentioned in Section 1.2.8 site cleaning activity was undertaken by MPPCB in 2005 with the help of M/s Ramkey Ltd. Mumbai. The total quantum of wastes and contaminated soil excavated and recovered by MPPCB are listed in **Table 3**.

2.3 Inspection of UCIL premises and surrounding area:

During the reconnaissance survey of the UCIL premises, the NGRI-NEERI team observed remains of various manufacturing plants, machinery, buildings and sheds within UCIL premises. Most of the plants and machinery was in dilapidated conditions and appeared to be contaminated (**Plate 2**).

As per the terms of reference (TOR) for the present study, the decontamination and safe disposal of plant, machinery, buildings and materials from the abandoned manufacturing units as well as clearing of dense bushes from the UCIL premises were to be completed by BGTRRD

Plate 2: Plant and machinery in dilapidated conditions

prior to the initiation of study by NGRI and NEERI. However, these tasks were not completed prior to the commencement of field studies. **Hence the areas, which were not clear of structure and bushes, could not be included by NGRI-NEERI in the present study**.

The reconnaissance survey of the open areas within plant premises revealed existence of a number of dumps, especially, in disposal area I and disposal area II which give very pungent smell of pesticides. The existence of dumps within UCIL premises indicated that the excavation and recovery of dumped material from the dumpsites, carried out by MPPCB through M/s Ramkey Ltd., is still incomplete (**Plate 3**).

Plate 3: Existence of dumps within UCIL premises

The boundary wall of the UCIL premises was found to be broken at many places and this provided an easy access to the people living around the premises. Some of the open areas of the premises were also used by children as a play ground. The UCIL premises were surrounded by thickly populated hutments. The wastewater released by hutments and adjacent industries was found to be accumulated at many places within UCIL premises (**Plate 4**).

The reconnaissance survey of the SEP area outside the UCIL premises revealed existence of one SEP which was partially filled with water. The SEP was un-guarded and was found to be littered with night soil and other domestic refuse (**Plate 5**).

Plate 4: Wastewater released by the hutments/industries in UCIL

During the reconnaissance survey, it was learnt that out of three SEPs, two were converted into a secured landfill for the disposal of dried sediments from SEPs. The high density polyethylene liners from SEP and secured landfill were found to be damaged/removed during the reconnaissance survey.

Existing dugwells, borewells in and around UCIL premises were surveyed during the reconnaissance survey. Based on the data/information available from past reports/records, upstream (control) and downstream wells were also identified for monitoring.

Plate 5: Improper management of SEP and abandoned landfill

Foreword

M/s. Union Carbide India Ltd., manufactured carbamate pesticides and the associated intermediate chemicals at their Bhopal unit during 1969 and 1984. The solid, liquid and tarry wastes generated during the manufacture of pesticides and associated chemicals were dumped by UCIL within their premises. The unit was closed down in December 1984 as a result of the accident of leakage of methyl iso-cyanate gas. Since, a considerable time has elapsed and no remedial actions have been taken in the past, the present status of soil and groundwater contamination in and around UCIL premises needed to be assessed so as to delineate suitable strategies for their remediation.

Based on the directives of the Task Force constituted by Hon'ble High Court of Madhya Pradesh, Bhopal Gas Tragedy Relief and Rehabilitation Department (BGTRRD), Govt. of Madhya Pradesh requested National Environmental Engineering Research Institute (NEERI), Nagpur and National Geophysical Research Institute (NGRI), Hyderabad to undertake a study on assessment of contamination and delineation of suitable strategies for the remediation of contaminated areas in and around the UCIL site. The study was awarded by BGTRRD in March 2009.

The studies were carried out by NEERI and NGRI which involved reconnaissance survey of the UCIL premises, geophysical and hydrogeological investigation, sampling and analysis of soil and groundwater in and around the UCIL. Based on these studies it was established that soil mostly within UCIL premises and solar evaporation pond area is contaminated and needed appropriate remediation with respect to isomers of hexachlorocyclohexane and mercury on the basis of USEPA standards for groundwater protection. It was also established that the groundwater in general inside the plant area is not contaminated. However, isolated contamination was observed in few wells possibly due to surface runoff from waste dumps or mismanagement of SEP and landfill. Considering the extent of contamination and present site conditions, immediate as well as long term remediation measures are delineated in the report.

T. Chakrabarti

(T. Chakrabarti)
Acting Director

June 26, 2010

Executive Summary

- M/s. Union Carbide India Ltd., manufactured carbamate pesticides and the associated intermediate chemicals at their Bhopal unit during 1969 and 1984. The solid, liquid and tarry wastes generated during the production of these chemicals were dumped by UCIL within their premises, resulting in contamination of soil and groundwater wihin and outside UCIL premises. The unit was closed down in December 1984 as a result of the accident of leakage of methyl iso-cyanate gas.

- Based on the directives of the Task Force constituted by Hon'ble High Court of Madhya Pradesh, the BGTRRD sponsored a joint study in March 2009 to National Environmental Engineering Research Institute (NEERI), Nagpur and National Geophysical Research Institute (NGRI), Hyderabad for assessment of contamination and delineation of suitable strategies for the remediation of contaminated areas in and around the UCIL site.

- Considering the past studies carried out by NEERI as well as apprehensions/issues raised by various agencies/organizations, field studies were carried out by NEERI and NGRI which involved reconnaissance survey of the UCIL premises, geophysical and hydrogeological investigation, sampling and analysis of soil and groundwater in and around the UCIL.

- The reconnaissance survey of the site revealed that most of the plant, machineries and buildings within UCIL premises are in dilapidated conditions and appeared to be contaminated. The reconnaissance survey of the UCIL premises also revealed existence of a number of dumps especially in disposal area I and disposal area II. The existence of dumps within UCIL premises indicated that the excavation and recovery of wastes carried out by Madhya Pradesh Pollution Control Board (MPPCB) through M/s Ramkey Ltd. was incomplete.

- The boundary wall of the UCIL premises was found to be broken at many places which provided an easy access to the people living around the premises.

- The reconnaissance survey of the SEP area outside the UCIL premises revealed existence of one SEP and an abandoned landfill which were found to be damaged.

- The field studies for assessment of contamination comprised of detailed hydrogeological investigations (geophysical investigations, borehole drilling, development of monitoring wells etc.), followed by collection and analysis of existing field samples (dumpsite, subsurface soil, and groundwater). The hydrogeological investigations were carried out by NGRI whereas sampling and characterization of soil and groundwater were carried out by NEERI.

- The geophysical investigations carried out by NGRI indicated possibility of contamination at three sites (Site I, Site III and Site V) out of nine sites. The depth of contamination at these sites is limited to about 2 m, except at one dump (Site III) that could be deeper (4-8m). These dumps were isolated form each other.

- The lithology of the area as determined through drilling of borewells by NGRI revealed existence of black and yellow silty clay up to a depth of 22 to 25 m below ground level. The groundwater in the area exists under confined below a depth of about 25 m from the ground surface. The general groundwater flow direction is towards east.

- Sampling and analysis of subsurface soil (collected during drilling of borewells) indicated contamination of soil up to a depth of about 2 m. Major contaminants detected at the site include: BHC, aldicarb, carbaryl, α-naphthol and mercury. The sampling and analysis of soil from possible dump areas (other than drilling areas) also indicated contamination of soil in terms of above mentioned contaminants. The soil in and around SEPs area located outside UCIL premises was also found to be contaminated.

- The total volume of soil (within and outside UCIL premises) amounts to 6,50,000 m^3 which is equivalent to about 11,00,000 MT.

- Monitoring of groundwater from the borewells constructed by NGRI within UCIL premises and the existing wells around UCIL premises indicated that groundwater in general is not contaminated due to seepage of contaminants from the UCIL dumps. However, isolated contamination in terms of pesticides and/or dichlorobenzene was observed in 5 well in the immediate vicinity of UCIL premises in the north-east and east direction. The source of contamination of these wells was, attributed to surface runoff from the dumps. The quantum of contaminated groundwater could not be estimated due to isolated nature of contamination.

- Considering the extent of contamination and various site conditions, immediate and well as long term remedial measures were recommended.

- Under immediate measures following recommendations were made:

    - Proper fencing and security to UCIL premises and SEP area for preventing unauthorized access and use of these areas by public.
    - Immediate sealing of five contaminated wells so as to prevent use of water from these wells for any purpose by the residents.
    - Excavation and recovery of dumps materials. The incinerable wastes should be disposed off in TSDF at Pithampur. The non-incinerable wastes to be disposed off in an on-site secured landfill facility to be constructed at UCIL.
    - Decontamination and decommissioning of plant, machineries and buildings prior to remediation of contaminated soil and groundwater.

- Under long-term measures, remediation of contaminated soil and groundwater was recommended. For remediation of contaminated soil, an on-site secured landfill facility was recommended. For contaminated groundwater, pump-and-treat system was recommended.

- The cost of soil remediation through secured landfill is estimated to be in the range of Rs 78 crore to 117 crore (average Rs. 100 crore). The capital cost for pump and treat unit shall be in the range of 25 to 30 lakhs. The operating and maintenance cost of such unit is in the rage of Rs. 10 to 15 lakhs per annum including cost of activated carbon and its disposal.
- It is recommended that, BGTRRD should engage competent professional contractors for detailed engineering, and execution of various remedial measures recommended by NEERI.

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3.0 Field Investigations for Assessment of Contamination

3.1 Preamble

The purpose of field investigations is to define and delineate the contaminants present and the general extent and location of contamination. The field investigations comprised of detailed hydrogeological investigations (geophysical investigations, borehole drilling, development of monitoring wells etc.), followed by collection and analysis of existing field samples (dumpsite, subsurface soil, and groundwater). The hydrogeological investigations were carried out by NGRI whereas sampling and characterization of soil and groundwater were carried out by NEERI. Details of these investigations are presented in the following sections.

3.2 Geophysical investigations

The purpose of geophysical investigations is to define and delineate the contaminants present and the general extent and location of contamination. Geophysical methods are used to identify the "hot spots" at a site and act as siting tools to optimize the locations of wells and boreholes over large study areas. Geophysical investigations mainly comprise measurement and interpretation of signals from natural or induced physical phenomena generated as a result of spatial changes in subsurface lateral and depth wise inhomogenity. These signals, measured repetitively at several points in space and time, are interpreted, considering geological information, in terms of sub-surface structures/features.

Among all the surface geophysical techniques for shallow subsurface prospecting, Electrical Resistivity Method is the most widely applied method. The electrical resistivity method can be classified in two categories viz. 1) vertical electric sounding (VES) and 2) electrical resitivity profiling (ERP). The VES is used for delineating vertical variations of the subsurface, whereas ERP is used to detect lateral variations (anomalies).

The geophysical investigations were carried out by NGRI in 1994 within UCIL premises for delineating subsurface formations (using resistivity sounding) as well as identifying possible dump areas (using resistivity profiling). The VES revealed a predominant subsurface formation of black cotton soil followed by silty soil, soft fractured sand stone and hard sandstone as bedrock. The combined thickness of black cotton soil and silty soil was inferred to be 15.3 to 58.9 m. The depth of hard sandstone was inferred to be 16.9 to 69.6 m below grand level. The ERP carried out at 11 traverses covering entire UCIL premises (**Fig. 3**) revealed that 5 traverses (D, E, G, H, and I) were laid over possible dump materials. The soil samples collected in these areas had confirmed existence of contaminants such as temik or sevin.

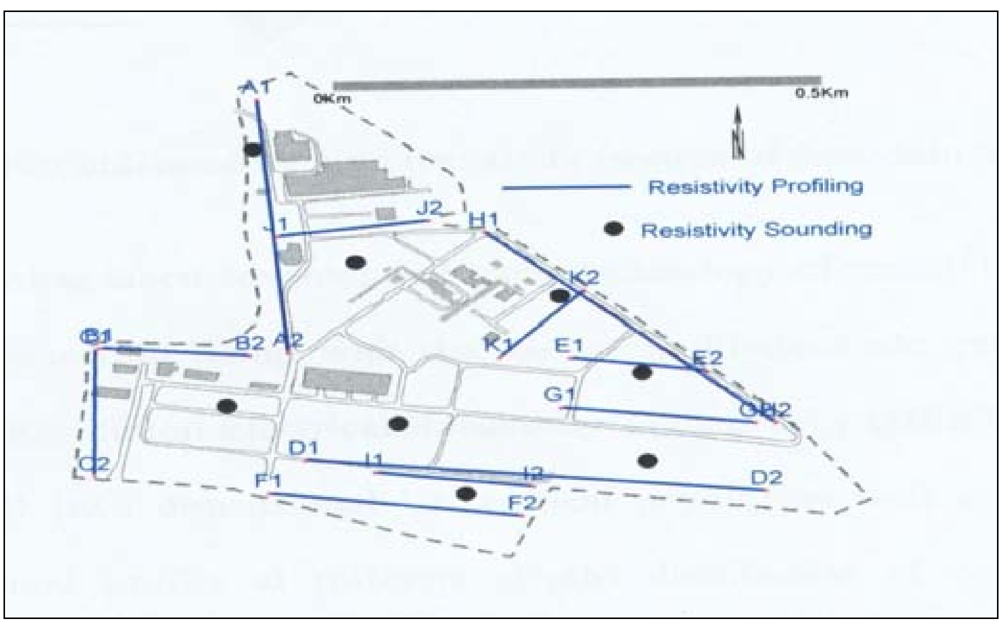

Fig. 3: Electrical Resistivity Profiling (ERP)

Considering the abovementioned back ground information on geophysical investigations carried out by NGRI and the extent of contamination reported by NEERI in 1996, the fresh geophysical investigations were carried out by NGRI during the present study.

The latest technology of resistivity imaging namely High Resolution Electrical Resistivity Tomography (HERT) was used by NGRI for obtaining two dimensional (vertical profile) as well as three dimensional (horizontal profile at different depth) distribution of resistivity of subsurface strata. An equipment, SAS4000 from ABEM, Sweden was used for the present study. The data were interpreted using RES2DINV (2005) software.

The HERT was carried out across the selected areas based on background information about the site as well as physical limitations at site (existence of concrete structures, sheds, bushes, water logging, roads etc). A total of nine sites within the UCIL premises were covered during the HERT survey. The locations of HERT survey are depicted in **Fig. 4.**

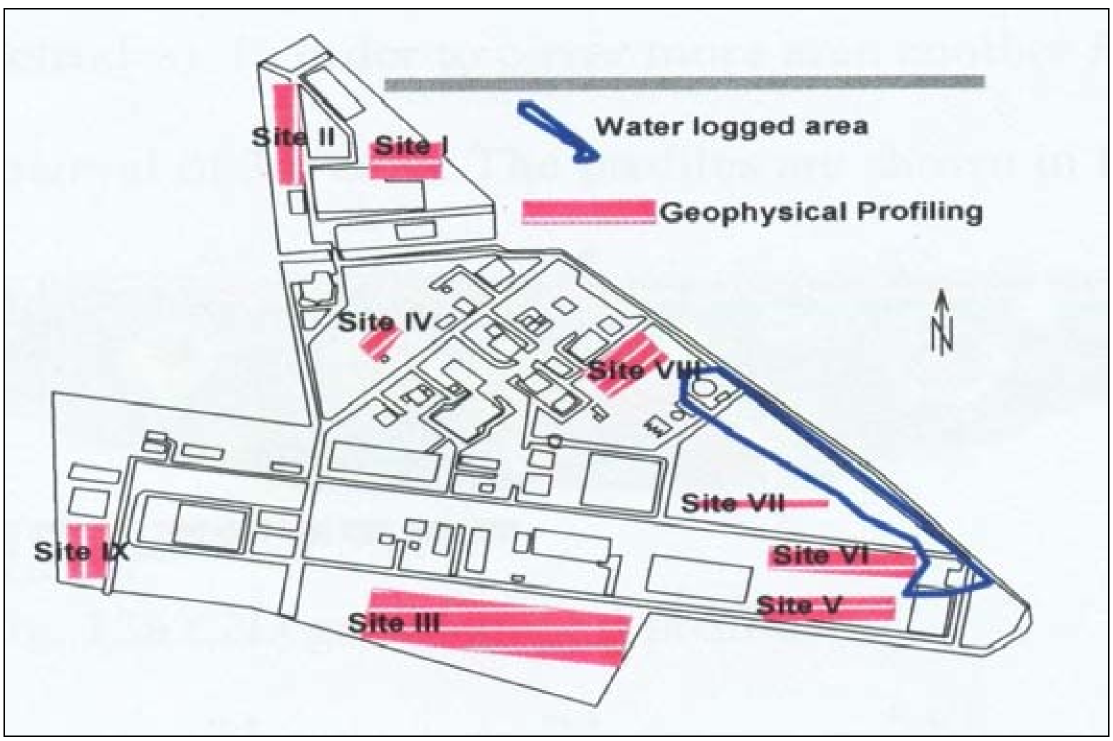

Fig. 4: Locations of HERT survey

The observations made by NGRI at these 9 sites are listed below:

Site I : The site is situated in the northern part of the premises in front of Formulation plant (**Fig. 5**). The heaps of dumps were visible at the open space emitting pungent smell of pesticides. The HERT profiles were laid across the dump in EW direction. at an electrode separation of 1m so that the dumps are adequately covered.. A total area of 9m x 48m was covered at this site. It was observed that the dumps showed higher resistivity of the order of 100 to 300 ohm-m as compared to the resistively of about 5 to 8 ohm-m for black cotton soil. The dumps were clearly demarcated in the profile with depth from few cms to about 1m.

Site II: This site is situated in the open space close to Cycle shed or West of Formulation plant across the road (**Fig. 5**). The profile was laid in NS direction at an electrode separation of 2m and 3m so that entire area is covered. The area showed the uniform resistivity of about 4 to 6 ohm-m with no sign of any dump.

Site III: The site is situated in the open area located in the southern part of premises and south of road opposite to Storage tank or near Neutralization pit (**Fig. 5**). The western part of the area is occupied by metal road and demolished structures hence that part is not covered. This area was reported as dumpsite in the previous study by NEERI. During the present study, the entire open area was covered by selecting electrode separation of 3m in EW direction. The resistivity profile of the area indicated possibility of only one dump with a maximum depth of about 4 to 8 m expected over a very small area.

Site IV: This site is situated in the open space close to tower (**Fig. 5**). Due to limitation of space, electrode spacing was restricted to 0.5m with total profile length as 23.5m in NS direction. This area also showed the uniform low resistivity with no sign of any dump.

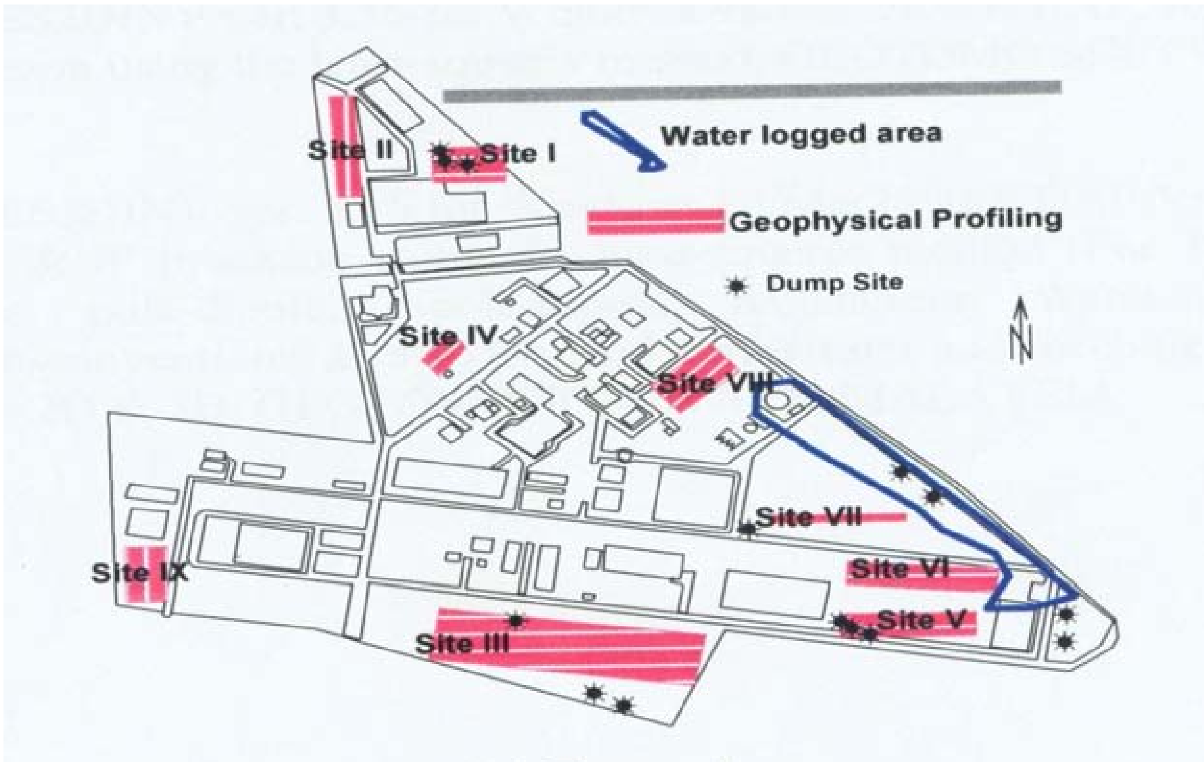

Figure 5: Locations of suspected dumps at UCIL premises

Site V: This site is situated in the area east of Police Post and the open space between Neutralization tank and SEP (**Fig. 5**). The SEP I and II were water logged as shown in Fig. 3 h, I and j, hence could not be covered. The SEP-I was filled with domestic waste from nearby settlements. The heaps of dump with strong smell of pesticides were visible along the road leading to SEP. The total area covered at this site is about 48mx14m.The resistivity profiles obtained in the area indicated existence of dumps up to a depth of about 0.7 to 1.3 m.

Site VI: The site is situated in the same area but in the northern most part along the road in EW direction (see **Fig. 5**). Due to limitation of space and water logging of the area, the electrode spacing was restricted to 2m with total profile length of 48 m in EW direction. There was no indication of any dump in this area.

Site VII: This site is situated in the eastern part of premises and north of SEP as shown in **Fig. 5**. The eastern part of this site was waterlogged where as many parts were covered with bushes. The profile was taken in EW direction with 2m electrode spacing. In this profile too the dumps were not detected, although there are tarry dump in the south of this profile as shown in **Plate 3.**

Site VIII: This site is situated in the close vicinity of the plant in the eastern direction. Part of this area was also water logged and some are covered with bushes. The profile was taken in NE as shown in **Fig. 5**. An area of 48mx12m was covered by these profiles. There was no indication of any dump in this part of premises.

Site IX: This site is situated at the open space near the main entrance, on the western side of road as shown in **Fig. 5**. The electrode separation was selected as 2m. At this site too there was no indication of any dump.

The resistivity profiles carried out using HERT at the above mentioned nine sites, indicated possibility of existence of dumps at three sites namely:

- Site I : North of Formulation Plant
- Site III : South of Storage tank and Police Post, and
- Site V : Between Neutralization tank and SEP including tarry waste dump in northern part.

Most of the dumps were limited to a depth of about 2 m, except one dump that could be deeper (4 to 8 m) over a small area. These dumps were isolated from each other.

The detailed report by NGRI on these investigations is appended as **Annexure I**.

3.3 Hydrogeological investigations

Based on the background data and information generated by previous studies and geophysical investigations carried out by NGRI during the present study detailed hydrogeological investigations were undertaken by NGRI within UCIL premises.

The background data/information on hydrogeology indicated the undulating topography in and around the city of Bhopal with hills formed by Vindhyan formations and valleys occupied by alluvium and basalts. 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. Geomorphologically the study area lies in the pediplain. The weathered basalt overlying the Vindhyans is reported to be thin, shallow and poor in groundwater potential. The general slope of the area is towards southeast.

The geophysical investigations indicated a thick layer of clay up to a depth of 25 to 30 m below ground level having a low resistivity. It is followed by increase in resistivity indicating saturated weathered basalt or weathered Vindhyans.

In order to understand the groundwater regime around the premises, well inventory was carried out by NGRI in and around the area in the month of November 2008 (**Table 4**).

Table 4: Well Inventory studied by NGRI

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

Total 8 wells were selected for monitoring groundwater levels. There is only one bore well within the UCIL plant premises which is located near the entrance of the plant. Seven other existing wells were selected in the periphery of the area for monitoring water level. The depth of these wells varies from 55 to 68 m except for well no. 2 which is shallow (9.5 m deep) dug well. The water level monitoring during November 2008 (Post monsoon) indicates that shallow groundwater exists 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 well hydrograph generated by NGRI indicated water level variation from 3.4 m to 23.37 m due to monsoon of 2008-09. The lowest variation of 3.4 m was observed in the shallow dug well outside the premises which may be a localized shallow aquifer. The remaining bore wells indicated similar behavior with a variation of about 9 to10 m, except for a well in the eastern part (23.37 m) which has very high abstraction (almost running for 24hrs).

In order to confirm the observations made from geophysical investigations and to generate precise data/information on subsurface lithology within the plant premises of UCIL, drilling of test borewells was carried out by NGRI during January 2010. Total five sites were selected to carry out drilling. The selected sites for drilling are shown in **Fig. 6.** Lithologs were collected at different intervals during drilling. **Plate 6** depicts drilling of borewells. The lithological description of each site is depicted in **Fig 7 to 11.** A fence diagram based on the lithologs is shown in **Fig. 12**.

Based on the data generated during drilling of test borewells it was observed that the weathered basalt is overlain by black silty clay of 10 to 17 m below ground surface. The basalt is further overlain by yellow silty clay and its depth varies from 22 to 25 m. 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 of UCIL premises. Water was struck at about 25 m below ground surface and risen to about 8.5 to 14 m indicating that aquifer may be in confined condition. The entire bore wells were screened only in the lower part against aquifer and remaining portion is sealed with iron casing so as to prevent cross contamination of aquifer.

Figure 6: Location of sites selected for drilling with in the UCIL premises

Plate 6: Drilling of borewells within UCIL premises

The slug tests were carried out by NGRI at the constructed borewells to determine the transmissivity and permeability of the aquifer. These transmissivity values were found to vary from 4.29 to 24m^2/d. It was also observed that the permeability of aquifer is slightly higher in the south western part and minimum in the north eastern part of the area.

In order to obtain groundwater flow in and around the study area, water levels in all the wells were monitored by NGRI during February 2010. 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. The data indicated that the groundwater flow direction is in south east direction. It was also reported that aquifer characteristics are variable and may change with time.

It may be concluded from the hydrogeological studies that entire area of UCIL premises is occupied by a thick layer of black silty clay and yellow silty clay upto a depth of about 22 to 25 m below ground level. The groundwater occurs in sandy alluvium with pebbles at a depth of around 25m below ground surface under confined condition. The groundwater flow direction in and around the UCIL premises was in south-east direction which could change with time. It was also reported by NGRI that there existed a subsurface elevation or mound near the central part of the UCIL premises, which diverted the subsurface water flow in north-east or south-east directions depending on the approach of the flow.

The detailed report on hydrogeological investigations carried out by NGRI is appended as **Annexure II**.

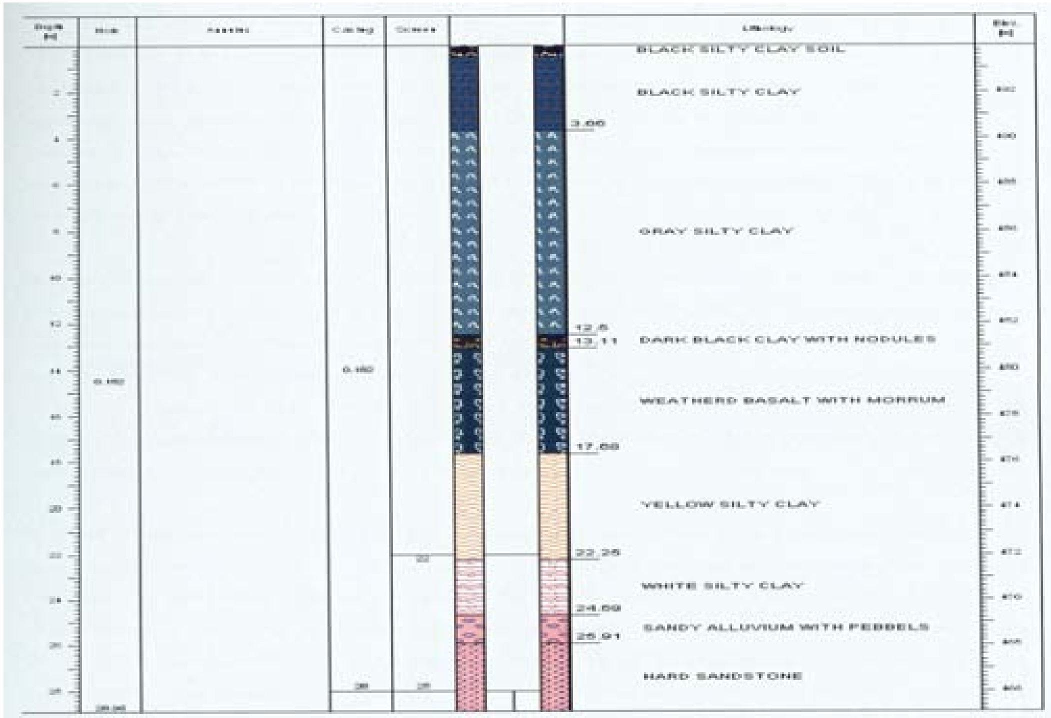

Figure 7: Litholog and drill-time log at bore well A

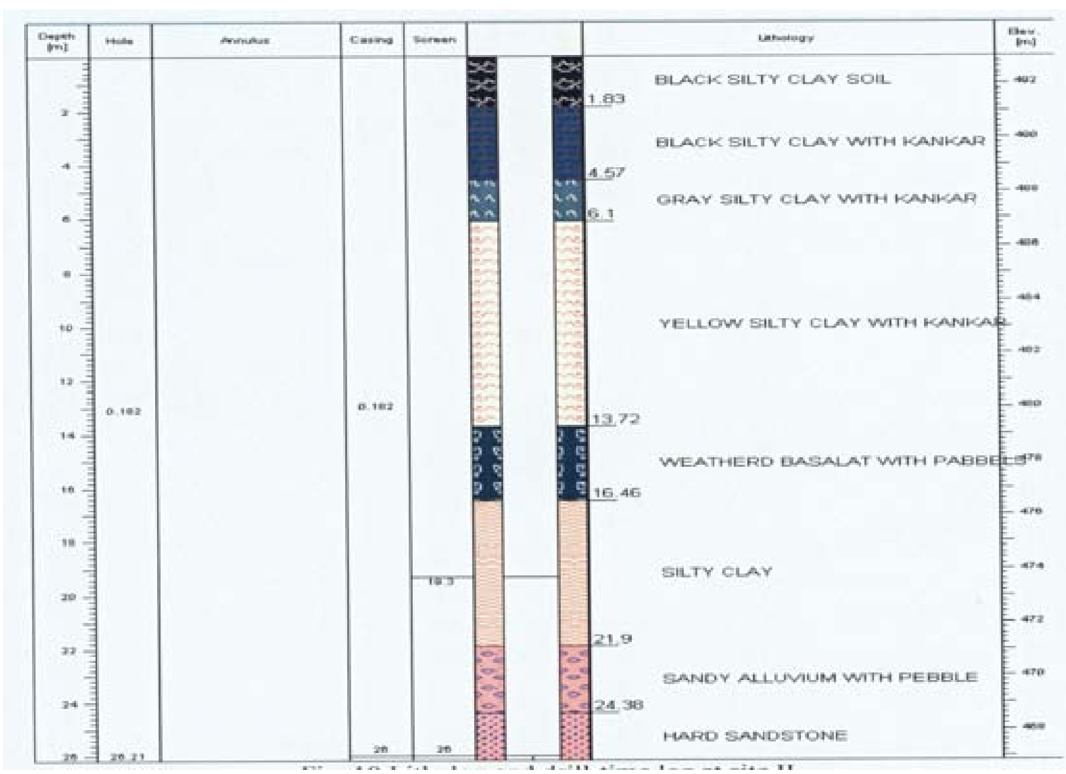

Figure 8: Litholog and drill-time log at bore well B

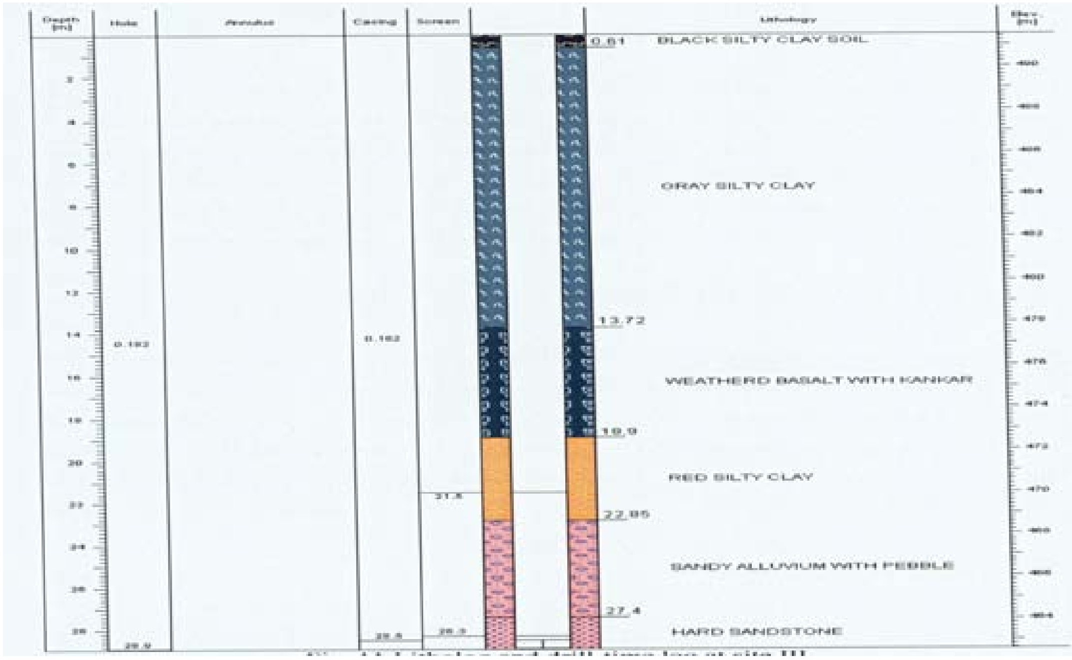

Figure 9: Litholog and drill-time log at bore well C

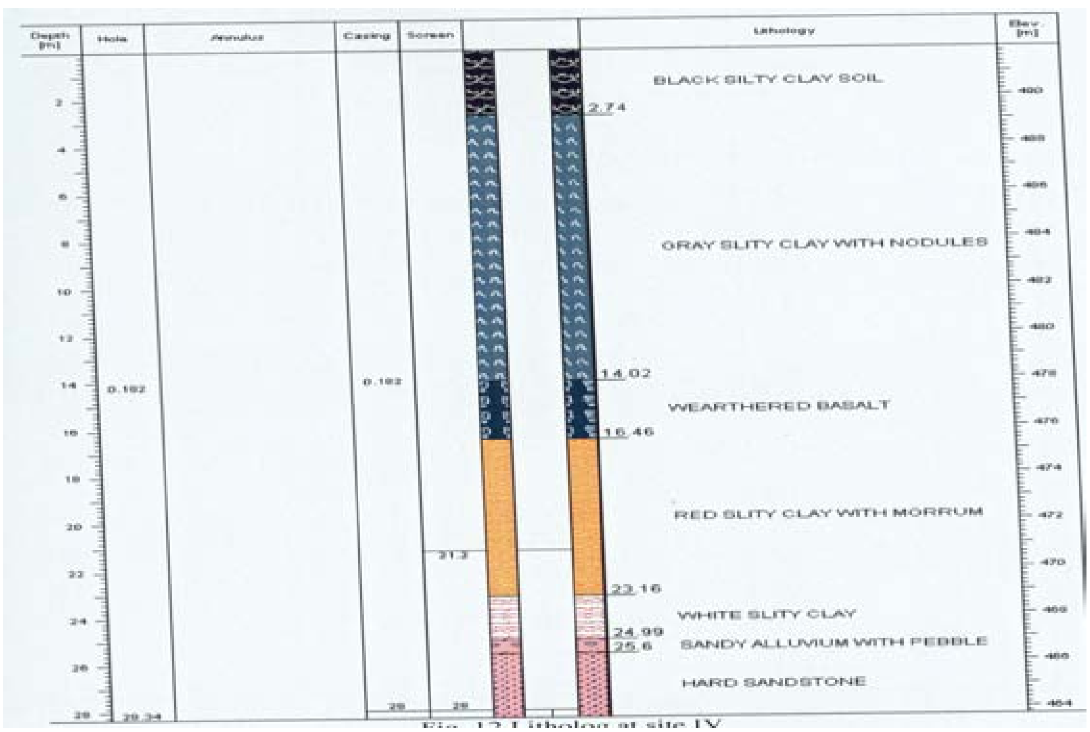

Figure 10: Litholog and drill-time log at bore well D

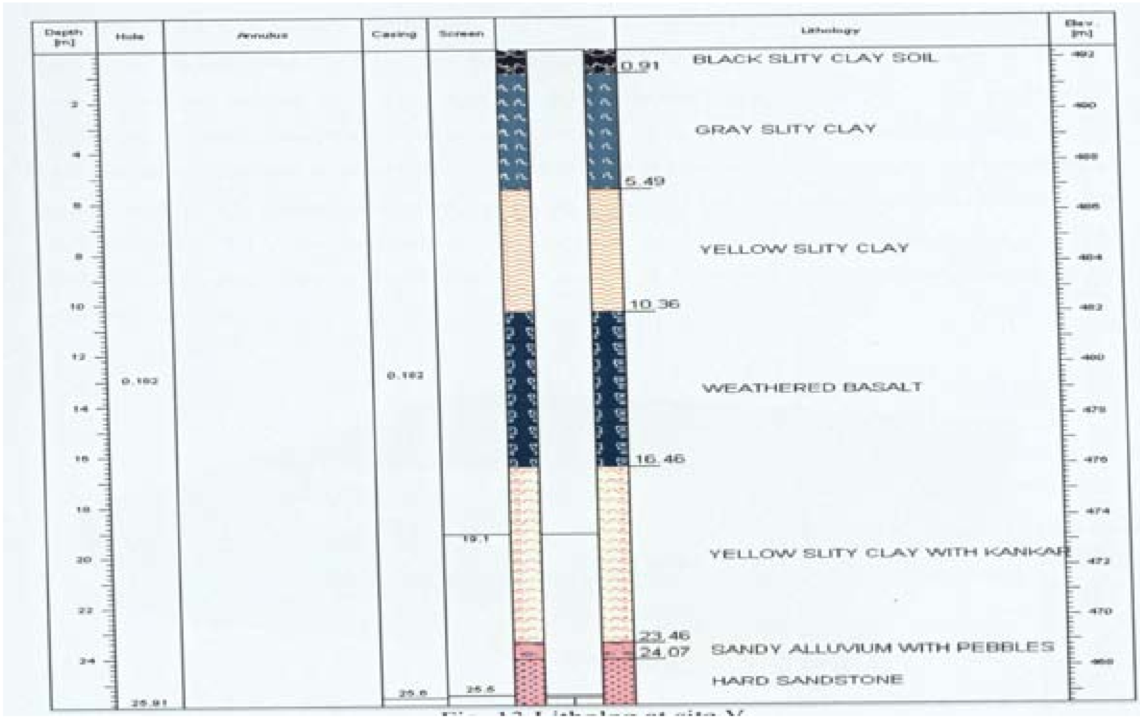

Figure 11: Litholog and drill-time log at bore well E

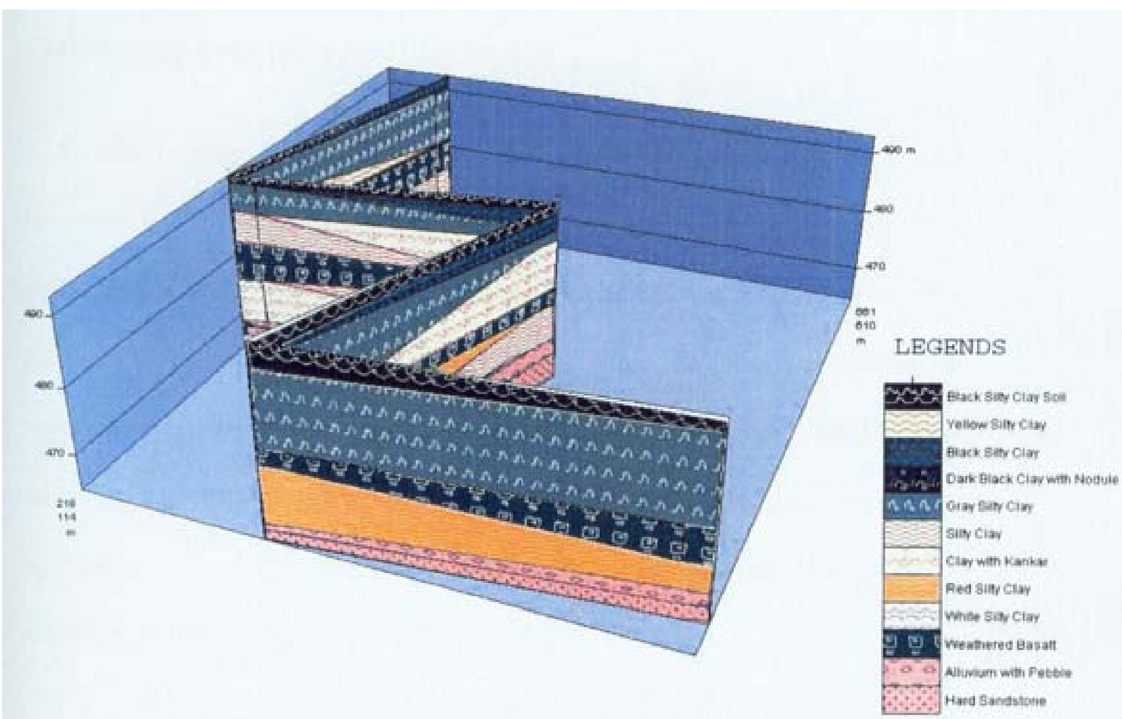

Figure 12: Fence diagram showing geological strata at UCIL premises

3.4 Monitoring of soil and groundwater

In order to assess vertical as well as lateral extent of contamination, soil and groundwater samples were collected from various locations in and around UCIL premises. The three rounds of sampling were undertaken (April 2009, January 2010 and May 2010) during the study. The sampling and analysis protocols followed during the monitoring of soil and groundwater are listed in **Table 5** and details are provided in following sections. The analytical results present in the report are average of three sampling. The results were cross-checked and confirmed on different analytical instruments.

Table 5: Sampling and analysis protocols followed in the study

S.No.	Item	Protocols/Methods used
1.	Samples collection, preservation, transportation, extraction and cleanup	USEPA SW-846, For water: EPA Method-3510,8318A For Soil: EPA Method-3540,8318A Cleanup: EPA Method-3610,3630
2.	Physico-chemical parameters	Standard Methods, IS:10158,1982
3.	Heavy Metals	Acid digestion: EPA Method-3050, 3051,3052,3060, 7471b,7470a,7062
4.	Chlorinated organics	GC-ECD: EPA Method-8081 GC/MS: EPA Method-8270
5.	Volatile organics	GC-FID, GC/MS: EPA Method-5035, 5021, 8015, 5032 & 8270C
6.	Carbaryl, Aldicarb and α-naphthol	HPLC: EPAMethod-8318 GC/MS: EPA Method-8270

a) Soil sampling within the UCIL premises

Based on background information about the waste disposal practices and the geophysical investigations, 5 boreholes were drilled by NGRI within UCIL premises. During the drilling of boreholes, soil samples were collected by NEERI from different depths from each borehole. The depth of drilling varied from 25 to 32 meters depending on the occurrence of ground water. Total 90 soil samples from 5 boreholes were collected. The location of boreholes is depicted in **Fig. 6**. The details of samples collected from different depths are listed in **Table 6 and Table 7**.

Table 6: Details of borehole locations

S.No.	Borehole	Location*
1.	A	Near Temik and Formulation plant
2.	B	Near MIC storage and water treatment plant
3.	C	Disposal area II on the eastern side of the plant
4.	D	Near storage tanks
5.	E	Near Naphthol plant

***** With respect to then existing layout

Table 7: Soil samples collected from different depths of five boreholes

Number of samples	Depth in meters				
	Bore A	Bore B	Bore C	Bore D	Bore E
Surface					
1.	0.3	0.3	0.3	0.3	0.3
2.	0.6	0.6	0.6	0.6	0.6
3.	0.9	0.9	0.9	0.9	0.9
4.	1.2	2.0	2.0	2.0	2.0
5.	2.0	3.0	3.0	3.0	3.0
6.	3.0	4.0	4.0	4.0	4.0
7.	4.0	5.0	5.0	5.0	5.0
8.	5.0	6.0	6.0	6.0	6.0
9.	6.0	7.0	7.0	7.0	7.0
10.	7.0	8.0	8.0	8.0	8.0
11.	8.0	10.0	9.0	9.0	9.0
12.	9.0	14.0	10.0	10.0	11.0
13.	11.0	16.0	12.0	12.0	13.0
14.	13.0	18.0	14.0	14.0	15.0
15.	15.0	20.0	16.0	16.0	17.0
16.	17.0	22.0	18.0	18.0	19.0
17.	22.0	27.0*	20.0	22.0	21.0
18.	27.0		25.0*	27.0*	26.0*
19.	32.0*				

***Occurrence of ground water**

The boreholes were drilled by NGRI adjacent to the suspected contaminated areas so as to prevent cross contamination of aquifer. Hence, additional 27 surface and subsurface (30 cm deep) soil samples were also collected from the exact locations of the suspected contaminated hot spots within UCIL premises (**Figure 13, Table 8**).

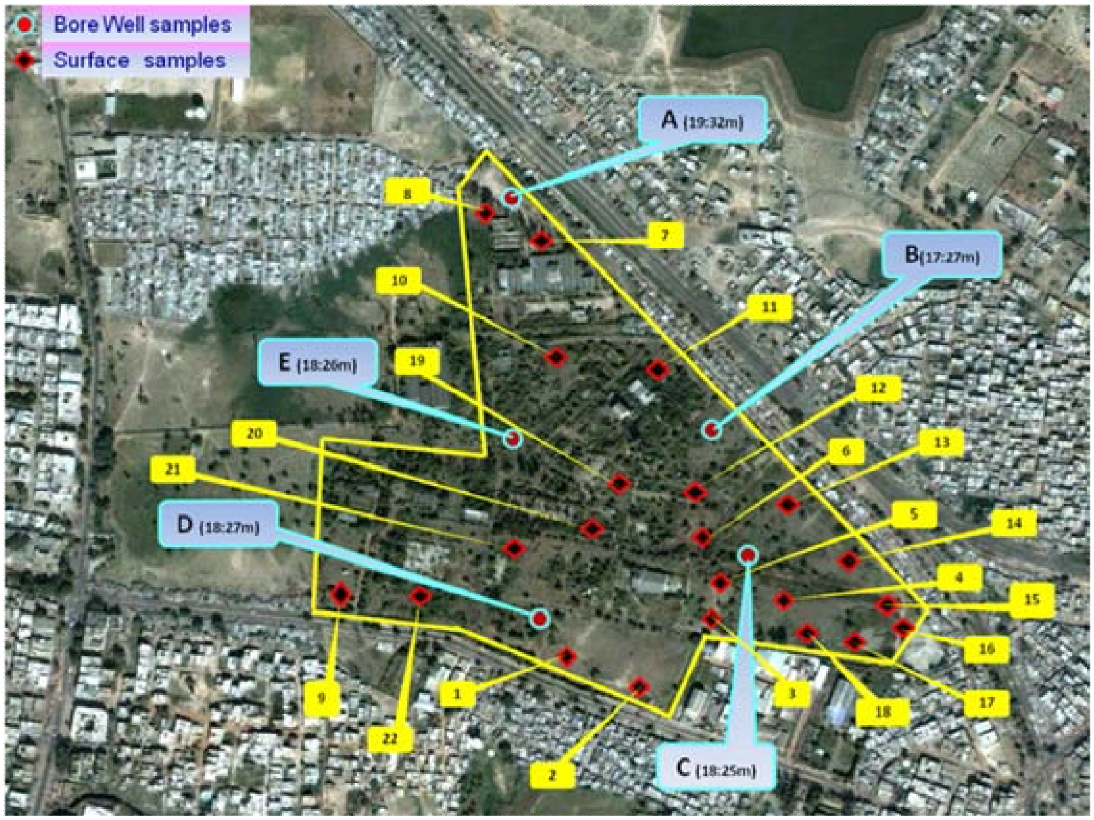

Figure 13: Locations of soil samples collected within UCIL plant premises

The soil samples for semi volatile and chloro-organic compounds were collected with stainless steel scoop and transferred into Ziploc plastic bags. Soil samples for Volatile Organic Compounds (VOC's) were collected in glass vials and sealed with aluminum cap having teflon-lined septa as per the EPA Methods: 5035, 5021 (**Table 5**). All the collected soil samples were preserved in the ice box at 4^0C, and then transported to NEERI, Nagpur for further processing and analysis.

Table 8: Location of soil samples collected within UCIL premises

S. No.	Samples ID	Sample Location
1.	**S-01**	Disposal site III
2.	**S-02**	Disposal site III
3.	**S-03**	Near neutralization pit outer boundary
4.	**S-04**	Near neutralization pit inner side of the plant
5.	**S-05**	In between the neutralization pit and BHC store
6.	**S-06**	Near BHC store
7.	**S-07**	Near formulation plant area
8.	**S-08**	Near Temik plant area
9.	**S-09**	Disposal site IX near the entrance gate
10.	**S-10**	Near soapstone shed
11.	**S-11**	Near Seven plant area
12.	**S-12**	Near water treatment plant
13.	**S-13**	Near disposal site VIII adjacent to the water treatment plant
14.	**S-14**	Adjacent to the boundary wall at disposal site VII
15.	**S-15**	Near the disposal site VI
16.	**S-16**	Near the security post at east side of the plant
17.	**S-17**	Near the disposal site V
18.	**S-18**	Near the disposal site V 5meter away from S-17
19.	**S-19**	Near the MIC plant
20.	**S-20**	Near naphthol plant
21.	**S-21**	In front of the naphthol plant
22.	**S-22**	In front of the Laboratory at a distance of five meters
23.	**AS**	Near Temik and formulation plant area
24.	**BS**	Near MIC storage and water treatment plant area
25.	**CS**	Disposal are II on the eastern side of the plant
26.	**DS**	Near neutralization pits
27.	**ES**	Near naphthol plant

b) Soil sampling outside the UCIL premises

In addition to the boreholes and suspected contaminated hotspots, soil samples were also collected from eight different locations outside the UCIL plant premises considering the ground water flow direction, which is generally towards the north-east or east direction as reported in previous studies. The soil samples at these locations were collected at three different depths (surface, 30 cm deep and 60 cm deep). Thus, total 24 soil samples were collected outside UCIL premises. Out of these eight locations, four locations were in upstream (South-West) of UCIL and four locations were in downstream (North-East) of UCIL. The sampling locations are depicted in **Figure 14 and details are listed in Table 9**.

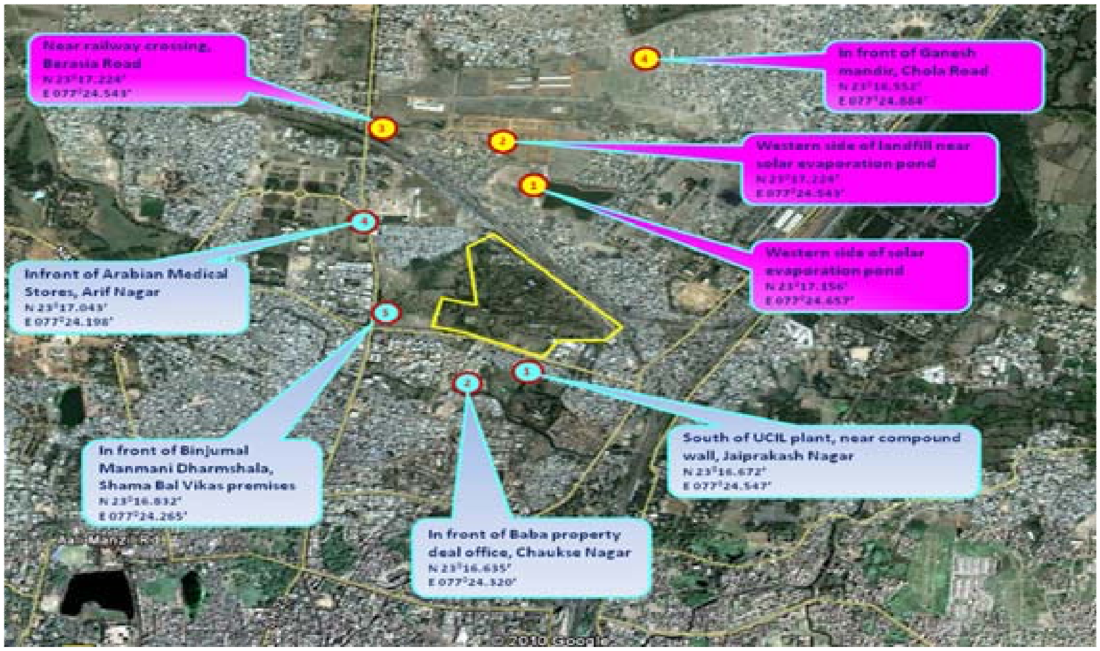

Figure 14: Locations of upstream and downstream soil samples collected outside the UCIL premises

Table 9: Details of upstream and downstream soil samples collected outside UCIL premises

S. No.	Sample ID	Sample Location	Geographic location
1.	**US-01**	South of UCIL plant, near compound wall, Jaiprakash Nagar	N 23^{0}16.672’ E 077^{0}24.547’
2.	**US-02**	In front of Baba property deal office, Chaukse Nagar	N 23^{0}16.635’ E 077^{0}24.320’
3.	**US-03**	In front of Binjumal Manmani Dharmashala, Shama Bal Vikas premises	N 23^{0}16.832’ E 077^{0}24.265’
4.	**US-04**	In front of Arabian Medical Stores, Arif Nagar	N 23^{0}17.043’ E 077^{0}24,198’
1.	**DS-01**	Western side of solar evaporation pond	N 23^{0}17.156’ E 077^{0}24.657’
2.	**DS-02**	Western side of land fill near solar evaporation pond	N 23^{0}17.224’ E 077^{0}24,543’
3.	**DS-03**	Near railway crossing Berasia Road	N23^{0}17.224’ E 077^{0}24.543’
4.	**DS-04**	In front of Ganesh mandir, Chola Road	N 23^{0}16.552’ E 077^{0}24.884’

c) **Groundwater sampling within the UCIL premises**

Groundwater samples were collected from the monitoring wells which were constructed from the drilled boreholes by NGRI in Janaury 2010. As mentioned earlier, total 5 boreholes were drilled by NGRI within UCIL premises which were converted to monitoring borewells. The groundwater samples were collected from these 5 borewells immediately after their construction. In addition groundwater sample from an existing borewell near main entrance was also collected within the premises. The samples were preserved as per the EPA Methods mentioned in the **Table 5**. For routine physic-chemical analysis one liter of sample collected and refrigerated at 4^0C. For carbamate pesticides, the samples were preserved by acidifying to pH 4.0 with 0.1 N chloroacetic acid and for other organics analysis acidified samples were kept in ice box at 4^0C. For heavy metals analysis, samples were preserved with nitric acid and brought to NEERI, Nagpur for analysis.

The confirmatory sampling of these borewells was attempted by NEERI in May 2010. However, during the visit, all the borewells constructed by NGRI were found to be broken, tampered and filled with unknown materials. Hence, repeat sampling could not be done for these borewells.

Plate 7: Tampered/broken borewells within UCIL premises

d) Groundwater sampling outside UCIL premises

In addition to the above mentioned groundwater samples, samples were also collected from the existing sources (dug wells, bore wells and hand pumps) around the UCIL premises. The groundwater sampling was done considering the groundwater flow direction, which is in general towards North-East. The locations and details of groundwater samples collected around the UCIL plant are presented in **Figure 15** and **Table 10.** The samples were preserved and transported as mentioned in the previous section.

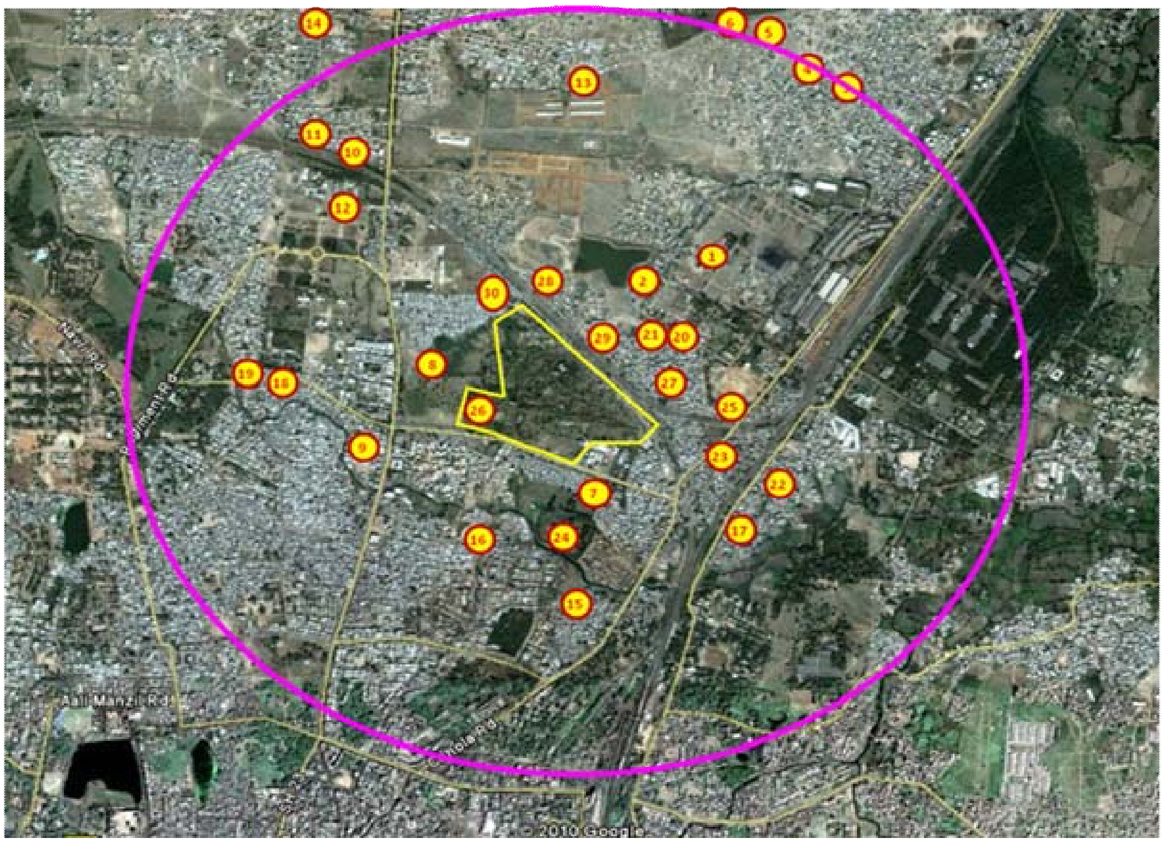

Figure 15: Locations of groundwater samples collected around UCIL premises

Table 10: Details of groundwater samples collected around UCIL premises

Sample ID	Description	Distance (Km)	Location
GW-1	Garib Nagar, Adjacent to Solar evaporation pond. Bore well (Handpump). Clear potable water.	0.566	N 23^0 17.073’ E 077^0 24.845’
GW-2	Sunder Nagar, Near over head water tank. Bore well (Electrical).	1.155	N 23^0 17.275’ E 077^0 25.117’
GW-3	Shiv nagar, in front of Chuarasia Mandir. Bore well (Hand pump).	1.497	N 23^0 17.452’ E 077^0 25.204’
GW-4	Shiv nagar , Phase III , Beside Durga mandir . Bore well (Hand pump), approximately 180 ft.	1.566	N 23^0 17.546’ E 077^0 25.134’
GW-5	Near shri chintahari Shiv mandir, Liladhar colony, Bhanpur.	2.755	N 23^0 17.858’ E 077^0 25.811’
GW-6	Rajwada family restaurant	2.665	N 23^0 18.231’ E 077^0 25.020’
GW-7	In front of UCIL , Jai Prakash nagar, MPEB compound , (well-40 ft)	0.424	N 23^0 16.670’ E 077^0 24.462’
GW-8	Chaukse Nagar Mr. Saleem Akbar. Plot No.- 233	0.751	N 23^0 16.572’ E 077^0 24.299’
GW-9	Jawaharlal Nehru hospital compound, DIG Bangla, Berasia road, Borewell (Mechanical pump), 150 ft.	0.804	N 23^0 16.762’ E 077^0 24.168’
GW-10	In front of Geetanjali (PGBT)Mahavidyalaya, Narial Kheda road Bore well(hand pump).	1.087	N 23^0 16.883’ E 077^0 23.997’
GW-11	In front of Anand medical store. Nariyal kheda road , Bore well (hand pump)	1.421	N 23^0 17.083’ E 077^0 23.843’
GW-12	Purv Nishadpur, Nariyal kheda road, In front of Arif nagar(West of UCIL), Bore well (handpump)	2.563	N 23^0 17.108’ E 077^0 23.157’
GW-13	Mr. Shamim Ahmed, Plot No. 15, Jia Colony, Near Mandi, Borewell (Mechanical Pump).	1.003	N 23^0 17.325 E 077^0 24.380
GW-14	Panna Nagar, Beside Vijay Sangh Mandir, in front of Mr. Bhupen Singh Rajputs House.	1.739	N 23^0 17.506 E 077^0 23.918
GW-15	Mr. M. K. Lokhande, Plot No. 609, Near Hari Mazar, Housing Board Colony, Berasia Road, Bhopal.	2.292	N 23^0 17.876’ E 077^0 23.904’
GW-16	Infront of Krishna Public School, Kapil Nagar, Karod. Borewell (Handpump)	1.458	N 23^0 17.623’ E 077^0 24.613’
GW-17	In front of Chola Dussera Maida, Fire Brigade Sub Station. Borewell (Mechanical Pump). Approximately 200 ft.	0.802	N 23^0 16.842’ E 077^0 25.106’
GW-18	Nav Jeevan Colony, Near Mahakaleshwar Mandir, Adjacent Passage. Borewell (Handpump)	0.454	N 23^0 16.879’ E 077^0 24.897’
GW-19	In front of Late Mr. Devisingh Prajapati’s house, Plot No. – 10, Lane No. 7, Nav Jeevan Colony.	0.476	N 23^0 16.879’ E 077^0 24.897’
GW-20	Mr.Ramesh Prasad Chaubey, House No. 1676, Prem Nagar, Road No. 2, Chola. In front of electric Transformer.	0.331	N 23^0 16.880’ E 077^0 24.823’
GW-21	Inside Mrs. Neelam Shukla’s House, House No. 37, Prem Nagar. Borewell (Handpump). Approximately 80ft.	0.268	N 230 16.887’ E 0770 24.782’
GW-22	In front of Mr. Saleem Bhai Rui Wale Ujjainwale’s Shop, Vidisha Road, Kaichi – 16, Near Railway Line. Borewell (Handpump).	0.691	N 230 16.693’ 0770 25.010’
GW-23	Mr. Suresh Sharma, House No. 56, Lane No. 1, Chola. Borewell (Handpump)	0.722	N 230 16.604’ E 0770 24.976’
GW-24	M/s. BSS Petrol Pump, Phuta Maqbara, Chola Road.	0.926	N 230 16.373’ E 0770 24.841’
GW-25	Shri Vishram Ghat, Borewell (handpump).	0.692	N 230 16.462’ E 0770 24.639’
GW-26	UCIL Premises, Near the front entrance.	0.624	N 230 16.504’ E 0770 24.700’
GW-27	In front of C V Raman High School, 116 Shiv Shakti Nagar, Near Archana Gas Godam, Chola Road.	0.776	N 230 17.220’ E 0770 24.817’
GW-28	Blue Moon Colony, in front of Mr. Prakash’s House.	0.384	N 230 17.037’ E 0770 24.578’
GW-29	Besides Mr. Ajmera’s house.	0.223	N 230 16.955’ E 0770 24.656’
GW-30	Beside Arif Nagar Stadium, Arif Nagar, Well.	0.489	N 230 17.042’ E 0770 24.454’

e) Analysis of soil and ground water samples

The parameters selected in the present investigation for characterization of soil and ground water are based on the site specific activities carried out by UCIL in the past. Based on the review of the past process operations as well as apprehensions raised by various agencies/organization following compounds/parameters were selected for monitoring:

- semi volatiles/pesticides (Carbaryl, aldicarb, alpha naphthol, hexachlorocychlohexane isomers and naphthalene)

- volatile organics (carbon tetrachloride, chloroform, methylene chloride, 1,2-dichlorobenzene, chlorotoluene and toluene)

- Relevant heavy metals (mercury, cadmium, nickel, chromium, cobalt, lead, zinc, and copper)

The processing and analysis of samples for abovementioned compounds/parameters were carried out as per the protocols listed in **Table 5**. The background soil in the area is laden with high concentrations of iron and manganese, and therefore, although these metals were analyzed, these are not reported as there were no abnormalities observed.

As mentioned earlier the soil and ground water samples were analyzed for the identified contaminants employing internationally accepted protocols as listed in **Table 5**. Accordingly the samples were extracted in specific solvents using prescribed procedures prior to analysis on the prescribed Instruments such as GC-ECD, GC-MS, HPLC, and ICP.

f) Screening and interpretation of analytical results

i) Soils samples collected upstream of UCIL premises (Control)

The concentration of selected contaminants (Aldicarb, Carbaryl, α-naphthol, HCH isomers and dichlorobenzene) in the surface and subsurface soil samples collected upstream of the UCIL premises are presented in **Tables 11 to 16.** None of the selected contaminants were found in the upstream soil samples.

Table 11: Presence of Aldicarb in the surface and subsurface soil samples around the UCIL premises

Sample location	US-1	US-2	US-3	US-4		DS-1	DS-2	DS-3	DS-4
Surface	ND	ND	ND	ND		8.158	ND	ND	ND
subsurface	ND	ND	ND	ND		ND	ND	ND	ND
All the values are presented in mg/kg, ND: not detected, US: upstream, DS: downstream Screening Standards (USEPA- DEC.2009) Industrial Soil:620 mg/kg; Ground water protection: 0.09 mg/kg									

Table 12: Presence of Carbaryl in the surface and subsurface soil samples around the UCIL premises

Sample location	US-1	US-2	US-3	US-4		DS-1	DS-2	DS-3	DS-4
Surface	ND	ND	ND	ND		6.888	ND	2.910	ND
subsurface	ND	ND	ND	ND		ND	ND	ND	ND
All the values are presented in mg/kg, ND: not detected, US: upstream, DS: downstream Screening Standards (USEPA- DEC.2009) Industrial Soil:62000 mg/kg; Ground water protection: 3.3 mg/kg									

Table 13: Presence of α-naphthol in the surface and subsurface soil samples around the UCIL premises

Sample location	US-1	US-2	US-3	US-4		DS-1	DS-2	DS-3	DS-4
Surface	ND	ND	ND	ND		3.516	ND	ND	ND
subsurface	ND	ND	ND	ND		ND	ND	ND	ND
All the values are presented in mg/kg, ND: not detected, US: upstream, DS: downstream Screening Standards (USEPA- DEC.2009) – Not specified									

Table 14: Presence of α-HCH in the surface and subsurface soil samples around the UCIL premises

Sample location	US-1	US-2	US-3	US-4		DS-1	DS-2	DS-3	DS-4
Surface	ND	ND	ND	ND		ND	ND	ND	ND
subsurface	ND	ND	ND	ND		ND	ND	ND	ND
All the values are presented in mg/kg, ND: not detected, US: upstream, DS: downstream Screening Standards (USEPA- DEC.2009) Industrial Soil:0.27 mg/kg; Ground water protection: 0.000062 mg/kg									

Table 15: Presence of β-HCH in the surface and subsurface soil samples around the UCIL premises

Sample location	US-1	US-2	US-3	US-4		DS-1	DS-2	DS-3	DS-4
Surface	ND	ND	ND	ND		2.55	0.403	ND	ND
subsurface	ND	ND	ND	ND		ND	ND	ND	ND
All the values are presented in mg/kg, ND: not detected, US: upstream, DS: downstream Screening Standards (USEPA- DEC.2009) Industrial Soil:0.96 mg/kg; Ground water protection: 0.00022 mg/kg									

Table 16: Presence of γ-HCH in the surface and subsurface soil samples around the UCIL premises

Sample location	US-1	US-2	US-3	US-4		DS-1	DS-2	DS-3	DS-4
Surface	ND	ND	ND	ND		ND	ND	ND	ND
subsurface	ND	ND	ND	ND		ND	ND	ND	ND
All the values are presented in mg/kg, ND: not detected, US: upstream, DS: downstream Screening Standards (USEPA- DEC.2009) Industrial Soil:2.1 mg/kg; Ground water protection: 0.00036 mg/kg									

The physico-chemical characteristics of upstream soils samples are listed in **Table 17**. All the upstream soil samples were found to be near neutral in pH. The organic content of these soils ranged between 4.99 and 13.13 %. Chlorides and fluorides varied from 249 to 1076 mg/kg and 2.04 to 8.85 mg/kg respectively. Concentration of sodium varied from 132 to 443 mg/kg, while concentration of potassium varied from 45 to 88 mg/kg. Sulfates, phosphates and nitrates are present in the range of 202 to 786, 1.74 to 69.21 and 1.37 to 12.35 mg/kg of soil respectively.

The heavy metal concentration in the upstream soils samples is listed in **Table 18**. All the upstream soils also contain lead in the range of 1.23 to 2.84 mg/kg. Mercury was not detected in any of the upstream soil samples.

Table 17: Physico-chemical characteristics of soil samples collected from upstream and downstream of the UCIL plant

Sample ID.	Location	pH	Organic Carbon (%)	Chloride (mg/kg)	Fluoride (mg/kg)	Sulphate (mg/kg)	Phosphate (mg/kg)	Nitrate (mg/kg)	Sodium (mg/kg)	Potassium (mg/kg)
UST-1	Surface	7.81	13.13	267	8.44	253	6.98	1.37	443	88
	Subsurface	7.70	4.99	250	5.29	249	6.19	2.79	262	65
UST-2	Surface	7.86	5.14	447	3.18	305	6.99	7.22	132	45
	Subsurface	7.63	5.02	393	2.04	204	5.99	19.47	159	53
UST-3	Surface	7.92	7.22	422	4.37	786	1.74	7.92	155	46
	Subsurface	7.58	6.19	249	3.88	304	52.77	5.55	154	51
UST-4	Surface	7.88	6.34	1076	4.90	202	55.94	12.35	278	72
	Subsurface	7.55	7.21	390	8.85	309	69.21	11.68	437	53
DST-1	Surface	7.70	6.54	434	4.61	798	6.13	13.03	160	86
	Subsurface	7.83	5.39	362	4.72	767	12.30	6.05	84	104
DST-2	Surface	7.50	5.68	210	4.51	301	6.19	1.39	575	96
	Subsurface	7.94	4.47	370	4.23	551	13.83	1.63	307	103
DST-3	Surface	8.05	5.13	200	23.35	355	1.24	3.83	755	90
	Subsurface	7.76	5.31	253	16.47	478	3.46	2.95	355	77
DST-4	Surface	7.96	4.56	163	5.35	488	0.31	1.07	258	58
	Subsurface	7.73	4.97	118	5.21	186	1.28	4.04	580	106

UST: Upstream, DST: Downstream,

Table 18: Metals concentration in the soils samples collected from upstream and downstream of the UCIL plant

Sample ID	Location	Zn	Pb	Cd	Ni	Co	Cr	Cu	Hg
US-1	Surface	8.06	1.62	0.21	3.32	2.48	N.D.	4.17	ND
	Subsurface	6.70	1.64	1.21	3.45	7.00	N.D.	2.93	ND
US-2	Surface	8.11	1.23	N.D.	3.43	2.37	N.D.	4.12	ND
	Subsurface	6.10	1.81	N.D.	3.20	4.47	N.D.	3.65	ND
US-3	Surface	7.69	2.23	5.08	3.51	2.54	1.45	1.02	ND
	Subsurface	2.50	1.29	N.D.	4.06	5.87	N.D.	3.55	ND
US-4	Surface	9.02	2.49	10.88	3.51	1.54	10.66	2.36	ND
	Subsurface	9.08	2.84	3.64	4.40	1.66	N.D.	3.10	ND
DS-1	Surface	6.27	3.53	1.40	5.05	1.35	5.21	5.27	0.30
	Subsurface	6.08	1.59	1.14	2.81	2.74	2.09	1.47	ND
DS-2	Surface	7.80	1.18	2.86	3.87	3.27	6.16	3.39	0.33
	Subsurface	6.47	1.73	1.40	2.75	2.98	1.11	3.22	ND
DS-3	Surface	7.76	2.11	1.49	2.76	1.50	3.87	3.20	ND
	Subsurface	5.63	2.52	N.D.	3.15	2.00	2.45	3.72	ND
DS-4	Surface	6.59	1.29	0.22	3.86	3.79	N.D.	2.24	ND
	Subsurface	7.58	2.86	2.74	2.35	3.01	2.47	3.04	ND

All values are reported in mg/kg, ND – Not Detected

ii) Soil samples collected within UCIL plant premises

The concentration of selected contaminants (Aldicarb, Carbaryl, α-naphthol, HCH isomers and dichlorobenzene) in soil samples collected within UCIL premises is listed in **Tables 19 to 26**.

Table 19: Presence of Aldicarb in soil samples from UCIL premises

Sample location	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10	S-11	S-12	S-13	S-14
Surface	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
subsurface	ND	ND	ND	ND	ND	ND	ND	923	596	ND	ND	ND	ND	ND

All the values are presented in mg/kg, ND: not detected,
Screening Standards (USEPA- DEC.2009) Industrial Soil:620 mg/kg; Ground water protection: 0.09 mg/kg

Cont…

Sample location	S-15	S-16	S-17	S-18	S-19	S-20	S-21	S-22	AS	BS	CS	DS	ES
Surface	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
subsurface	ND	ND	ND	ND	ND	ND	ND	ND	3.734	3.778	3.770	3.884	3.713

All the values are presented in mg/kg, ND: not detected,
Screening Standards (USEPA- DEC.2009) Industrial Soil:620 mg/kg; Ground water protection: 0.09 mg/kg

Table 20: Presence of Carbaryl in the soil samples from UCIL premises

Sample location	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10	S-11	S-12	S-13	S-14
Surface	1.25	10729	5493	ND	1.06	2.48	1.3	24.3	251.3	ND	ND	ND	ND	ND
subsurface	3.883	ND	233	ND	ND	ND	ND	14.2	486	24.6	0.126	0.174	ND	ND

All the values are presented in mg/kg, ND: not detected
Screening Standards (USEPA- DEC.2009) Industrial Soil:62000 mg/kg; Ground water protection: 3.3 mg/kg

Cont…

Sample location	S-15	S-16	S-17	S-18	S-19	S-20	S-21	S-22	AS	BS	CS	DS	ES
Surface	0.273	ND	ND	ND	ND	ND	ND	ND	ND	ND	3.241	ND	3.540
subsurface	1.577	ND	2.728	ND	18.3	ND	7.68	10.77	0.038	0.304	3.708	ND	0.288
All the values are presented in mg/kg, ND: not detected Screening Standards (USEPA- DEC.2009) Industrial Soil:62000 mg/kg; Ground water protection: 3.3 mg/kg													

Table 21: Presence of α-naphthol in the soil samples from UCIL premises

Sample location	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10	S-11	S-12	S-13	S-14
Surface	13.02	1208	1460	ND	0.721	1.55	1.90	42.7	ND	ND	ND	ND	ND	ND
subsurface	6.877	ND	297.2	ND	ND	ND	ND	ND	ND	14.94	0.54	0.511	ND	ND
All the values are presented in mg/kg, ND: not detected Screening Standards (USEPA- DEC.2009) – Not specified														

Cont…

Sample location	S-15	S-16	S-17	S-18	S-19	S-20	S-21	S-22	AS	BS	CS	DS	ES
Surface	1.507	ND	ND	ND	ND	ND	ND	ND	3.673	3.754	ND	ND	1.82
subsurface	2.995	ND	1.037	ND	2.3	ND	24.23	37.9	0.86	0.267	3.594	ND	0.077
All the values are presented in mg/kg, ND: not detected Screening Standards (USEPA- DEC.2009) Industrial Soil:31000 mg/kg; Ground water protection: NA													

Table 22: Presence of α-HCH in the soil samples from UCIL premises

Sample location	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10	S-11	S-12	S-13	S-14
Surface	ND	ND	ND	ND	ND	ND	6.37	13.96	ND	5.02	ND	ND	ND	ND
subsurface	0.313	ND	ND	ND	ND	ND	ND	19.82	ND	0.24	0.43	0.31	ND	ND

All the values are presented in mg/kg, ND: not detected
Screening Standards (USEPA- DEC.2009) Industrial Soil:0.27 mg/kg; Ground water protection: 0.000062 mg/kg

Cont…

Sample location	S-15	S-16	S-17	S-18	S-19	S-20	S-21	S-22	AS	BS	CS	DS	ES
Surface	2.08	4.21	ND	ND	ND	0.21	0.64	ND	0.415	0.423	0.392	ND	0.408
subsurface	1.82	2.64	ND	0.53	ND	ND	0.21	ND	0.395	0.407	0.286	0.148	0.362

All the values are presented in mg/kg, ND: not detected Screening Standards (USEPA- DEC.2009) Industrial Soil:0.27 mg/kg; Ground water protection: 0.000062 mg/kg

Table 23: Presence of β-HCH in the soil samples from UCIL premises

Sample location	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10	S-11	S-12	S-13	S-14
Surface	ND	ND	6.93	ND	ND	ND	6.17	ND	ND	0.48	0.38	0.15	ND	ND
subsurface	ND	13.34	ND	ND	ND	0.498	0.584	ND	ND	0.36	0.26	0.34	ND	ND

All the values are presented in mg/kg, ND: not detected
Screening Standards (USEPA- DEC.2009) Industrial Soil:0.96 mg/kg; Ground water protection: 0.00022 mg/kg

Cont…

Sample location	S-15	S-16	S-17	S-18	S-19	S-20	S-21	S-22	AS	BS	CS	DS	ES
Surface	3.14	3.58	ND	ND	ND	0.62	0.80	0.18	0.660	0.614	0.635	ND	ND
subsurface	2.06	2.89	0.20	0.63	0.27	0.31	0.53	0.31	0.597	0.549	ND	ND	ND

All the values are presented in mg/kg, ND: not detected
Screening Standards (USEPA- DEC.2009) Industrial Soil:0.96 mg/kg; Ground water protection: 0.00022 mg/kg

Table 24: Presence of γ-HCH in the soil samples from UCIL premises

Sample location	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10	S-11	S-12	S-13	S-14
Surface	ND	ND	5.59	ND	ND	ND	5.52	ND	ND	ND	ND	ND	ND	ND
subsurface	ND	ND	ND	ND	ND	ND	0.568	16.54	ND	0.16	0.08	0.15	ND	ND

All values are presented in mg/kg, ND: not detected
Screening Standards (USEPA- DEC.2009) Industrial Soil:2.1 mg/kg; Ground water protection: 0.00036 mg/kg

Cont…

Sample location	S-15	S-16	S-17	S-18	S-19	S-20	S-21	S-22	AS	BS	CS	DS	ES
Surface	1.83	2.06	ND	ND	ND	0.41	ND	ND	0.637	ND	ND	ND	0.614
subsurface	2.48	3.41	ND	ND	ND	0.16	ND	ND	ND	ND	ND	ND	ND

All values are presented in mg/kg, ND: not detected
Screening Standards (USEPA- DEC.2009) Industrial Soil:2.1 mg/kg; Ground water protection: 0.00036 mg/kg

Table 25: Presence of δ-HCH (mg/kg) in the soil samples from UCIL premises

Sample location	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10	S-11	S-12	S-13	S-14
Surface	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
subsurface	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

All the values are presented in mg/kg, ND: not detected
Screening Standards (USEPA- DEC.2009) Industrial Soil: NA mg/kg; Ground water protection: NA

Cont…

Sample location	S-15	S-16	S-17	S-18	S-19	S-20	S-21	S-22	AS	BS	CS	DS	ES
Surface	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
subsurface	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

All the values are presented in mg/kg, ND: not detected
Screening Standards (USEPA- DEC.2009) Industrial Soil: NA mg/kg; Ground water protection: NA

Table 26: Presence of Dichlorobenzene in the soil samples from UCIL premises

Sample location	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10	S-11	S-12	S-13	S-14
Surface	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
subsurface	ND	ND	ND	ND	ND	ND	0.000013	0.000097	ND	ND	0.000017	ND	ND	ND
All the values are presented in mg/kg, ND: not detected Screening Standards (USEPA- DEC.2009) Industrial Soil: 9800 mg/kg; Ground water protection: 0.36 mg/kg														

Cont…

Sample location	S-15	S-16	S-17	S-18	S-19	S-20	S-21	S-22	AS	BS	CS	DS	ES
Surface	0.165	ND	0.108	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
subsurface	0.0001	ND	ND	ND	0.118	ND	0.0001	0.110	ND	0.000013	ND	ND	0.00009
All the values are presented in mg/kg, ND: not detected Screening Standards (USEPA- DEC.2009) Industrial Soil: 9800 mg/kg; Ground water protection: 0.36 mg/kg													

Table 19 lists the concentration of aldicarb in all the soil samples collected within UCIL premises. Aldicarb was not detected in any of surface soil samples of UCIL premises. In the subsurface soil samples, aldicarb was detected only at seven locations viz. S-8, S-9, AS, BS, CS, DS and ES with the concentrations ranging from 3.713 to 923 mg/kg.

In the case of carbaryl, most of the surface and subsurface soils are containing carbaryl with varying concentrations ranging from 0.038 to 10729 mg/kg (**Table 20**). α-naphthol is present in most of the surface and subsurface soil samples throughout the plant premises with a varying concentrations from 0.511 to 1460 mg/kg (**Table 21**).

As far as HCH isomers are concerned, only three isomers (α, β, γ) were detected in the soil samples of UCIL premises, but δ-HCH isomer was not found in any of the soil samples. The concentrations of α, γ, β-HCH isomers ranged from 0.148 to 19.82; 0.568 to 16.54 and 0.498 to 13.34 mg/kg respectively (**Tables 22, 23, 24, 25 & 26**). Dichlorobenzene was detected only in few subsurface soil samples with concentrations ranging from 0.000013 to 0.165 mg/kg (**Table 26**).

Traces of mercury are present in most of the surface and subsurface soil samples of UCIL premises except S-2, S-3, S4, S-9, S-21 and S-22 (**Table 27**). The concentration of mercury in the UCIL soil is varied from 0.10 to 4.17 mg/kg.

The physico-chemical characteristics of soil samples collected within UCIL premises is listed in **Table 28**. All the soil samples from different locations of UCIL premises were found to be near neutral in pH. The percent of organic carbon ranged from 3.82 to 11.64%. Chlorides and fluorides are present in the range of 164 to 3998 mg/kg and 0.09 to 4.54 mg/kg respectively. The concentrations of other physico-chemical parameters are similar to upstream soil samples.

Table 27: Metals concentration in the soils samples collected from the UCIL premises

Sample ID	Location	Zn	Pb	Cd	Ni	Co	Cr	Cu	Hg
S-01	Surface	3.70	4.51	0.76	2.74	7.72	3.97	2.87	3.07
	Subsurface	4.82	5.37	1.76	2.14	5.80	1.92	1.61	0.519
S-02	Surface	6.76	5.24	1.97	2.63	9.90	2.59	1.74	ND
	Subsurface	5.24	7.58	1.46	1.91	13.61	1.67	1.87	ND
S-03	Surface	5.60	5.73	1.03	2.62	10.38	1.28	0.17	ND
	Subsurface	3.57	4.96	1.75	1.75	10.72	2.09	1.90	ND

Contd…

Sample ID	Location	Zn	Pb	Cd	Ni	Co	Cr	Cu	Hg
S-04	Surface	3.96	5.34	1.55	1.39	10.08	2.40	1.25	ND
	Subsurface	3.66	5.42	1.03	2.60	10.41	1.13	0.34	0.76
S-05	Surface	3.58	6.87	1.60	2.95	10.14	2.88	1.96	0.43
	Subsurface	4.31	2.49	1.27	2.03	11.43	1.35	1.08	0.36
S-06	Surface	4.32	5.99	1.79	1.18	11.78	3.02	2.11	4.17
	Subsurface	4.03	5.66	1.59	1.84	12.35	2.08	1.76	0.19
S-07	Surface	3.42	4.29	0.41	2.84	15.53	2.32	2.93	1.29
	Subsurface	2.57	2.37	0.18	2.39	4.68	1.65	1.82	1.29
S-08	Surface	3.48	3.18	0.58	3.06	8.56	2.22	0.94	ND
	Subsurface	3.56	4.30	0.54	3.04	7.34	1.98	1.01	ND
S-09	Surface	1.26	2.62	0.48	3.37	7.66	2.05	1.85	1.04
	Subsurface	1.22	3.08	0.50	3.04	10.21	2.46	1.23	ND
S-10	Surface	3.42	5.21	0.76	3.81	10.32	2.97	2.01	2.10
	Subsurface	2.46	5.64	1.56	2.06	2.23	2.46	2.00	0.34
S-11	Surface	4.42	6.64	1.32	3.84	3.24	1.83	3.81	ND
	Subsurface	6.72	5.92	0.74	3.44	9.38	1.48	3.16	ND
S-12	Surface	6.36	4.62	1.02	2.06	9.72	2.41	2.16	0.41
	Subsurface	7.36	1.22	0.63	3.02	7.80	2.30	2.08	0.21
S-13	Surface	4.60	2.14	0.58	2.72	7.61	1.67	2.17	0.36
	Subsurface	4.28	2.31	0.72	2.20	8.42	1.42	2.08	ND
S-14	Surface	3.64	2.81	0.78	3.61	8.76	2.97	1.94	0.81
	Subsurface	3.04	1.67	1.18	1.26	7.93	2.08	1.82	ND

Cont…

Sample ID	Location	Zn	Pb	Cd	Ni	Co	Cr	Cu	Hg
S-15	Surface	3.48	3.18	0.65	3.21	6.21	1.10	2.46	0.14
	Subsurface	1.26	2.16	0.58	3.10	5.89	2.10	2.16	ND
S-16	Surface	2.70	3.08	0.76	3.12	6.02	2.06	1.94	0.63
	Subsurface	3.41	2.62	0.82	3.40	6.01	2.31	2.34	ND
S-17	Surface	4.06	1.22	1.34	2.06	7.23	2.18	2.86	ND
	Subsurface	4.13	1.46	1.62	2.41	7.41	2.04	2.65	ND
S-18	Surface	3.64	2.13	0.82	2.72	3.32	2.12	1.89	0.61
	Subsurface	2.84	2.36	0.76	2.20	9.21	3.10	1.95	0.21
S-19	Surface	2.81	0.89	0.54	1.26	7.86	3.04	2.31	0.10
	Subsurface	2.41	0.98	0.56	1.84	8.24	2.82	2.61	ND
S-20	Surface	4.12	0.96	0.63	3.41	8.42	2.61	2.09	0.41
	Subsurface	3.89	1.02	0.81	3.06	7.93	3.80	2.01	ND
S-21	Surface	1.84	1.23	0.91	2.07	6.42	2.91	2.87	ND
	Subsurface	1.86	2.03	0.87	2.14	6.73	2.04	2.96	ND
S-22	Surface	2.18	2.41	1.84	2.06	7.81	1.98	1.94	ND
	Subsurface	2.06	2.08	1.26	2.73	8.46	1.75	1.68	ND

Table 28: Physico-chemical characteristics of soil samples collected from the UCIL plant premises

Sample ID	Location	pH	Organic Carbon (%)	Chloride (mg/kg)	Fluoride (mg/kg)	Sulphate (mg/kg)	Phosphate (mg/kg)	Nitrate (mg/kg)	Sodium (mg/kg)	Potassium (mg/kg)
S-1	Surface	7.94	3.82	164	2.27	1177	0.83	1.32	111	54
	Subsurface	7.68	4.12	387	2.81	585	0.18	0.73	127	179
S-2	Surface	7.63	4.72	359	1.50	857	0.82	7.27	112	58
	Subsurface	7.38	5.06	423	2.31	682	6.59	6.64	135	204
S-3	Surface	7.56	5.56	338	1.61	1872	4.11	5.42	214	133
	Subsurface	7.64	4.81	332	2.23	735	8.46	6.49	233	97
S-4	Surface	7.86	4.24	473	0.40	1846	2.40	8.38	431	84
	Subsurface	8.05	4.35	354	0.56	1756	4.02	9.04	830	81
S-5	Surface	7.41	4.85	230	0.66	1365	2.03	4.10	97	63
	Subsurface	7.39	4.61	510	0.20	557	6.09	1.68	90	52
S-6	Surface	6.99	5.48	406	0.17	1638	7.12	14.51	166	142
	Subsurface	7.13	5.08	415	0.09	922.	6.80	1.19	119	81
S-7	Surface	7.19	4.71	417	0.17	769	6.42	4.22	86	153
	Subsurface	7.12	4.22	362	0.79	737	5.91	3.93	86	136

Contd….

Sample ID	Location	pH	Organic Carbon (%)	Chloride (mg/kg)	Fluoride (mg/kg)	Sulphate (mg/kg)	Phosphate (mg/kg)	Nitrate (mg/kg)	Sodium (mg/kg)	Potassium (mg/kg)
S-8	Surface	7.60	4.16	280	2.04	586	5.31	2.21	104	50
	Subsurface	7.14	4.91	304	2.04	621	4.81	1.89	112	40
S-9	Surface	7.31	4.89	269	1.98	732	3.72	1.64	98	38
	Subsurface	7.42	4.21	408	1.84	963	1.92	2.08	100	50
S-10	Surface	7.60	4.95	989	1.13	119	0.69	1.93	163	58
	Subsurface	7.60	4.72	859	1.13	984	1.64	1.09	210	50
S-11	Surface	7.97	4.32	1964	2.01	113	0.39	1.17	101	40
	Subsurface	7.62	3.84	1068	2.02	104	0.43	2.08	126	35
S-12	Surface	7.78	4.99	1986	1.15	115	0.75	2.67	171	62
	Subsurface	7.70	4.61	1435	1.98	110	1.82	1.64	148	60
S-13	Surface	7.72	6.33	999	3.70	1122	0.03	1.33	179	59
	Subsurface	7.70	5.9	800	3.71	1089	0.51	2.41	156	49
S-14	Surface	7.75	4.45	1499	3.96	1141	0.02	0.05	199	47
	Subsurface	7.72	4.28	1368	2.16	1068	0.04	1.02	190	43
S-15	Surface	7.14	11.64	2799	2.37	1934	0.03	3.81	326	101
	Subsurface	7.39	7.46	1989	2.30	184	0.03	3.05	240	98
S-16	Surface	7.40	5.57	2599	2.37	151	0.65	0.69	126	48
	Subsurface	7.40	5.25	1894	1.97	1463	0.28	0.09	130	49
S-17	Surface	7.80	7.22	3998	2.02	1560	0.04	4.85	300	104
	Subsurface	7.76	7.46	2098	1.86	1342	0.61	3.86	280	97
S-18	Surface	7.50	6.62	1499	2.09	1249	0.01	1.21	373	113
	Subsurface	7.52	6.51	1049	2.00	1106	0.42	2.17	264	100
S-19	Surface	7.35	7.14	1978	2.86	1216	0.12	2.32	105	88
	Subsurface	7.42	5.97	1623	2.01	1043	0.63	1.94	98	80
S-20	Surface	7.90	7.24	1498	4.54	1186	0.12	3.74	153	95
	Subsurface	7.86	5.57	1086	3.16	1100	1.09	2.64	108	84
S-21	Surface	7.89	4.53	1986	3.15	108	0.7	0.85	179	53
	Subsurface	7.80	3.94	1807	2.49	100	0.96	1.84	130	48
S-22	Surface	7.80	5.90	1569	2.69	105	1.70	0.93	151	49
	Subsurface	7.82	5.66	1500	2.08	100	0.94	1.43	141	50

The comparison of analytical results of upstream and UCIL premises soil samples clearly indicate that soil in UCIL premises is contaminated with aldicarb, carbaryl, α -naphthol, three HCH isomers, dichlorobenzene and mercury as none of these compounds are present in the upstream soil samples collected outside the UCIL plant. The waste disposal area as reported by NEERI in its report of 1996 was 7 hectares. In addition to these, contamination has also spread to other open areas within the plant premises possibly due to surface runoff. Moreover, the open areas in and around the abandoned manufacturing units, sheds, buildings are likely to be contaminated during the decontamination and decommissioning activities to be taken up by BGTRRD through suitable contractor. **The quantum of such areas is estimated to be 9 hectares. Thus the total contaminated area within UCIL premises that would require remediation is about 16 hectares**.

In order to evaluate the depth of contamination, analytical results (**Tables 29 to 33)** for the subsurface soil samples collected from five bore wells were reviewed.

Table 29: Contaminants profile of soil samples collected from the Temik and formulation plant area

Sample ID	Carbaryl	Aldicarb	α-naphthol	γ-HCH	α-HCH	β-HCH	δ-HCH	Dichloro-benzene	Hg
AS-1	ND	ND	3.029	0.637	0.415	0.660	ND	ND	0.221
AS-2	3.109	3.734	3.673	ND	0.395	0.597	ND	ND	0.093
AS-3	2.719	4.068	4.372	0.600	0.551	0.601	ND	ND	0.342
AS-4	2.939	6.231	ND	0.535	0.393	0.580	ND	ND	ND
AS-5	ND	ND	ND	0.649	0.777	0.626	ND	0.000022	ND
AS-6	ND	ND	ND	ND	ND	ND	ND	ND	ND
AS-7	ND	ND	ND	ND	ND	ND	ND	ND	ND
AS-8	ND	ND	ND	ND	ND	ND	ND	ND	ND
AS-9	ND	ND	ND	ND	ND	ND	ND	ND	ND
AS-10	ND	ND	ND	ND	ND	ND	ND	ND	ND
AS-11	ND	ND	ND	ND	ND	ND	ND	ND	ND
AS-12	ND	ND	ND	ND	ND	ND	ND	ND	ND
AS-13	ND	ND	ND	ND	ND	ND	ND	ND	ND
AS-14	ND	ND	ND	ND	ND	ND	ND	ND	ND
AS-15	ND	ND	ND	ND	ND	ND	ND	ND	ND
AS-16	ND	ND	ND	ND	ND	ND	ND	ND	ND
AS-17	ND	ND	ND	ND	ND	ND	ND	ND	ND
AS-18	ND	ND	ND	ND	ND	ND	ND	ND	ND
AS-19	ND	ND	ND	ND	ND	ND	ND	ND	ND

All the values are expressed in mg/kg, ND: not detected

Table 30: Contaminants profile of soil samples collected from MIC storage and water treatment plant area

Sample ID	Carbaryl	Aldicarb	α-naphthol	γ-HCH	α-HCH	β-HCH	δ-HCH	Dichloro-benzene	Hg
BS-1	ND	ND	ND	ND	0.423	0.614	ND	ND	0.405
BS-2	3.284	3.778	3.754	ND	0.407	0.549	ND	0.000013	0.358
BS-3	ND	3.725	ND	ND	0.358	0.531	ND	ND	ND
BS-4	ND	ND	ND	0.467	0.395	0.539	ND	ND	ND
BS-5	ND	ND	ND	0.391	0.409	0.528	ND	ND	ND
BS-6	ND	ND	ND	ND	ND	ND	ND	ND	ND
BS-7	ND	ND	ND	ND	ND	ND	ND	ND	ND
BS-8	ND	ND	ND	ND	ND	ND	ND	ND	ND
BS-9	ND	ND	ND	ND	ND	ND	ND	ND	ND
BS-10	ND	ND	ND	ND	ND	ND	ND	ND	ND
BS-11	ND	ND	ND	ND	ND	ND	ND	ND	ND
BS-12	ND	ND	ND	ND	ND	ND	ND	ND	ND
BS-13	ND	ND	ND	ND	ND	ND	ND	ND	ND
BS-14	ND	ND	ND	ND	ND	ND	ND	ND	ND
BS-15	ND	ND	ND	ND	ND	ND	ND	ND	ND
BS-16	ND	ND	ND	ND	ND	ND	ND	ND	ND
BS-17	ND	ND	ND	ND	ND	ND	ND	ND	ND

All the values are expressed in mg/kg, ND: not detected

Table 31: Contaminants profile of soil samples collected from disposal area II on the eastern side of the plant area

Sample ID	Carbaryl	Aldicarb	α-naphthol	γ-HCH	α-HCH	β-HCH	δ-HCH	Dichloro-benzene	Hg
CS-1	3.241	ND	ND	ND	0.392	0.635	ND	ND	0.081
CS-2	3.708	3.770	3.594	ND	0.286	ND	ND	ND	0.176
CS-3	ND	3.761	ND	ND	0.223	ND	ND	ND	ND
CS-4	ND	ND	ND	ND	0.290	ND	ND	ND	ND
CS-5	2.21	ND	ND	ND	ND	ND	ND	ND	ND
CS-6	ND	ND	ND	ND	ND	ND	ND	ND	ND
CS-7	ND	ND	ND	ND	ND	ND	ND	ND	ND
CS-8	ND	ND	ND	ND	ND	ND	ND	ND	ND
CS-9	ND	ND	ND	ND	ND	ND	ND	ND	ND
CS-10	ND	ND	ND	ND	ND	ND	ND	ND	ND
CS-11	ND	ND	ND	ND	ND	ND	ND	ND	ND
CS-12	ND	ND	ND	ND	ND	ND	ND	ND	ND
CS-13	ND	ND	ND	ND	ND	ND	ND	ND	ND
CS-14	ND	ND	ND	ND	ND	ND	ND	ND	ND
CS-15	ND	ND	ND	ND	ND	ND	ND	ND	ND
CS-16	ND	ND	ND	ND	ND	ND	ND	ND	ND
CS-17	ND	ND	ND	ND	ND	ND	ND	ND	ND
									ND

All the values are expressed in mg/kg, ND: not detected

Table 32: Contaminants profile of soil samples collected near storage tanks

Sample ID	Carbaryl	Aldicarb	α-naphthol	γ-HCH	α-HCH	β-HCH	δ-HCH	Dichloro-benzene	Hg
DS-1	ND	ND	ND	ND	ND	ND	ND	ND	0.245
DS-2	ND	3.884	ND	ND	0.148	ND	ND	ND	0.197
DS-3	ND	5.407	ND	ND	0.263	ND	ND	ND	ND
DS-4	ND	5.486	ND	ND	0.247	ND	ND	ND	ND
DS-5	ND	ND	ND	ND	ND	ND	ND	ND	ND
DS-6	ND	ND	ND	ND	ND	ND	ND	ND	ND
DS-7	ND	ND	ND	ND	ND	ND	ND	ND	ND
DS-8	ND	ND	ND	ND	ND	ND	ND	ND	ND
DS-9	ND	ND	ND	ND	ND	ND	ND	ND	ND
DS-10	ND	ND	ND	ND	ND	ND	ND	ND	ND
DS-11	ND	ND	ND	ND	ND	ND	ND	ND	ND
DS-12	ND	ND	ND	ND	ND	ND	ND	ND	ND
DS-13	ND	ND	ND	ND	ND	ND	ND	ND	ND
DS-14	ND	ND	ND	ND	ND	ND	ND	ND	ND
DS-15	ND	ND	ND	ND	ND	ND	ND	ND	ND
DS-16	ND	ND	ND	ND	ND	ND	ND	ND	ND
DS-17	ND	ND	ND	ND	ND	ND	ND	ND	ND
DS-18	ND	ND	ND	ND	ND	ND	ND	ND	ND

All the values are expressed in mg/kg, ND: not detected

Table 33: Contaminants profile of soil samples collected from naphthol plant

Sample ID	Carbaryl	Aldicarb	α-naphthol	γ-HCH	α-HCH	β-HCH	δ-HCH	Dichloro-benzene	Hg
ES-1	3.540	ND	ND	0.614	0.408	ND	ND	ND	1.971
ES-2	3.38	3.713	ND	ND	0.362	ND	ND	0.00001	0.171
ES-3	3.57	3.603	ND	ND	0.387	ND	ND	ND	ND
ES-4	ND	ND	ND	ND	0.254	ND	ND	ND	ND
ES-5	ND	ND	ND	ND	0.281	ND	ND	ND	ND
ES-6	ND	ND	ND	ND	ND	ND	ND	ND	ND
ES-7	ND	ND	ND	ND	ND	ND	ND	ND	ND
ES-8	ND	ND	ND	ND	ND	ND	ND	ND	ND
ES-9	ND	ND	ND	ND	ND	ND	ND	ND	ND
ES-10	ND	ND	ND	ND	ND	ND	ND	ND	ND
ES-11	ND	ND	ND	ND	ND	ND	ND	ND	ND
ES-12	ND	ND	ND	ND	ND	ND	ND	ND	ND
ES-13	ND	ND	ND	ND	ND	ND	ND	ND	ND
ES-14	ND	ND	ND	ND	ND	ND	ND	ND	ND
ES-15	ND	ND	ND	ND	ND	ND	ND	ND	ND
ES-16	ND	ND	ND	ND	ND	ND	ND	ND	ND
ES-17	ND	ND	ND	ND	ND	ND	ND	ND	ND
ES-18	ND	ND	ND	ND	ND	ND	ND	ND	ND

All the values are expressed in mg/kg, ND: not detected

Borehole A: Soil samples collected from the borehole **A,** located near the Temik and formulation plant, showed the presence of aldicarb, carbaryl, α-naphthol, α, γ, and β isomers and dichlorobenzene up to the depth of 2 meters (**Table 29**). None of these compounds were detected beyond 2 m at this location. The traces of mercury (0.093 to 0.342 mg/kg) were also detected at this location near surface soil samples.

Borehole B: Soil samples collected from the borehole **B,** located near MIC storage and water treatment plant, showed the presence of aldicarb, carbaryl, α-naphthol, α, γ, and β isomers of HCH and dichlorobenzene (**Table 30**). The maximum depth to which these compounds were detected is again 2 m at this location. None of these compounds were detected beyond 2 m at this location. The concentration of mercury at this location was in the range of 0.358 to 0.405 mg/kg and was detected only in the near surface soil samples.

Borehole C: Soil samples collected from the borehole **C,** located in disposal area II, showed the presence of aldicarb, carbaryl, α-naphthol, α, γ, β isomers of HCH (**Table 31**). The maximum depth to which these compounds were detected is also 2 m at this location. None of these compounds were detected beyond 2 m at this location. The concentration of mercury at this location was in the range of 0.081 to 0.176 mg/kg and was detected up to a depth of 0.9 m.

Borehole D: Soil samples collected from the borehole **D,** located near storage tanks, showed the presence of aldicarb, and α, isomer of HCH (**Table 32**). The maximum depth to which these compounds were detected at this location is 0.9 m. None of these compounds were detected beyond this depth. The concentration of mercury at this location was in the range of 0.197 to 0.245 mg/kg and was detected in surface soil samples.

<u>Borehole E</u>: Soil samples collected from the borehole **E,** located near naphthol plant, showed the presence of aldicarb, carbaryl, α, γ isomers of HCH and dichlorobenzene (**Table 33**). The maximum depth to which these compounds were detected at this location is 2 m. None of these compounds were detected beyond this depth. The concentration of mercury at this location was in the range of 0.171 to 1.971 mg/kg and was detected in surface soil samples.

Thus depth wise review of individual borehole in terms of distribution of various contaminants within UCIL premises, indicate that maximum depth of contamination at present is restricted to 2 m. The shallow depth of contamination may be attributed to the existence of a thick (22 to 25 m) layer of black and yellow silty clay within the UCIL premises, as delineated by geophysical and hydrogeological investigations carried out by NGRI. Natural clay has extremely low permeability (10^{-9} cm/s) which may act as a barrier to the flow of liquids.

iii) Soil samples collected downstream of UCIL

The results of analysis of soil samples collected downstream of UCIL are presented in **Tables 11 to 18.** Out of these four samples, soil sample collected near solar evaporation pond (**Fig. 14**) showed the presence of aldicarb, carbaryl, α-naphthol and β-HCH. The concentrations of these contaminants were 8.15, 6.88, 3.51 and 2.55 mg/kg respectively. The concentration of mercury at this location was found to be 0.30 mg/kg. Another soil sample collected near the western side of secured landfill adjacent to solar evaporation pond reveled traces of β-HCH isomer (0.40 mg/kg). The concentration of mercury at this location is about 0.33 mg/kg. The contamination at these locations may be attributed to unscientific management of landfill and solar evaporation pond (as stated in Section 2.3). As reported in previous studies, the area occupied by SEP and landfill is about 14 hectares. Since no drilling was carried out by NGRI in this area, it was not possible to assess the depth of contamination. However, considering the existence of clay in and around UCIL premises and as established in previous section, the depth of contamination in this area is assumed to be 2 m.

From the results it is indicated that the upstream soils are free from the contaminants which were detected in the UCIL premises. UCIL premises soil is contaminated with selected compounds which were produced/used in the past. The contamination was found to be confined within the premises of UCIL. The percolation of these contaminants into the soils were restricted upto two meters only, beyond that none of the contaminants were detected. Absence of these contaminants in the downstream soil samples, in general shows the downstream soils were not contaminated with the compounds present in the UCIL premises.

iv) Groundwater samples collected within UCIL premises

The analysis of groundwater samples collected from the Borewells constructed by NGRI and one existing borewell near the main entrance of UCIL are listed in **Table 34**. None of these groundwater samples showed any contamination or presence of selected compounds. This clearly indicates that the contaminants within UCIL plant have not percolated through the clayey soil strata and have not reached the groundwater.

Table 34: Presence of contaminants in the groundwater samples collected within UCIL plant

Sample ID	Aldicarb	Carbaryl	α-naphthol	α -HCH	γ-HCH	β-HCH	δ-HCH	Dichloro-benzene	Hg
Borewell A	ND	ND	ND	ND	ND	ND	ND	ND	ND
Borewell B	ND	ND	ND	ND	ND	ND	ND	ND	ND
Borewell C	ND	ND	ND	ND	ND	ND	ND	ND	ND
Borewell D	ND	ND	ND	ND	ND	ND	ND	ND	ND
Borewell E	ND	ND	ND	ND	ND	ND	ND	ND	ND
GW-26	ND	ND	ND	ND	ND	ND	ND	ND	ND

v) Groundwater samples collected outside UCIL premises

The analysis results for groundwater samples collected outside UCIL premises are listed in **Table 35 and 37**.

Table 35: Presence of contaminants in the groundwater samples collected around the UCIL plant

Sample ID	Aldicarb	Carbaryl	α-naphthol	α -HCH	γ-HCH	β -HCH	δ-HCH	Dichloro-benzene
GW-01	ND	ND	ND	ND	ND	ND	ND	ND
GW-02	ND	ND	ND	ND	ND	ND	ND	ND
GW-03	ND	ND	ND	ND	ND	ND	ND	ND
GW-04	ND	ND	ND	ND	ND	ND	ND	ND
GW-05	ND	ND	ND	ND	ND	ND	ND	ND
GW-06	ND	ND	ND	ND	ND	ND	ND	ND
GW-07	ND	ND	ND	ND	ND	ND	ND	ND
GW-08	ND	ND	ND	ND	ND	ND	ND	ND
GW-09	ND	ND	ND	ND	ND	ND	ND	ND
GW-10	ND	ND	ND	ND	ND	ND	ND	ND
GW-11	ND	ND	ND	ND	ND	ND	ND	0.0002
GW-12	ND	ND	ND	ND	ND	ND	ND	0.0002
GW-13	ND	ND	ND	ND	ND	ND	ND	ND
GW-14	ND	ND	ND	ND	ND	ND	ND	ND
GW-15	ND	ND	ND	ND	ND	ND	ND	ND
GW-16	ND	ND	ND	ND	ND	ND	ND	ND
GW-17	ND	ND	ND	ND	ND	ND	ND	ND
GW-18	ND	ND	ND	ND	ND	ND	ND	ND
GW-19	ND	ND	ND	ND	ND	ND	ND	ND
GW-20	ND	ND	ND	ND	ND	ND	ND	ND
GW-21	ND	ND	ND	ND	ND	ND	ND	ND
GW-22	ND	ND	ND	ND	ND	ND	ND	ND
GW-23	ND	ND	ND	ND	ND	ND	ND	ND
GW-24	ND	ND	ND	ND	ND	ND	ND	ND
GW-25	ND	ND	ND	ND	ND	ND	ND	ND
GW-27	3.4	ND	ND	ND	ND	ND	ND	0.0003
GW-28	3.7	ND	ND	ND	ND	ND	ND	ND
GW-29	3.4	ND	ND	ND	ND	ND	ND	0.0001
GW-30	ND	ND	ND	ND	ND	ND	ND	ND

All values are in mg/L ND- Not Detected

Table 36: Physico-chemical characteristics of groundwater samples collected around the UCIL plant

Sample ID	pH	Chloride	Fluoride	Sulphate	Phosphate	Nitrate	Sodium	Potassium
GW-1	8.1	204	0.54	71.8	9.42	2.19	269	6.4
GW-2	7.76	229	0.17	79.3	8.38	1.19	220	7.9
GW-3	8.21	239	ND	88.3	6.78	0.93	134	5.8
GW-4	7.74	234	0.15	156.0	3.83	1.48	388	6.1
GW-5	7.52	224	0.02	106.2	8.19	1.12	112	5.8
GW-6	8.35	104	0.12	64.2	0.48	0.82	154	5.9
GW-7	7.96	124	0.23	101.5	0.19	0.12	135	7.9
GW-8	7.55	194	0.16	95.0	0.17	0.28	204	7.1
GW-9	7.67	199	0.14	104.1	0.07	0.62	196	5.8
GW-10	7.94	84	0.25	52.7	0.30	0.64	141	5.4
GW-11	7.61	109	0.26	55.5	0.14	0.69	117	6.3
GW-12	8.38	89	0.39	38.0	0.32	0.18	663	48
GW-13	8.54	169	0.30	119.2	1.42	1.22	498	47
GW-14	8.62	139	0.28	59.8	0.94	1.65	280	5.6
GW-15	8.26	134	0.30	71.2	0.33	2.63	346	6
GW-16	8.7	99	0.04	68.7	0.42	0.74	256	6.2
GW-17	7.76	369	ND	108.2	0.52	1.46	174	7.4
GW-18	7.89	339	0.06	80.5	0.53	1.06	295	6.4
GW-19	7.64	474	0.12	83.4	0.40	ND	411	14.6
GW-20	8.54	344	0.03	89.1	1.38	1.48	323	7.4
GW-21	8.03	274	0.09	72.4	4.15	2.47	401	7.1
GW-22	7.68	119	0.13	63.8	5.59	0.90	125	7.9
GW-23	7.79	179	0.14	81.7	4.31	2.00	232	8.4
GW-24	7.78	99	0.11	38.0	0.13	1.04	99	10.8
GW-25	7.84	324	ND	136.5	0.47	1.49	352	20.5
GW-27	7.93	349	0.19	81.7	0.59	1.00	863	21
GW-28	8.2	529	0.44	32.1	0.01	2.60	679	9.3
GW-29	8.41	114	ND	17.2	0.04	0.39	139	5.4
GW-30	8.58	129	0.09	380.4	0.80	1.30	260	144

All values are in mg/L ND- Not Detected

Table 37: Metals concentration in the groundwater samples collected around the UCIL plant

Sample ID	Zn	Pb	Hg	Cd	Ni	Co	Cr	Cu
GW 1	0.048	ND	ND	ND	0.014	ND	0.019	0.012
GW 2	0.407	ND	ND	ND	ND	ND	0.017	ND
GW 3	0.634	ND	ND	ND	0.013	0.011	0.02	0.008
GW 4	0.062	ND	ND	0.005	0.013	0.013	0.021	ND
GW 5	0.001	ND	ND	ND	0.016	0.012	0.028	ND
GW 6	0.027	ND	ND	0.006	0.018	0.011	0.03	0.02
GW 7	0.001	ND	ND	0.007	ND	0.013	0.029	ND
GW 8	0.032	ND	ND	0.006	0.024	0.016	0.038	ND
GW 9	ND	ND	ND	0.006	ND	0.014	0.028	ND
GW 10	0.17	ND	ND	0.007	0.015	0.013	0.03	ND
GW 11	ND	ND	ND	ND	0.015	ND	0.011	0.005
GW 12	0.566	ND	ND	0.006	ND	0.027	0.013	0.045
GW 13	0.018	ND	ND	ND	0.015	0.013	0.015	0.008
GW 14	0.141	ND	ND	0.003	0.012	ND	0.012	0.004
GW 15	ND	ND	ND	0.005	0.012	ND	0.018	0.005
GW 16	0.565	ND	ND	ND	0.015	0.01	0.02	0.009
GW 17	0.029	ND	ND	0.007	ND	0.016	0.027	0.007
GW 18	0.098	ND	ND	0.006	ND	0.016	0.023	0.012
GW 19	1.389	ND	ND	ND	ND	0.047	0.028	0.02
GW 20	1.099	ND	ND	0.008	ND	0.033	0.024	ND
GW 21	0.071	ND	ND	0.003	0.012	ND	0.016	0.004
GW 22	0.034	ND	ND	0.001	0.007	ND	0.006	0.002
GW 23	0.055	ND	ND	0.004	0.007	ND	0.005	0.006
GW 24	0.004	ND	ND	0.004	0.004	ND	0.008	0.002
GW 25	1.257	ND	ND	0.004	0.014	0.007	0.009	0.002
GW 27	0.101	ND	ND	0.003	0.011	0.012	0.013	0.009
GW 28	0.262	ND	ND	0.004	0.012	0.013	0.019	0.006
GW 29	0.046	ND	ND	0.002	0.007	0.014	0.01	0.01
GW 30	0.089	ND	ND	0.006	ND	ND	0.036	0.016
Drinking water standards IS 10500, 1991	**5.0**	**0.05**	**0.001**	**0.01**	**NM**	**NM**	**0.05**	**0.05**

All the values are presented in mg/l, ND: not detected, NM: not mentioned

From the results it was observed that two groundwater samples (GW-11 &12) were containing traces of dichlorobenzene (0.0002 mg/l). However, other compound such as adicarb, carbaryl and HCH isomers were not detected in these samples. Since these locations are at a distance of about 1.4 and 2.5 km from the UCIL plant in the upstream of groundwater flow direction, the possibility of contamination, due to seepage of contaminants through subsurface strata to the aquifer is ruled out.

Similarly groundwater samples from GW-27 and 29, indicated the presence of aldicarb (3.4 mg/l) and dichlorobenzene (0.0003 & 0.0001 mg/l respectively). Groundwater samples GW-28 was containing only aldicarb with a concentration of 3.7 mg/l. These groundwater sampling locations (GW-27, 28 and 29) are situated very close to UCIL premises as well as nearer to the solar evaporation ponds and abandoned landfill. It was reported by NGRI that the area in between the UCIL plant and the railway track is low lying and water accumulates in this area during the rainy season. Hence, there is a possibility of surface runoff carrying over contaminants to these wells. Remaining groundwater samples did not show any contamination with respect to UCIL derived contaminants.

The exhaustive monitoring of groundwater in and around UCIL premises thus indicated isolated contamination of groundwater in the 5 wells. The source of contamination of these wells can not be attributed to leaching of contaminants from the dumped waste and migration of aquifer. This is due to the fact that a thick (22 to 25 m) layer of clay is overlain on the aquifer. The contamination of these wells, may be attributed to surface runoff from the dumps. The quantum of contaminated groundwater could not be estimated due to isolated nature of contamination.

3.5 Overall observations on extent of contamination

Based on the geophysical and hydrogeological investigation carried out by NGRI as well as sampling and analysis of soil and groundwater carried out by NEERI the following observation and conclusions were made on the extent of contamination:

- The geophysical investigations carried out by NGRI indicated possibility of contamination only at three sites (Site I, Site III and Site V) out of nine sites (Fig. 4) The depth of contamination at these sites was limited to about 2 m, except at one dump (Site III) that could be deeper (4-8m). These dumps were isolated and limited to few spots.

- The lithology of the area as determined through drilling of borewells by NGRI revealed existence of black and yellow silty clay up to a depth of 22 to 25 m below ground level. The clay has very low permeability (of the order of 10^{-9} cm/s) and acts as natural barrier to the flow water/leachate to the aquifer. The groundwater in the area exists under confined below a depth of about 25 m from the ground surface.
- Confirmatory sampling and analysis of subsurface soil (collected during drilling of borewells) also indicated contamination of soil up to a depth of about 2 m. Major contaminants detected at the site include: BHC, aldicarb, carbaryl, α-naphthol and mercury.
- The additional sampling and analysis of soil from the possible dump areas also indicated contamination of soil in terms of above mentioned contaminants. The total area of soil contamination is estimated to be around 7 hectares.
- Since the plants, buildings, tanks and other equipment were not decontaminated and decommissioned prior to the commencement of study by NGRI and NEERI, the open areas around such structures could not be monitored by NGRI and NEERI during the present study. During decontamination and decommissioning the area in and around these structures is likely to be contaminated. The quantum of this area is about 9 hectares.
- With these considerations, the total contaminated area within UCIL premises amounts to 16 hectares. Considering and area of 16 hectares and a average depth of contamination of 2 m the total volume of contaminated soil to be remediated from UCIL premises is about 3,20,000 m^3.
- The SEPs and the secured landfill located outside UCIL premises cover an area of about 14 hectares. This area also needs to be remediated. Assuming a depth of contamination of 2 m, the total volume of soil to be remediated in SEP area is about 2,80,000 m^3.

- As stated earlier contamination one locations cold be as deep as 8 m. A total volume of contaminated soil from such is assumed to be about 50,000 m^3.
- The total volume of contaminated soil (within and outside UCIL premises) thus amounts to 6,50,000 m^3. Assuming a bulk density of 1.7 gm/cc of soil, the total quantum of contaminated soil requiring remediation amounts to 11,00,000 MT.
- Monitoring of groundwater from the borewells constructed by NGRI within UCIL premises and the existing wells around UCIL premises indicated that groundwater in general is not contaminated due to seepage of contaminats from the UCIL dumps. However isolated contamination in terms of pesticides was observed in 5 well in the immediate vicinity of UCIL premises in the north-east and east direction. The source of contamination of these wells can not be attributed to leaching of contaminants from the dumped waste and migration of aquifer, due to the fact that a thick (22 to 25 m) layer of clay is overlain on the aquifer. The contamination of these wells, was therefore, attributed to surface runoff from the dumps. The quantum of contaminated groundwater could not be estimated due to isolated nature of contamination.

4.0 Strategy for Remediation of Contaminated Soil and Groundwater

4.1 Preamble:

The uncontrolled and unscientific disposal of liquid, solid, semi-solid wastes by UCIL during its operation from 1969 to 1984 has resulted in contamination of soil and groundwater as stated in previous chapter. Fortunately, the soil and ground water contamination is restricted to the UCIL premises and its immediate vicinity. The total quantum of contaminated soil was estimated at 11,00,000 MT. The total quantum of contaminated groundwater could not be estimated as explained in the previous chapter. The contaminated soil and groundwater needs to be remediated to a risk based levels. Considering the quantum of contamination and various site conditions Immediate and well as long term remedial measures have been identified and presented in the are following sections.

4.2 Immediate remedial measures:

- As discussed in Section 2.3, the boundary wall of the UCIL premises is broken at many places providing easy and uncontrolled access to nearby residents. Moreover, the SEP and the abandoned secured landfill area is also un-guarded and found to be damaged. BGTRRD is therefore advised to take immediate steps for ensuring proper fencing and security to these areas for preventing unauthorized access and use of these areas by public.
- It is recommended that as an immediate short-term measure, the five contaminated wells as specified in previous chapter should be immediately sealed so as to prevent use of water from these wells for any purpose by the residents.

- As mentioned in Section 2.3, excavation and recovery of dump material from the disposal areas by M/s Ramkey Ltd was incomplete as huge quantities of wastes (tarry wastes, off-specification products) still exist at various locations within UCIL premises. It is, therefore, recommended that these dumps should be carefully excavated and the excavated material should be properly collected, stored. The incinerable material, from such dumps shall be disposed off at an authorized TSDF at Pithampur in Madhya Pradesh, in accordance with the prevailing hazardous waste management rules and regulations. The non-incinerable wastes being larger in quantity shall be disposed off at an on-site secured landfill facility as per the plan delineated under long-term measure.
- It was also observed during the reconnaissance survey that various plants, buildings, sheds and equipments located within UCIL premises are in dilapidated conditions and appeared to be contaminated. It is recommended that decontamination and decommissioning of these items should be taken by BGTRRD on priority, as per the plan delineated by IICT, Hyderabad. **These activities must be completed prior to the commencement of full scale soil and groundwater remediation as these activities may further result in contamination of soil and groundwater**. As informed by IICT, about 300 MT of waste is likely to be generated during decontamination and decommissioning activities. These wastes shall also be disposed off at an on-site secured landfill facility as per the plan delineated under long-term measure.

4.3 Long-term remedial measures

Remediation of contaminated soil and groundwater may be taken-up by BGTRRD as a long-term measure. The main objective of the long-term measure is to remediate the contaminated land and groundwater below the risk based clean-up levels. A range of technologies is available for remediation of pesticide and heavy metal contaminated soil and Groundwater to the risk based remediation/clean-up level. General approaches to remediation of contaminated soils include isolation, immobilization, toxicity reduction, physical separation and extraction. One or more of these approaches are often combined for more cost-effective treatment. A number of the available technologies have been demonstrated in full-scale applications and are presently commercially available. These include both in-situ (in place) and ex-situ remediation technologies such as thermal desorption, soil vapor extraction, air sparging, bioventing, permeable reactive barriers, natural attenuation, bioremediation, chemical oxidation, thermal technologies, secured landfilling and pump and treat system. These technologies were assessed vis-à-vis site-specific condition (extent of contamination, quantum of soil, nature of soil and availability of off-site facilities and cost). The risk based remediation levels and details of technologies considered for the study are presented in the following section.

4.3.1 Risk based remediation levels

Since clean-up standards for hazardous waste contaminated sites are yet to be developed and notified by the regulatory agencies in India, the latest (2009) standards/screening levels published by USEPA *("Regional Screening Level (RSL) Summary Table", USEPA, December 2009)* have been considered for the present study. The USEPA has published two sets of screening levels depending upon the landuse category (industrial, residential) and the objective (groundwater protection) of the remediation. Considering the possible use of groundwater in the area for drinking and also considering the possibility of contamination of groundwater in future due any natural calamities, the soil remediation standards for protection of groundwater have been considered for the present study. The standards for the contaminants identified for the present study are listed in **Table 38**.

Table 38: Screening standards for assessing the contamination levels (Compounds relevant to the studies)

S.No.	Name of the compound	Screening Standards (USEPA- DEC.2009)	
		Industrial Soil (mg/kg)	**Ground water protection (mg/kg)**
1	Carbaryl	62000	3.3
2	Aldicarb	620	0.09
3	Alpha Naphthol(nearest is Naphtha)	31000	NA
4	Alpha HCH	0.27	0.000062
5	Beta HCH	0.96	0.00022
6	Gama HCH(Lindane)	2.1	0.00036
7	Technical HCH	0.96	0.00022
8	Chloroform	1.5	0.000053
9	Toluene	45000	1.6
10	Chlorotoluene	20000	0.71
11	Dichloro benzene	9800	0.36
12	Trichloro benzene	4900	0.087
13	Elemental mercury	34	0.03

For remediation of contaminated groundwater, the clean-up level is considered as the background concentration of these contaminants in surroundings groundwater and soil which is practically zero in this case.

4.3.2 Remediation of contaminated soil

As estimated in previous Chapter, approximately 11,00,000 MT of soil is contaminated within and outside UCIL premises. In addition, non-incinerable wastes excavated from the dumpsites and wastes generated during decontamination and decommissioning of plant and machinery are also required to be disposed off. Due to the clayey nature of the contaminated soil, and persistant nature of contaminants in-situ technologies such as thermal desorption, permeable reactive barriesrs, bioremediation etc. may not be feasible in the present case. Therefore an ex-situ treatment and disposal is recommended.

Further, the excavation and transportation of such a huge quantum of soil to the Pithampur TSDF facility , which is located at about 150 km from UCIL, Bhopal, would require tremendous man and machine resources. Moreover, TSDF may not be designed to handle, treat and dispose off this additional load of contaminated soil. Hence an onsite disposal is recommended. **Thus an ex-situ on-site remediation is recommended for implementation.**

The most feasible ex-situ on-site remediation system would be the establishment of a secured landfill system within the premises of UCIL. Under this option, the soil from the contaminated area needs be excavated, treated (if necessary) and disposed off in the secure landfill facility. The landfill shall comprise of layers of clay and flexible membrane liners, leachate collection and removal systems, landfill cover system (clay, flexible membrane liners, and vegetative cover), landfill gas collection system, leachate and landfill gas treatment system. The construction, operation and monitoring of onsite secured landfill should be as per the prevailing guidelines specified by CPCB.

Since the major waste disposal in the past has taken place in disposal area II, it is recommended to establish the TSDF in this area. This would minimize the backfilling of excavated areas by fresh soil. The requirement of fresh soil for backfilling of excavated areas may further be minimized by used of uncontaminated construction debris.

Cost estimates for establishment of onsite secured landfill:

Based on the data/information collected from various secured landfill contractors, the cost of construction of secured landfill facility varies from Rs. 600 to 900 per m^3 of waste volume. Considering a total volume of contaminated soil of about 6,50,000 m^3 and nearly 6,50,000 m^3 for binders (1:1 ratio) for solidification/stabilization, the total quantum of treated soil becomes 13,00,000 m^3. Thus, the cost of construction of secured landfill will be in the range of Rs 78 crore to 117 crore (average Rs. 100 crore). This cost is subject to 20 % variation depending on the pretreatment needs which can only be determined at the time of disposal. This cost estimates are based on the prevailing rates may vary from contractor to contractor.

4.3.2 Remediation of contaminated groundwater

Based on the detailed literature review on remediation of pesticide contaminated sites, a pump and treat system is recommended for remediation of contaminated groundwater at UCIL.

The pump and treat system would comprise of pump, storage tanks, sand filter and activated carbon filter. The size and capacity of these units will depend on the borewell discharge. Considering the security issues outside the UCIL premises it is recommended to install the pump and treat system with in the UCIL premises. In this case contaminated water from the five borewells should be transported to the treatment system by any suitable means. The exhausted activated carbon from this treatment unit should be disposed off through incineration at an authorized TSDF as per prevailing hazardous waste management rules and regulations. Since the quantum of contaminated groundwater is not known, these units should be operated till the background concentration of the contaminants are achieved.

Cost estimates for remediation of contaminated groundwater:

The capital cost for such pump and treat unit shall be in the range of 25 to 30 lakhs. The operating and maintenance cost of such unit is in the rage of Rs. 10 to 15 lakhs per annum including cost of activated carbon and its disposal.

It is recommended that, BGTRRD should engage competent professional contractors for detailed engineering, and execution of these options.

5.0 Conclusions and Recommendations

- M/s. Union Carbide India Ltd. (UCIL), manufactured carbamate pesticides and the associated intermediate chemicals at their Bhopal unit from 1969 to 1984. The unit was closed down in December 1984 as a result of the infamous accident of leakage of methyl iso-cyanate gas (MIC).

- The solid, semi-solid, liquid and tarry wastes generated during the manufacture of pesticides and associated chemicals were dumped by UCIL within their premises from 1969 to 1984.

- The unscientific disposal of these wastes could have resulted in contamination of land and water environment in and around plant premises of UCIL and may require remediation, in case the contamination levels exceed the permissible limits delineated by national/international regulations.

- The contamination of soil and groundwater in and around UCIL premises is solely due to dumping of various wastes during 1969 to 1984, and MIC gas tragedy has no relevance to it.

- Based on the directives of the Task Force constituted by Hon'ble High Court of Madhya Pradesh, the BGTRRD sponsored a joint study to NEERI and NGRI in March 2009 for assessment of contamination and delineation of suitable strategies for the remediation of contaminated areas.
- Considering the background data/information generated by the past studies carried out by NEERI, and apprehensions/issues raised by various agencies/organizations, the field studies were carried out by NEERI and NGRI during April 2009 and May 2010 which involved reconnaissance

survey, geophysical and hydrogeological investigations, sampling and analysis of soil and groundwater in and around the UCIL.

- During the reconnaissance survey, NGRI-NEERI team observed remains of various manufacturing plants, machinery, buildings and sheds within UCIL premises. Most of these structures were in dilapidated conditions and appeared to be contaminated.

- As per the terms of reference (TOR) for the present study, the decontamination and safe disposal of plant, machinery, buildings and materials from the abandoned manufacturing units as well as clearing of dense bushes from the UCIL premises were to be completed by BGTRRD prior to the initiation of study by NGRI and NEERI. However, these tasks were not completed prior to the commencement of field studies. Therefore, the areas, which were not clear of structure and bushes, could not be included by NGRI-NEERI in the present study.

- The reconnaissance survey of the open areas within plant premises revealed existence of a number of dumps especially in disposal area I and disposal area II. The existence of dumps within UCIL premises indicated that the excavation and recovery of wastes from the dumpsites by MPPCB through M/s Ramkey Ltd. is still incomplete.

- During the reconnaissance survey it was also observed that the boundary wall of the UCIL premises is broken at many places which provided an easy access to the people living around the premises. The site was used by children as a play ground.

- The reconnaissance survey of the SEP area outside the UCIL premises revealed existence of one SEP and an abandoned landfill which were found to be damaged.

- The field studies for assessment of contamination comprised of detailed hydrogeological investigations (geophysical investigations, borehole drilling, development of monitoring wells etc.), followed by collection and analysis of existing field samples (dumpsite, subsurface soil and groundwater). The hydrogeological investigations were carried out by NGRI whereas sampling and characterization of soil and groundwater were carried out by NEERI.

- The geophysical investigations carried out by NGRI indicated possibility of contamination at three sites (Site I, Site III and Site V) out of nine sites. The depth of contamination at these sites was limited to about 2 m, except at one dump (Site III) that could be deeper (4-8m). These dumps were isolated form each other.

- The hydrogeological studies carried out by NGRI revealed that entire area of UCIL premises is occupied by a thick layer of black silty clay and yellow silty clay up to a depth of about 22 to 25 m below ground level. The groundwater occurs in sandy alluvium with pebbles at a depth of around 25 m below ground surface under confined condition. The groundwater flow direction, in and around the UCIL premises, was in south-east direction which could change with time. It was also reported by NGRI that there existed a subsurface elevation or mound near the central part of the UCIL premises, which diverted the subsurface water flow in north-east or south-east directions depending on the approach of the flow.

- In order to assess vertical as well as lateral extent of contamination, soil and groundwater samples were collected by NEERI from various locations in and around UCIL premises. Three rounds of sampling were undertaken. The standard international sampling and analysis protocols as delineated in the report, were followed during the monitoring of soil and groundwater.

- Based on the review of the past process operations as well as apprehensions raised by various agencies/organization the relevant parameters were selected for monitoring. These include semi volatiles/pesticides (Carbaryl, aldicarb, α-naphthol, hexachlorocychlohexane isomers and naphthalene), volatile organics (carbon tetrachloride, chloroform, methylene chloride, 1,2-dichlorobenzene, chlorotoluene and toluene), and heavy metals (mercury, cadmium, nickel, chromium, cobalt, lead, zinc, and copper).

- Monitoring of soil quality in the upstream of UCIL premises (control samples) reveled that none of the volatiles and semi-volatile compounds are present in the soil.

- Analysis of subsurface soil (collected during drilling of 5 borewells) indicated contamination of soil up to a depth of about 2 m. Major contaminants detected at the site include: HCH isomers, aldicarb, carbaryl, α-naphthol and mercury.

- The analysis of soil collected from possible dump areas (other than drilling areas) also indicated contamination of soil in terms of above mentioned contaminants.

- The soil in and around SEP area located outside UCIL premises was also found to be contaminated in terms of some of these contaminants.

- The concentrations of other physico-chemical parameters in soil samples collected from UCIL premises and SEP area are similar to upstream soil samples.

- The comparison of analytical results of upstream and soil samples collected from UCIL premises and SEP area clearly indicate that soil in these areas is contaminated with aldicarb, carbaryl, α-naphthol, three HCH isomers, dichlorobenzene and mercury as none of these compounds are present in the upstream soil samples collected outside the UCIL plant.

- The total volume of contaminated soil (within and outside UCIL premises) is estimated to be 6,50,000 m^3. Assuming a bulk density of 1.7 gm/cc of soil, the total quantum of contaminated soil requiring remediation amounts to 11,00,000 MT.

- The monitoring of groundwater samples collected from the borewells constructed by NGRI and one existing borewell near the main entrance of UCIL indicated that none of the volatiles and semi-volatiles are present in these samples. This clearly indicates that the contaminants within UCIL plant have not percolated through the clayey soil strata (22 to 25 m thick) and have not reached the groundwater. The repeat sampling of these borewells could not be carried out by NEERI since these borewell were found to be broken, tampered and filled with unknown materials.

- Monitoring of groundwater collected around UCIL premises indicated isolated contamination of 5 wells in the vicinity of UCIL premises. Since, some of the wells are in the upstream of groundwater flow direction the possibility of contamination, due to seepage of contaminants through subsurface strata to the aquifer is ruled out. Few of these groundwater sampling locations are situated very close to UCIL premises as well as nearer to the solar evaporation ponds and abandoned landfill. The possibility of contamination of these wells may be attributed to surface runoff from the UCIL dumps and improper management of SEP and landfill. Remaining groundwater samples did not show any contamination with respect to UCIL derived contaminants.

- Considering the extent of contamination and various site conditions, immediate and well as long-term remedial measures were recommended.

- Under immediate measures following recommendations were made:

  - Proper fencing and security to UCIL premises and SEP area for preventing unauthorized access and use of these areas by public.
  - Immediate sealing of five contaminated wells so as to prevent use of water from these wells for any purpose by the residents.
  - Excavation and recovery of dumps materials. The incinerable wastes should be disposed off in TSDF at Pithanpur. The non-incinerable wastes to be disposed off in on-site secured landfill facility.
  - Decontamination and decommissioning of plant, machineries and buildings prior to remediation of contaminated soil and groundwater

- Under long-term measures remediation of contaminated soil and groundwater was recommended. For remediation of contaminated soil, an on-site secured landfill facility was recommended. For contaminated groundwater, pump-and-treat system was recommended.
- The cost of soil remediation through secured landfill is estimated to be in the range of Rs 78 crore to 117 crore. The capital cost for such pump and treat unit shall be in the range of 25 to 30 lakhs. The operating and maintenance cost of such unit is in the rage of Rs. 10 to 15 lakhs per annum including cost of activated carbon and its disposal.
- It is recommended that, BGTRRD should engage competent professional contractors for detailed engineering, and execution of various remedial measures suggested by NEERI.

…TIGATIONS TO ASSESS INDUSTRIAL …MPED AT UCIL, BHOPAL

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 wastes are dumped at different places. In order to assess the locations and dimensions of these dumps, geophysical investigations have been carried out. Geophysical investigations are used to identify buried industrial waste that cannot be easily identified by visual inspection. It is most economical and successful technique to assess the buried dump before a more detailed investigations or remedial measures can be adopted. The investigations have been financed by MP State Govt. namely BGRD (Bhopal Gas Relief Directorate) and Ministry of Chemical and Fertilizer (Govt. of India).

Introduction:

UCIL was established to produce pesticides at Bhopal and the factory is located in the north of Bhopal Railway Station, along the railway track 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 (Fig. 2a, b, c, d, e, and f). There are heaps of industrial wastes lying at different places that can be easily seen at the ground surface (Fig. 3a, b, c, d, e, f, g, h, i, j and k). Many of these dumps give very pungent smell of pesticides even today, as one visits the dump sites. Although these heaps of dumps are seen at many places, it is not known how deep or extensive these dumps are? It is this

…gations have been carried out. The waste materials constitute mostly of solid waste (off specification products resulted from the manufacture of pesticides), terry residue from distillation unit, burnt and unburnt produce (NEERI, 1996). Apart from these, the Solar Evaporation Pond (SEP) situated in south eastern corner contains dried waste. These are described in detail by NEERI (1996) and Burmeier et al (2005).

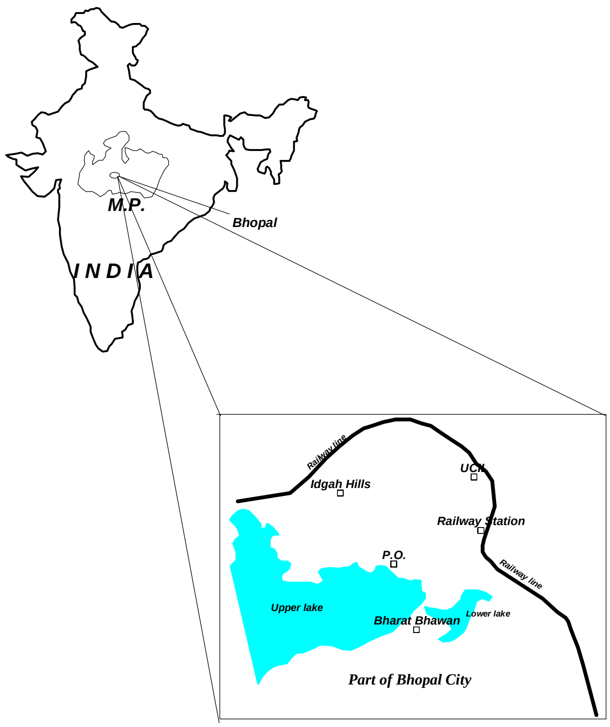

Fig. 1 Location map of study area


Fig. 2a Part of Plant


Fig. 2b Part of Plant


Fig. 2c Part of Plant


Fig. 2d Part of Plant


Fig. 2e Part of Plant


Fig. 2f Part of Plant

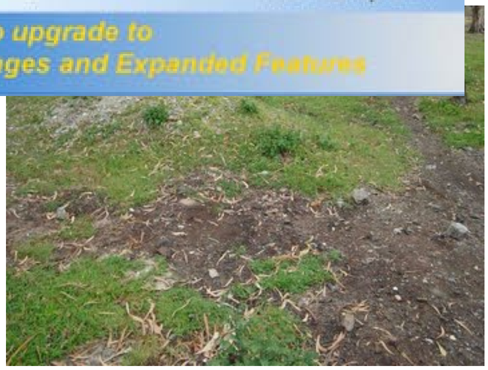
Fig. 3a Heap of dump near formulation plant


Fig. 3b Landfill site


Fig. 3c: Heap of dump east of Police post


Fig. 3d: Terry Dump north of Police post


Fig. 3e: Dumps in pit at southern part


Fig. 3f: Dump pit filled with water

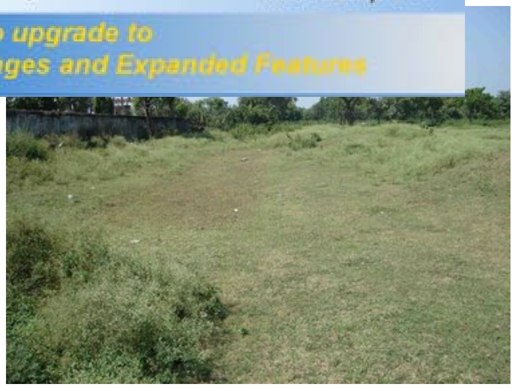

Fig. 3g: Dump pit in southern part

Fig. 3h: SEP-II filled with water

Fig. 3i: SEP-I filled with water

Fig. 3j: SEP-I attracting domestic waste

Fig. 3k: Burned waste in eastern part

Geophysical Investigations : Geophysical investigation mainly comprises measurement and interpretation of signals from natural or induced physical phenomena generated as a result of spatial changes in subsurface lateral and depth wise inhomogenity. These signals measured repetitively at several points in space and time, are interpreted, on, in terms of sub-surface structures/features. Depending upon the scale of operations, geophysical survey can help to delineate regional hydrogeologic features. A reliable interpretation of geophysical survey data requires a good knowledge of sub-surface geology in the area. Geophysical investigations are the best tools for indirectly mapping the sub-surface rock formations and structures. Among all the surface geophysical techniques for shallow subsurface prospecting, Electrical Resistivity Method is the most widely applied method. This is because of its efficacy to delineate subsurface strata besides being simple and inexpensive to carry out the field operations.

The rock matrix of most of the geological formation is basically highly resistive and does not conduct electricity. There are, however, exceptions like clay, shale etc., which comprise conducting minerals. These formations have low electrical resistivities when compared to other rock formations. The resistivity of a rock formation reduces only when it contains moisture. The reduction in resistivity of a rock depends upon the relative quantity and quality of water it contains. Thus by measuring or determining the resistivities of earth layers at different depths, it is possible to infer the hydro-geological character of a particular subsurface layer.

In order to delineate subsurface stratigraphy, geophysical investigations are adopted. It is cost effective and easy to get subsurface lithological information. Earlier during 1994, NGRI carried out geo-electrical profilings and soundings to delineate dump site as well as subsurface strata in the premises of UCIL (Jain et al, 1994). Conventional four electrode resistivity meter was used. Schlumberger array and Wenner array were adopted to generate data. Fig. 4 shows the locations of soundings and profilings. The

…ut using Wenner array with 2, 5 and 10m electrode separations. The details of the profilings are described by Jain et al (1994). Based on the variations in the resistivities the probable dump sites are concluded as shown in Fig.5a. The top layer resistivity data also indicated higher resistivity in the southern part, north and northeastern parts as that could be location of dumps (Fig. 5b). A low resistivity between Storage Tanks and Neutralization Tanks indicated degradation of soil.

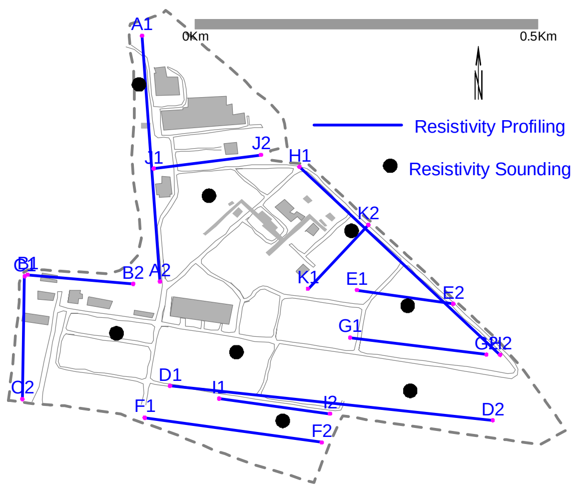

Fig. 4: Resistivity profiling & soundings during 1994

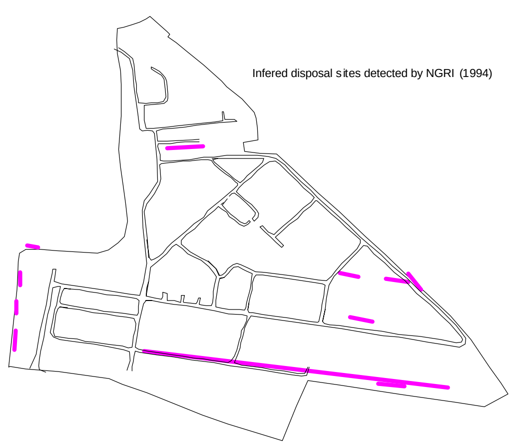

Fig. 5a The possible dump sites (after Jain et al, 1994.)

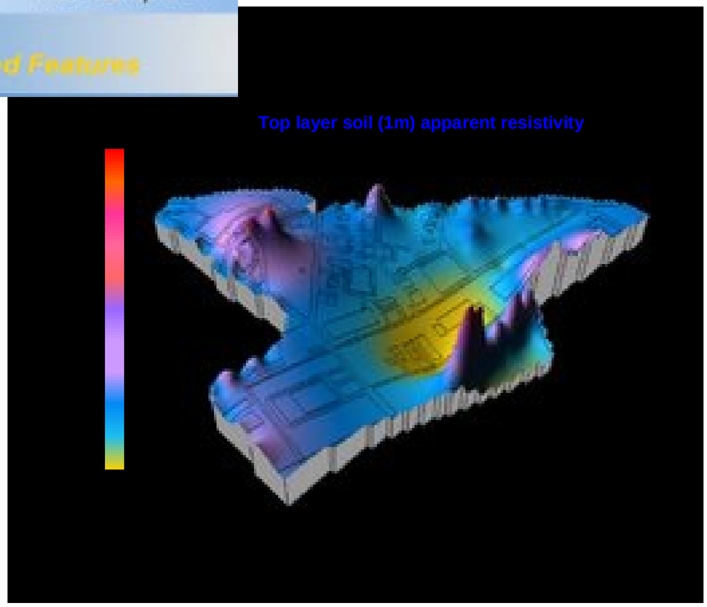

Fig. 5b Possible dump sites indicated by high resistivity (source of data: Jain et al, 1994)

The present study has taken advantage of latest technology of resistivity imaging and its application for detecting dump with the use of multi-electrode geo-electrical investigation. The High Resolution Electrical Resistivity Tomography (HERT) has been carried out to obtain 2D (two dimensional i.e. vertical profile) as well as 3D (three dimensional i.e. horizontal profile at different depth) distribution of resistivity of subsurface strata. An equipment SAS4000 (Fig. 6) from ABEM, Sweden has been used. The data were interpreted using RES2DINV (2005) software. Equipment SAS4000 consists of Terrameter, Junction box, multi core cables and electrodes as shown in Fig. 6. The four channel system allows selecting the array and then data is recorded on the terrameter. The data is then transferred to PC and software RES2DINV is used to process the data. Initially, data is converted to proper format then edited for any error. The 2D data is then inverted to layered resistivity model. The gradient array system was adopted to obtain data.

Fig 6 ABEM Terrameter with accessories (source: www.abem.se)

The various sequences of measurements to build up 2D profile are depicted in Fig. 7. With a particular electrode arrangement one gets a layer of information. Further, it can be seen from Fig. 7 that as one moves from station 1 to 2 the information depth also increases.

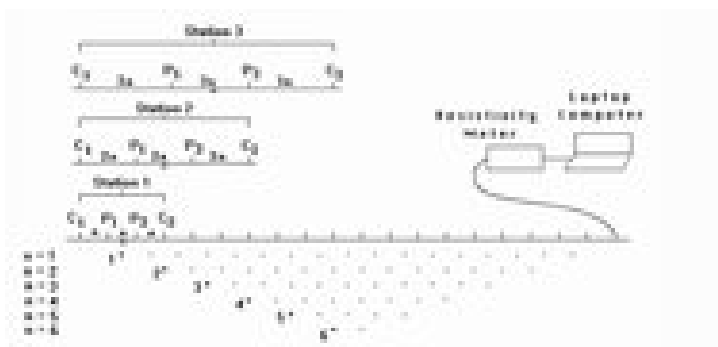

Fig. 7 : Sequence of measurements (Source: RES2DINV Manual)

The entire downloaded data were first checked for errors. Any error in the measured data was removed while processing through RES2DINV. An example of bad data record is shown in Fig. 8 . Such bad data records are removed before interpreting the profile.

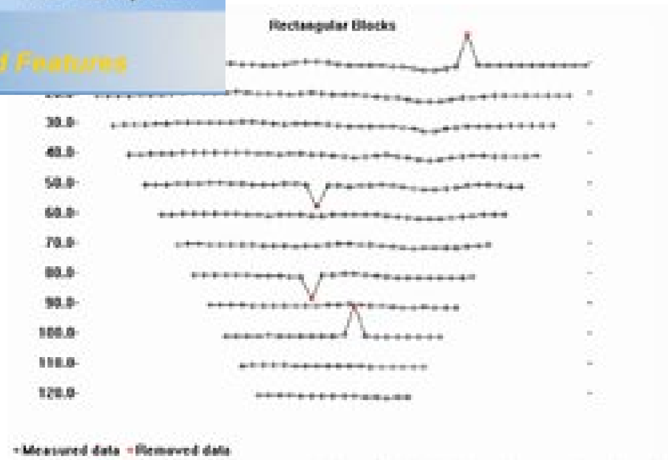

Fig. 8: Example of data set with few bad points (source: RES2DINV Manual)

The data obtained during field work were used to get subsurface resistivity distribution using RES2DINV window based software. A forward modeling technique is first used to calculate resistivities then non-linear least square optimization technique is used to invert the model. The optimization method basically deploys minimization of difference between calculated and observed resistivity and is reflected in terms of root mean squared (RMS) error. The low RMS or when RMS does not change significantly is considered as best model.

The data obtained during the field were processed for removal of error and then interpreted using RES2DINV and iterations were made till a low value of RMS and stable RMS was obtained.

The UCIL premises is occupied with concrete, demolished buildings, plant, sheds and metal road as shown in Fig 9.

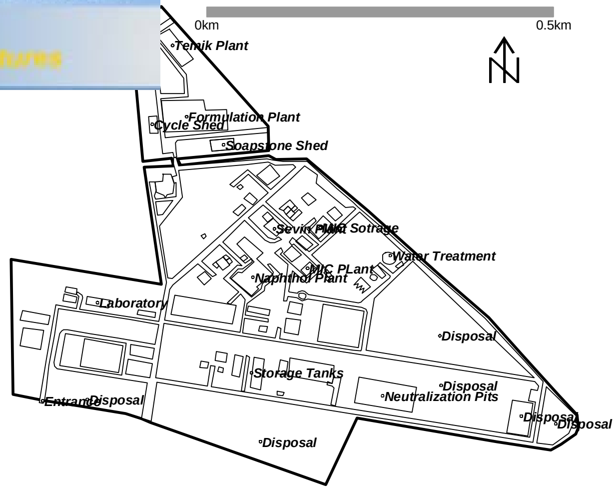

Fig.9 UCIL premises (source : Burmeier et al, 2005)

As it can be seen that most of the area is covered with construction, roads etc., and the soil covered area is the only place where we can perform HERT. Again many part of the open land area is covered with bushes (Fig.10) and it is difficult to penetrate these thorny bushes. There are ponds such as SEP in the southeastern part, pits filled with water and surrounded with bunds (in southern and eastern part) of premises. Such places cannot be scanned with geophysical method. A reconnaitory survey has been carried out to locate suitable places for HERT and effort has been to cover as much area as possible. The location of these profiles is shown in Fig.11.

Fig. 10 DenseBushes in UCIL premises

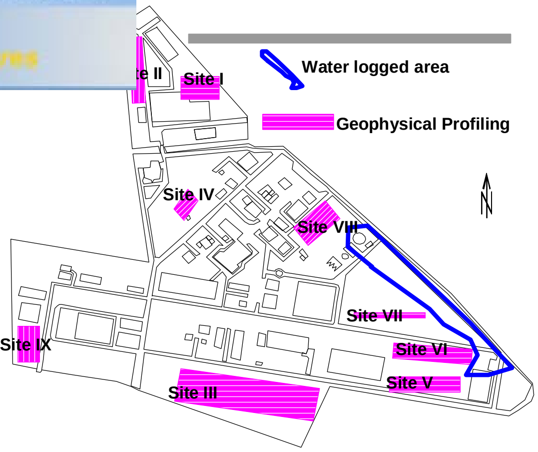

Fig. 11. Locations of Geophysical profiles

Site I : The site is situated in the northern part of the premises in the front of Formulation plant (Fig. 11). The heaps of dumps are visible at the open space. There is pungent smell of pesticides and it is intolerable. It is not known if the heap of dumps are in the pit or merely lying on the surface. Therefore the HERT profiles are laid across the dump in EW direction. The electrode separation was kept as 1m so that the dumps are adequately covered. Total 48 electrodes were used with profile length as 48m. The obtained data was edited for erroneous data and then interpreted using RES2DINV with enough iterations to get minimum root mean square error. The final profile showing resistivity distribution along the profile is depicted in Fig. 12 .

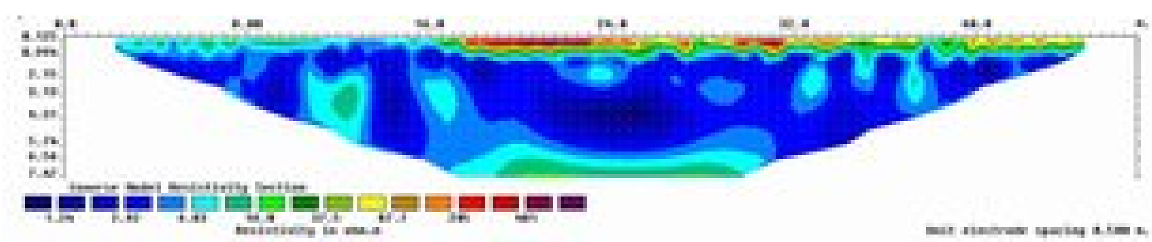

Fig. 12 : 2D geo-electrical profile

It can be seen that the dumps have higher resistivity of the order of 100 to 300 ohm m whereas the host black soil has about 5 to 8 ohm.m. The dumps are clearly demarcated in the profile having depth from few cm (between 38th to 48th electrodes) to about 1m order to cover more area another four parallel profiles have been taken at the interval of 3m each. The profiles are shown in Fig 13a, b, and c.

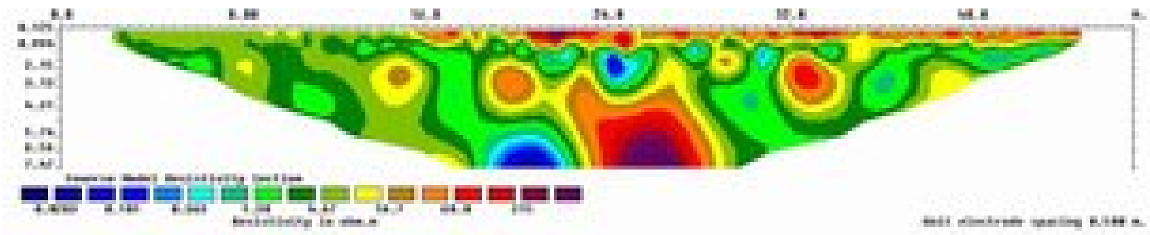

Fig. 13a : 2D geo-electrical profile

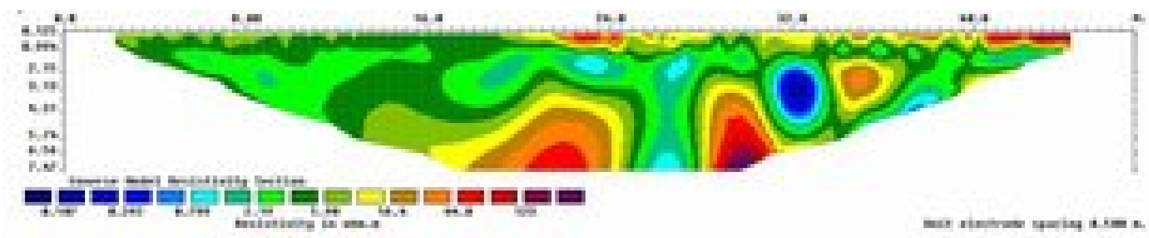

Fig. 13b : 2D geo-electrical profile

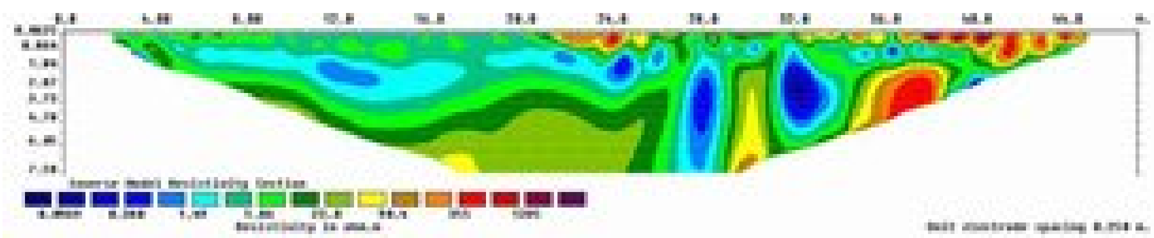

Fig. 13c : 2D geo-electrical profile

It can be seen that as we move northward the depth of eastern dumps decreases whereas the depth of western dump increases. Therefore an area of 9mx48m has been covered. Since there are demolished structures, we could not cover further area in this part of premises. The 2D data were used to infer 3D profile using software RES3DINV and the distribution of resistivity at different depths is shown in Fig. 14 . It can be easily seen that the dumps and their depths are clearly indicated. Further, it can be observed that the soil below the dumps have low resistivity of about 1 ohm.m. Could it be affected by leaching of dumps?

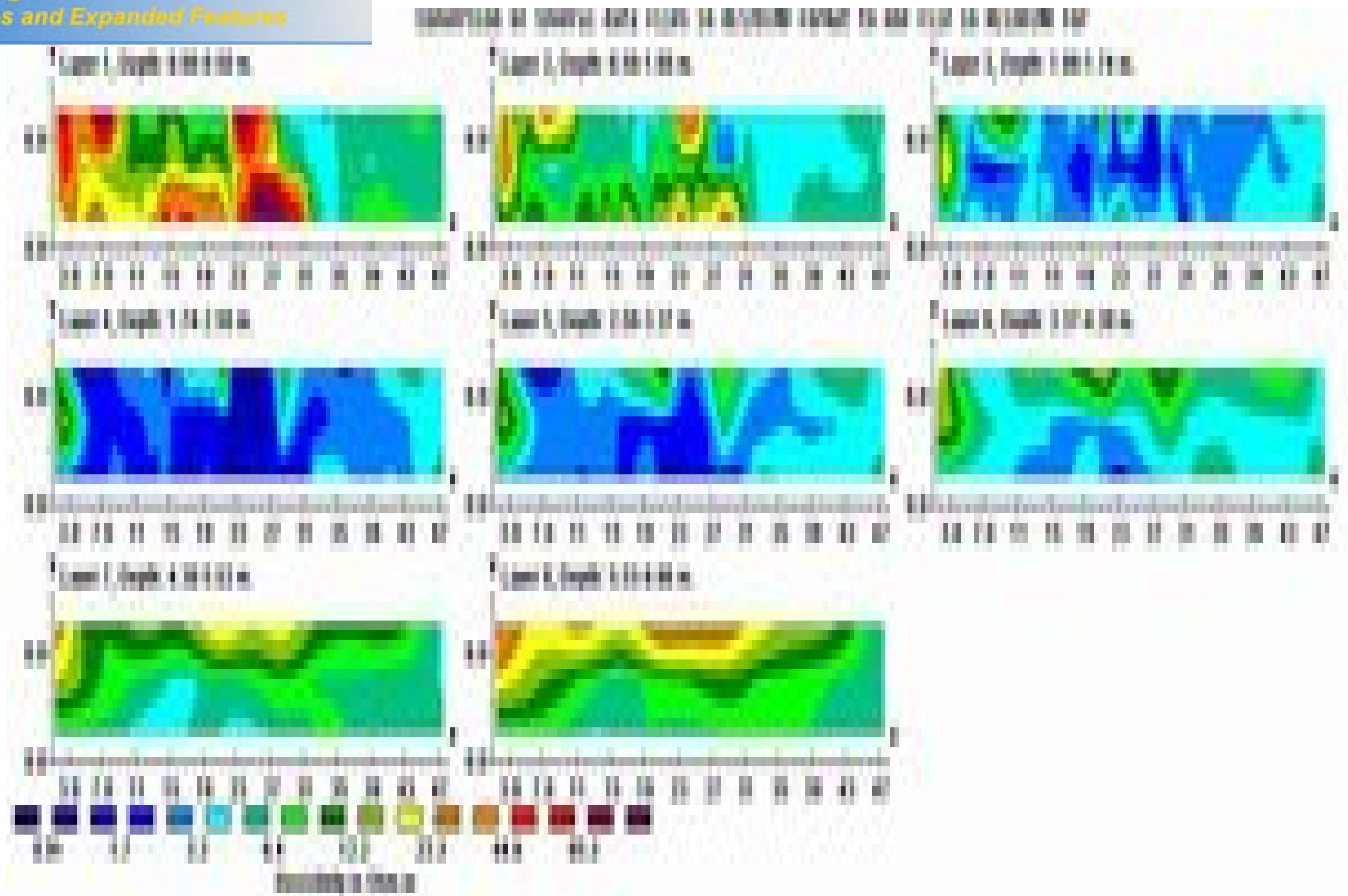

Fig. 14 : 3D geo-electrical profile at different depths

ons has been selected in the open space close to Cycle shed of West of Formulation plant across the road (Fig. 11). The profile is laid in NS direction (close to western boundary) with 1st electrode in the south, close to cycle shed. The electrode separation was chosen as 2m so that entire area is covered. The subsequent profiles were laid at 3m separations which covered entire area. The 2D profiles are shown in Fig. 15a, b and c. It can be seen that there is no sign of any dump and the top layer resistivity is about 4 to 6 ohm.m. However, the low resistivity of 2 to 3ohm.m is found between 5 to 12m, which need further prob. Similar to previous exercise, in this case too we have converted 2D data into 3D as explained above. The 3D profile at different depth is shown in Fig. 16 , indicating no sign of near surface dump.

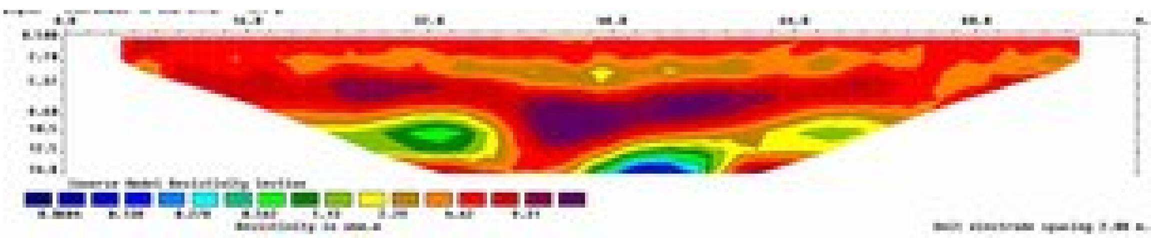

Fig. 15a : 2D geo-electrical profile

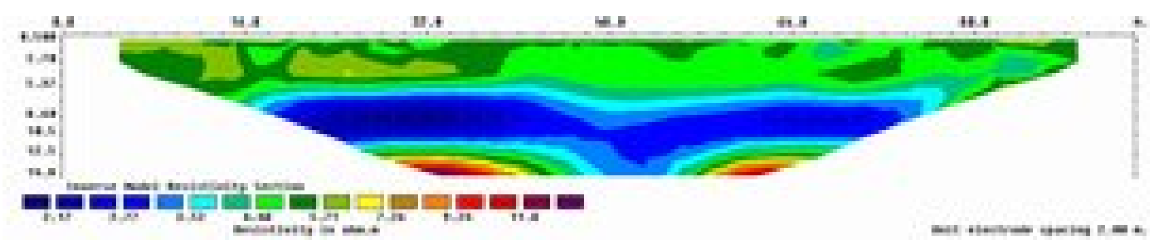

Fig. 15b : 2D geo-electrical profile

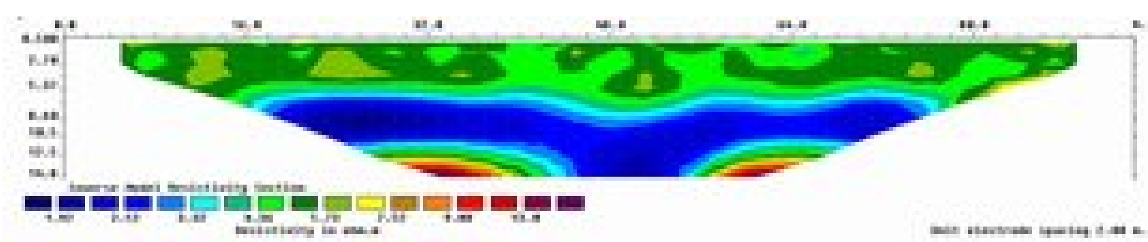

Fig. 15c : 2D geo-electrical profile

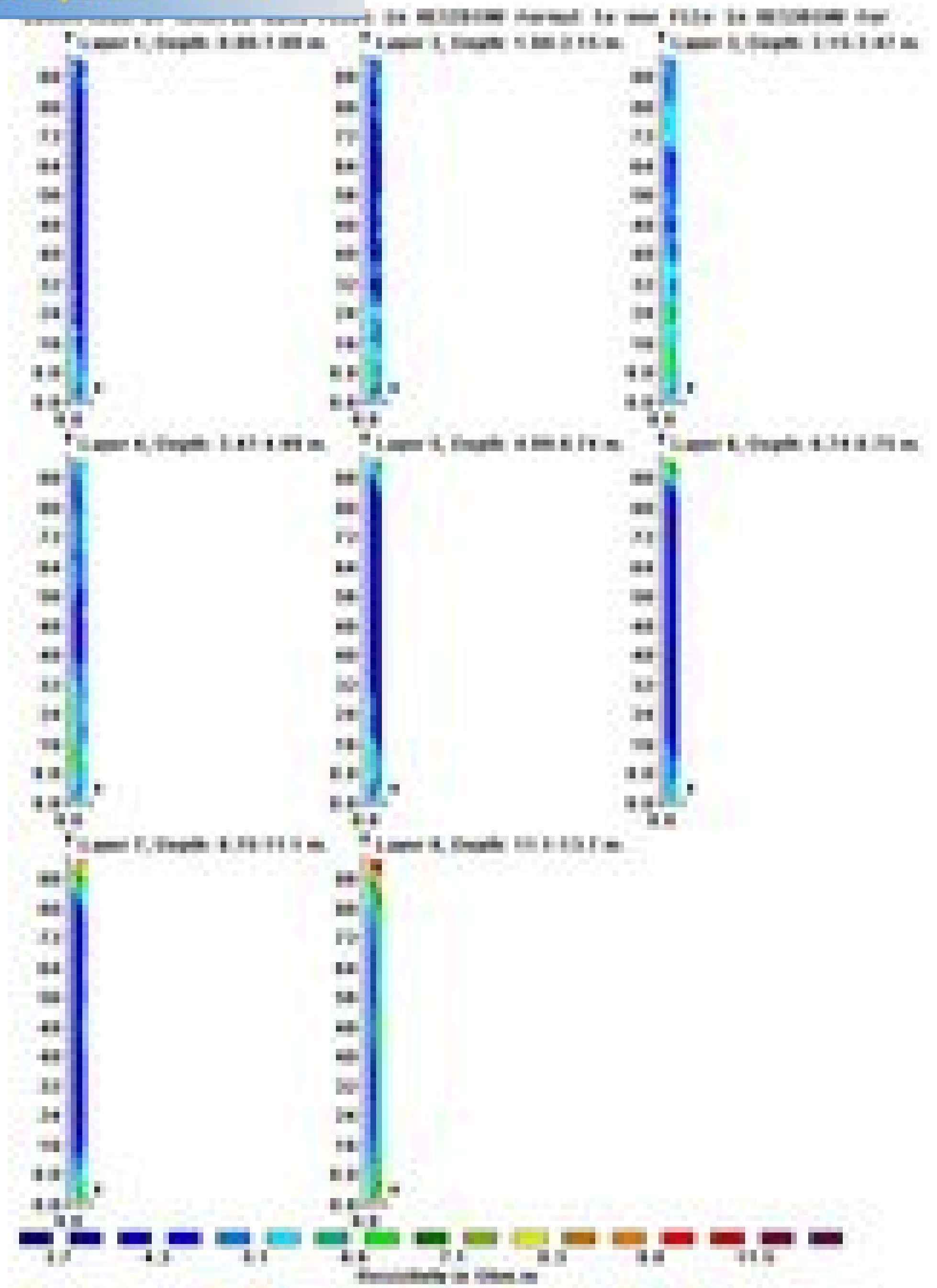

Fig. 16 : 3D geo-electrical profile at different depths

Site III: There are pits where burned materials and waste materials are reported (NEERI, 1999) to be dumped as shown in Fig. 3 e, f and g at this site which covers a vast open land (Fig. 11). Due to water logged in these pits and uneven topography we were

...wever these are known dump sites. Although there is no sign of any dump heap, we covered entire open area by selecting electrode separation of 3m in EW direction with 1st electrode in the area that is opposite Police post. The site is selected in the open area which is in the southern part of premises and south of road opposite to Storage tank or near Neutralization pit (Fig. 11). The western part of the area is occupied by metal road and demolished structures hence that part is not covered. The obtained data is interpreted as described above and the profile is shown in Fig. 17.

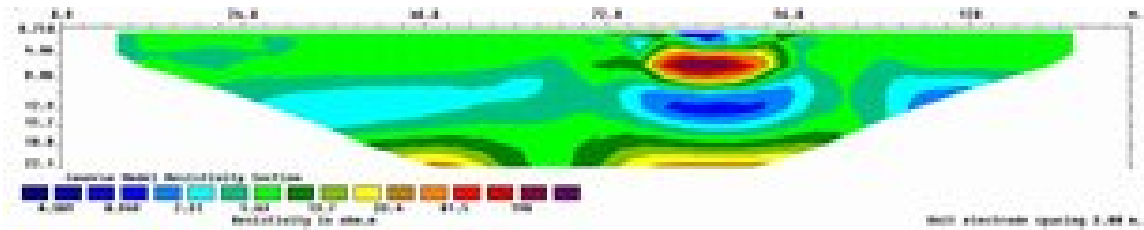

Fig. 17: 2D geo-electrical profile

It can be seen that about 78m along the profile there is anomaly of high resistivity (30 to 200 ohm.m) against low resistivity (4 to 8 ohm.m) of soil zone. The dump could be 4m deep and up to 8m that is not visible at ground surface. Further, there is low resistivity (less than 1 ohm.m) up to 16m and it may be leaching effect of dump. In order to map the lateral extent of this anomaly another five profiles had been laid at the intervals of 10m each covering an area of 141mx50m. The obtained profiles are shown in Fig. 18a, b, c, d and e. It can be seen that the shallow dump as seen in first profile is not found in remaining profiles indicating lateral limitation of this dump. The 3D profile generated from these 2D data is shown in Fig. 19 . It is clear that the dump may be up to 8m deep at a place only.

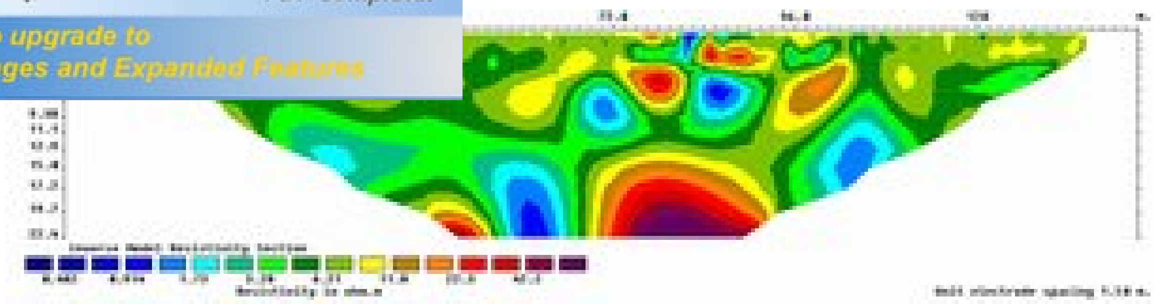

Fig. 18a : 2D geo-electrical profile

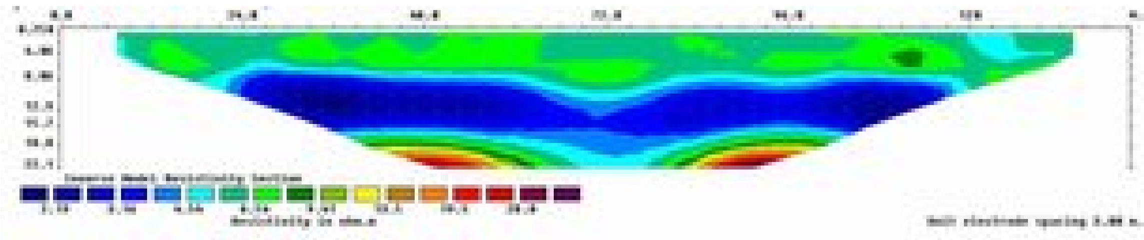

Fig. 18b : 2D geo-electrical profile

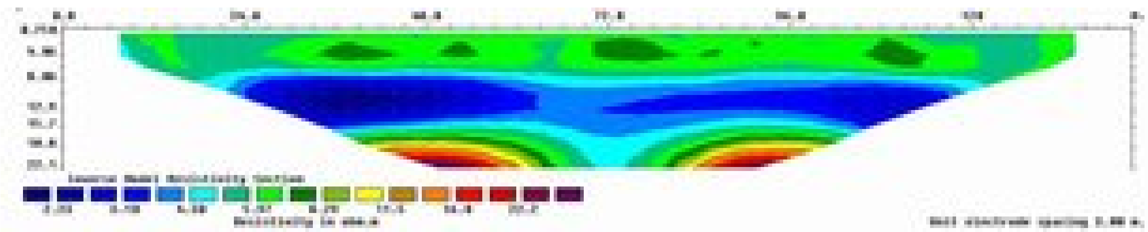

Fig. 18c : 2D geo-electrical profile

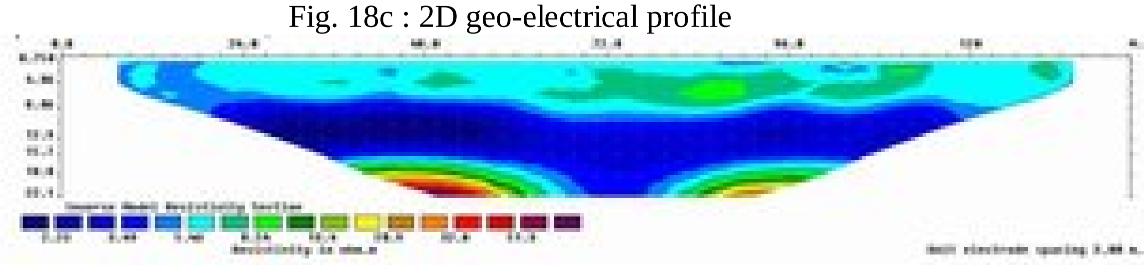

Fig. 18d : 2D geo-electrical profile

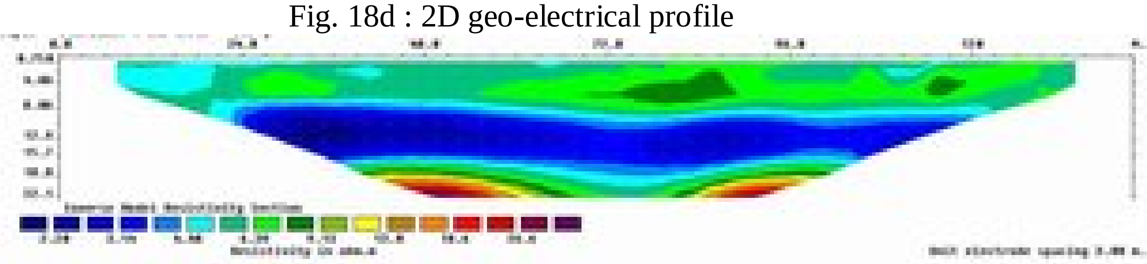

Fig. 18e : 2D geo-electrical profile

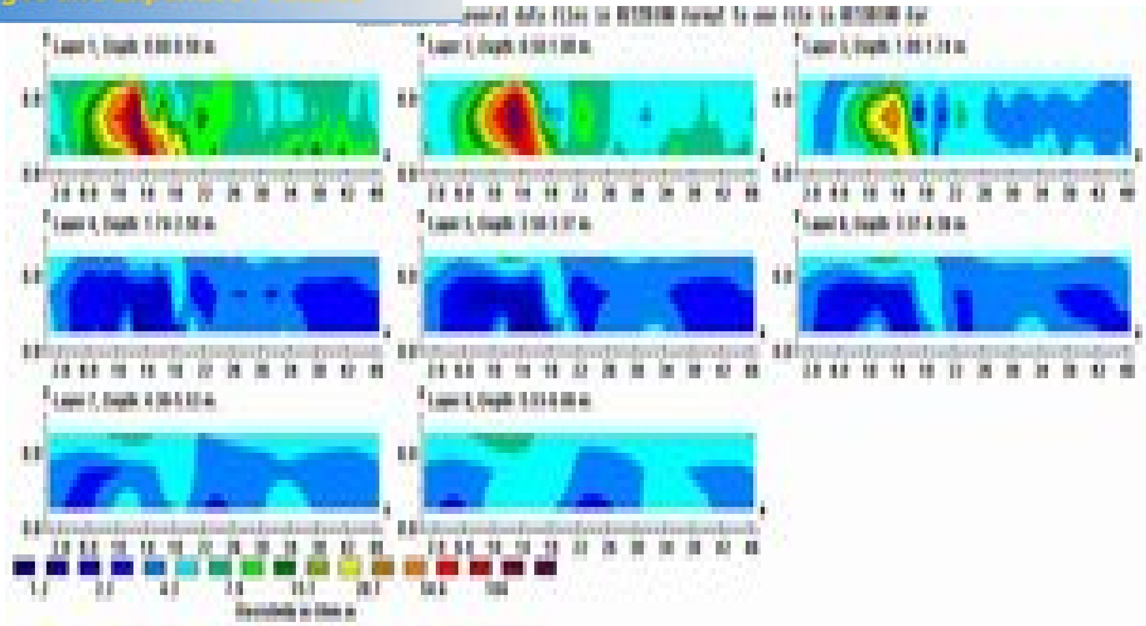

Fig. 19 : 3D geo-electrical profile at different depths

Another profile has been carried out at this open space to assess subsurface strata. The electrode spacing has been increased to 5m in EW direction with 1st electrode in the play ground of nearby school. The 2D profile thus obtained is shown in Fig. 20. It can be seen that top layers have low resistivity (3-6 ohm m) indication clay and below 22m the resistivity increases indication sandy layer of weathered Vindhyans. The profile indicates that up to 40m there is no indication of Vindhyan formation and perhaps it could be deeper in the area.

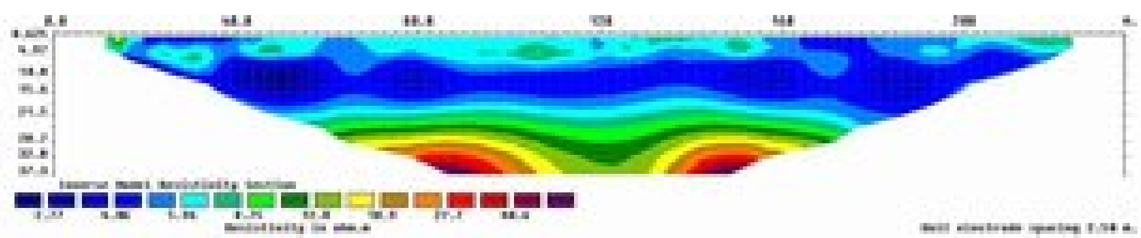

Fig. 20: 2D geo-electrical Profile

n the open space close to tower (Fig. 11). Due to limitation of space we restricted electrode spacing to 0.5m with total profile length as 23.5m in NS direction. The spacing between another two profiles was kept as 2m each. The obtained data was edited for error and interpreted using RES2DINV software. The final profile obtained after several iterations is shown in Fig. 21a, b and c.

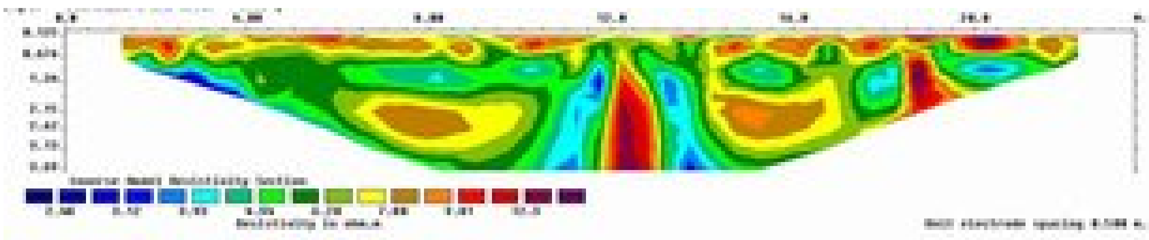

Fig. 21a: 2D geo-electrical Profile

A low resistivity profile indicates clay and no dump were inferred from this profile. However in the middle of profile slightly high resistivity is recorded and it is due to pot hole created in the ground along the cracks in the clayey soil. A 3D profile at various depth is shown in Fig. 22.

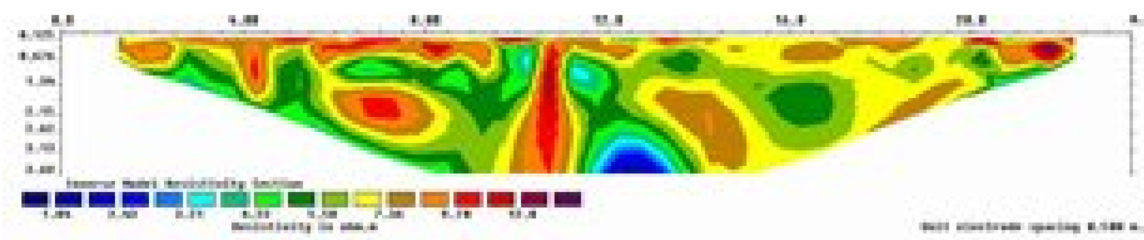

Fig. 21b: 2D geo-electrical Profile

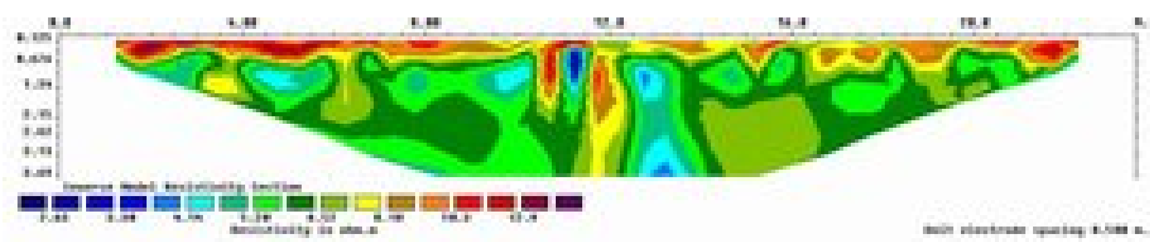

Fig. 21c: 2D geo-electrical Profile

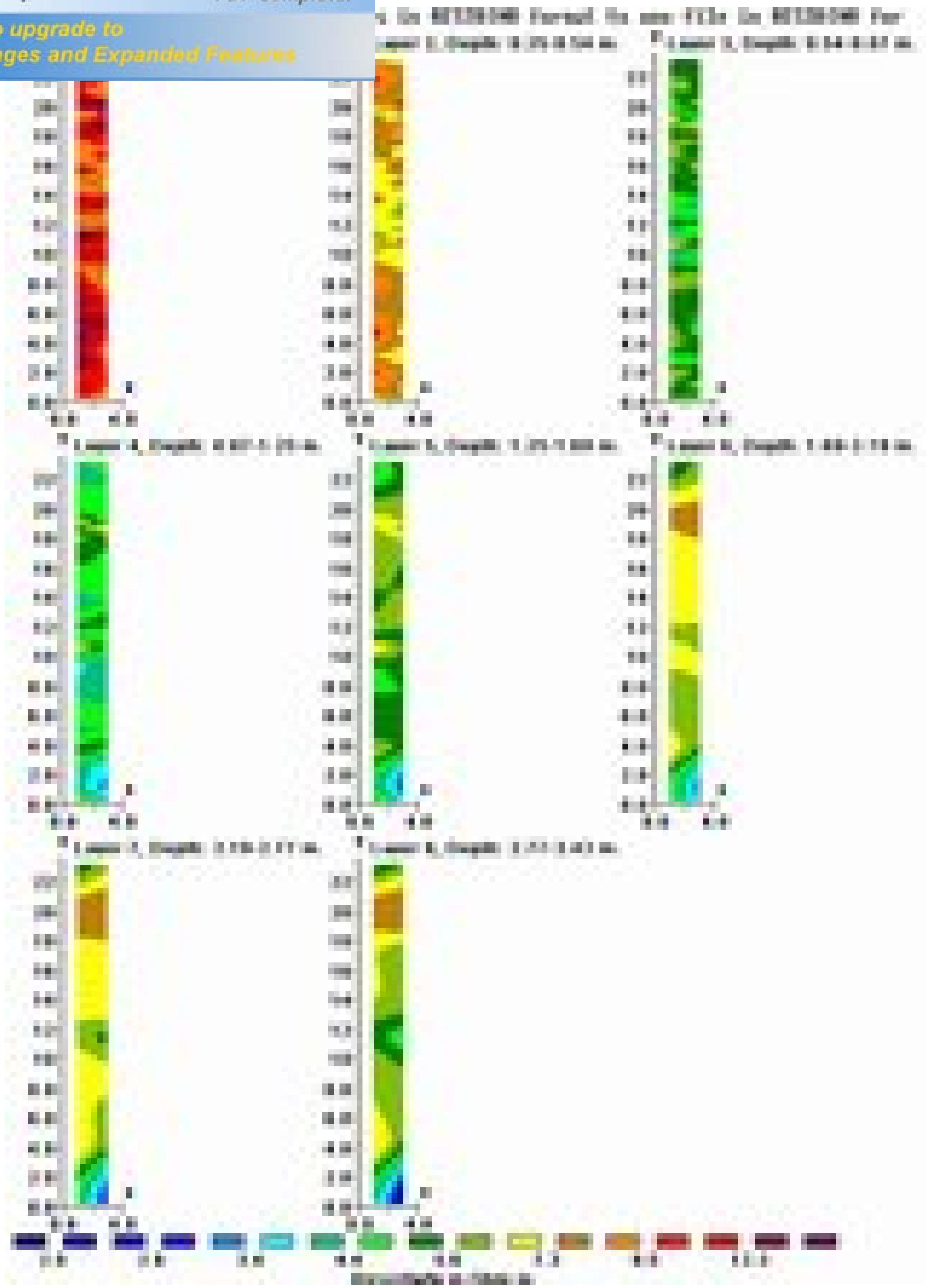

Fig. 22: 3D geo-electrical Profile

area east of Police Post and the open space between Neutralization tank and SEP (Fig. 11). The SEP I and II are water logged as shown in Fig. 3 h, I and j, hence could not be covered. The SEP-I is also made a dump site for domestic waste from nearby settlements. The heaps of dump are seen along the road leading to SEP. A strong smell of pesticides makes it difficult to work in the area. The first profile is selected along the road in EW direction across the dump as shown in Fig. 11. The electrode separation was kept as 1m so that maximum space available of 48m will be covered. The 1st electrode was kept in west near Police post. The data was obtained and processed for any error and interpreted using RES2DINV software. The final profile obtained after several iteration is shown in Fig. 23. It can be observed that the dumps are clearly depicted in the profile. The dump is shallow (0.7m) between 8 to 10m along the profile and deep (1.3m) between 10 to 16m along the profile. Again the dump becomes shallow all along the profile.

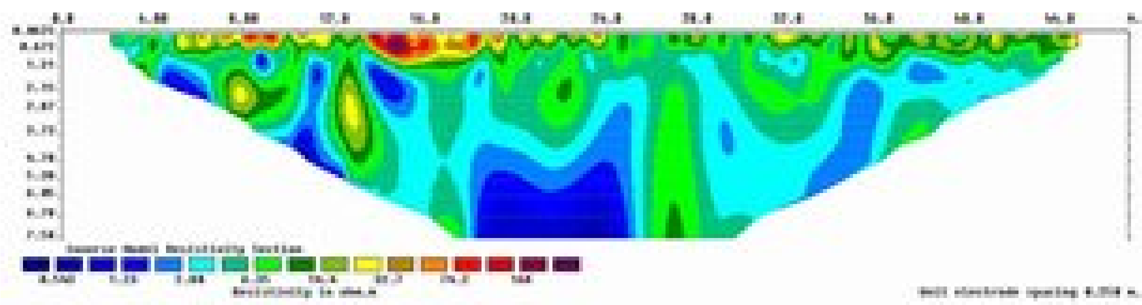

Fig. 23: 2D geo-electrical profile

In order to get northward lateral extension of dump another 3 profiles were taken at 3m, 3m and 5m interval. Hence the total area covered is 48mx14m. The profiles are shown in Fig. 24a, b, and c. It can be observed that the depth of dumps have increased as we is generated using all the 2D data and the inferred 3D profile at various depths is shown in Fig. 25.

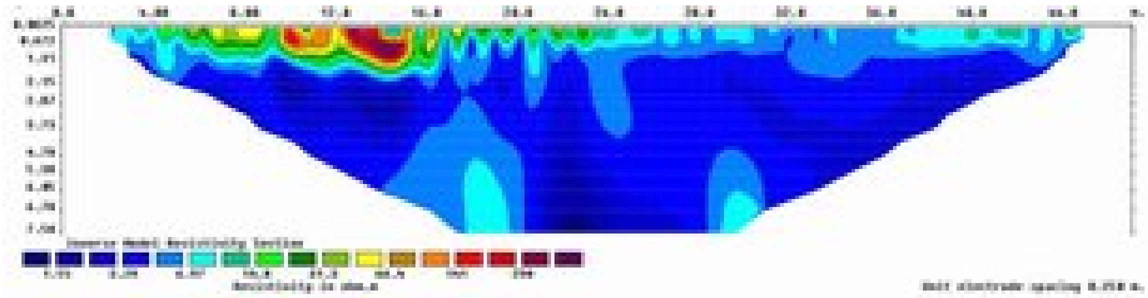

Fig. 24a: 2D geo-electrical profile

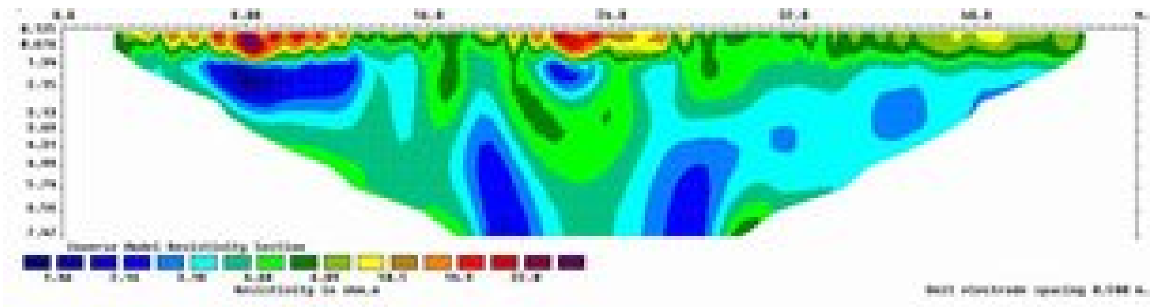

Fig. 24b: 2D geo-electrical profile

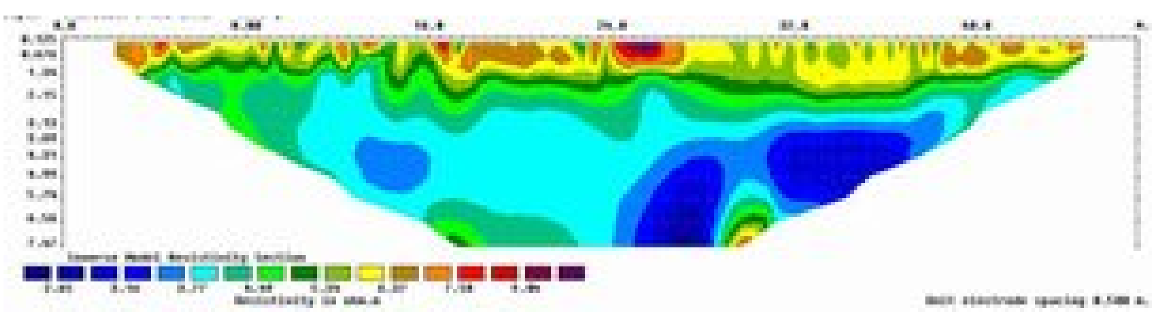

Fig. 24c: 2D geo-electrical profile

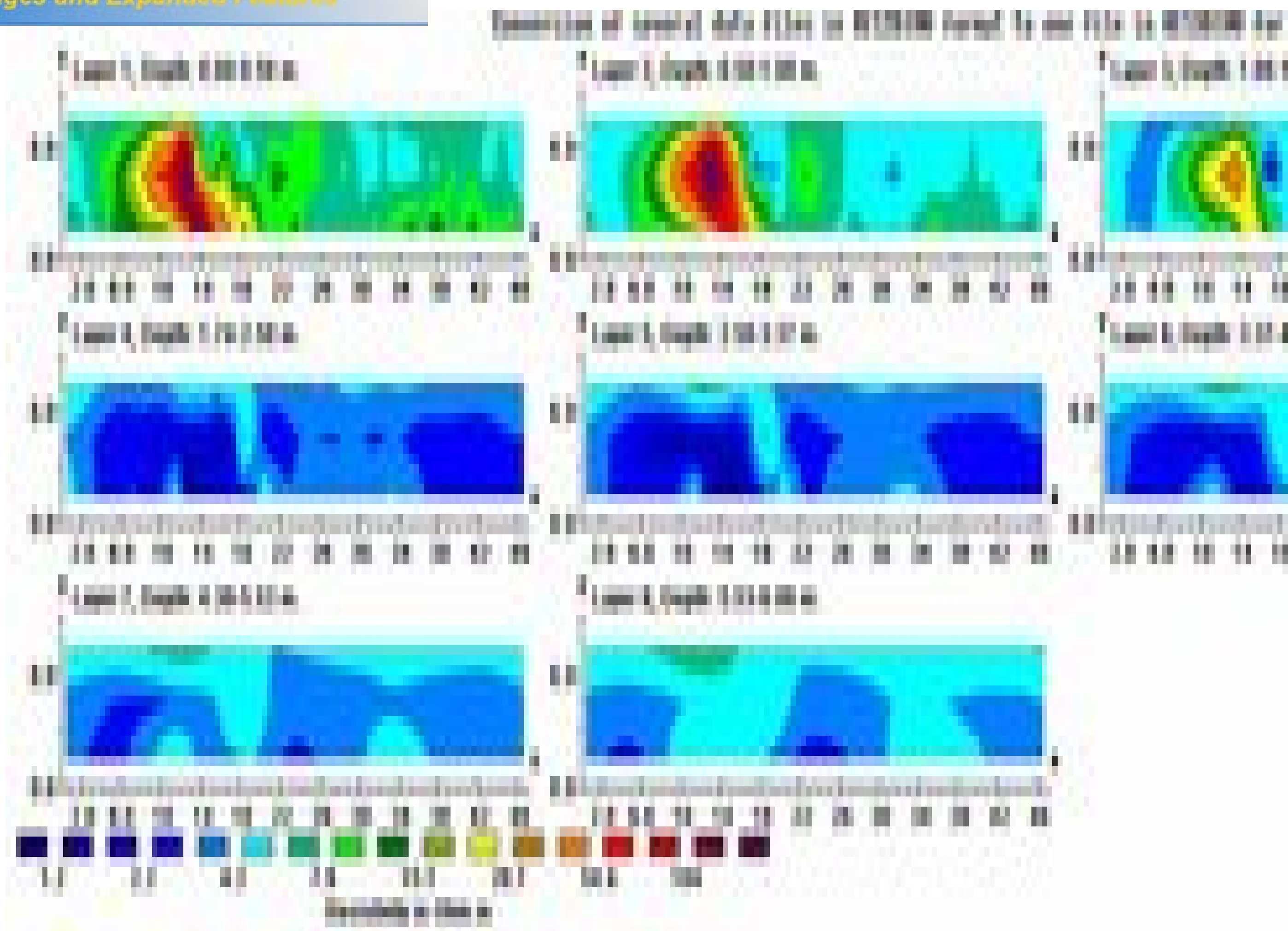

Fig. 25: 3D profile at various depth at site V

same area but in the northern most part along the road in EW direction (see Fig.11.). At the western end there is built up area and the eastern end is water logged, hence the space available had given us no choice but to select the electrode separation as 2m with total profile length as 48m in EW direction along the road. The bushes were cleared to get as close as possible to expected dump. The 2D data was corrected and interpreted to get geo-electrical distribution as shown in Fig. 26.

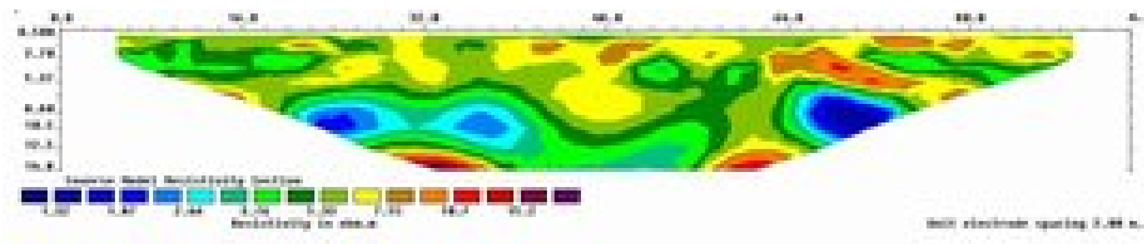

Fig. 26: 2d geo-electrical profile

There was no indication of any dump along this profile. Two more profiles were taken at 10m separation and the profile obtained is shown in Fig. 27a and b. These profiles have also indicated that there may not be any dump in this area. The 2D data is then converted into 3D and the depth wise profile is depicted in Fig. 28.

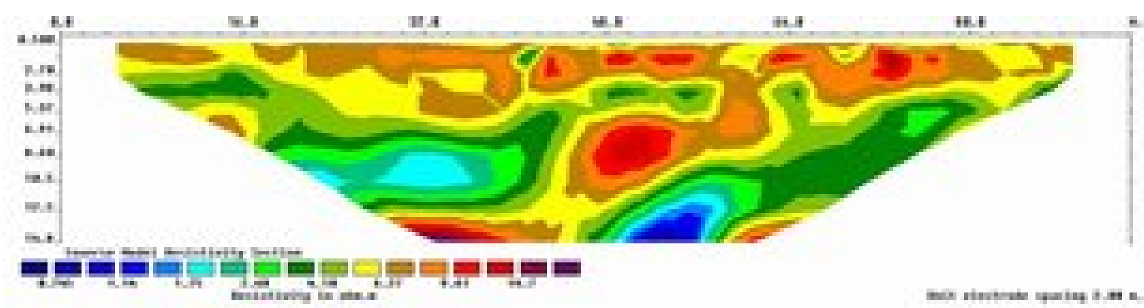

Fig. 27a: 2D geo-electrical profile

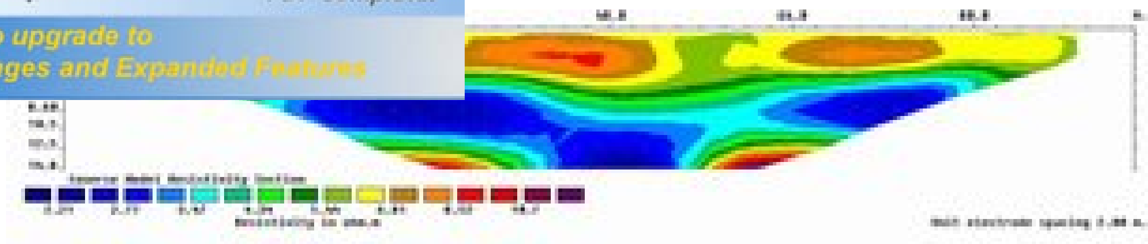

Fig. 27b: 2D geo-electrical profile

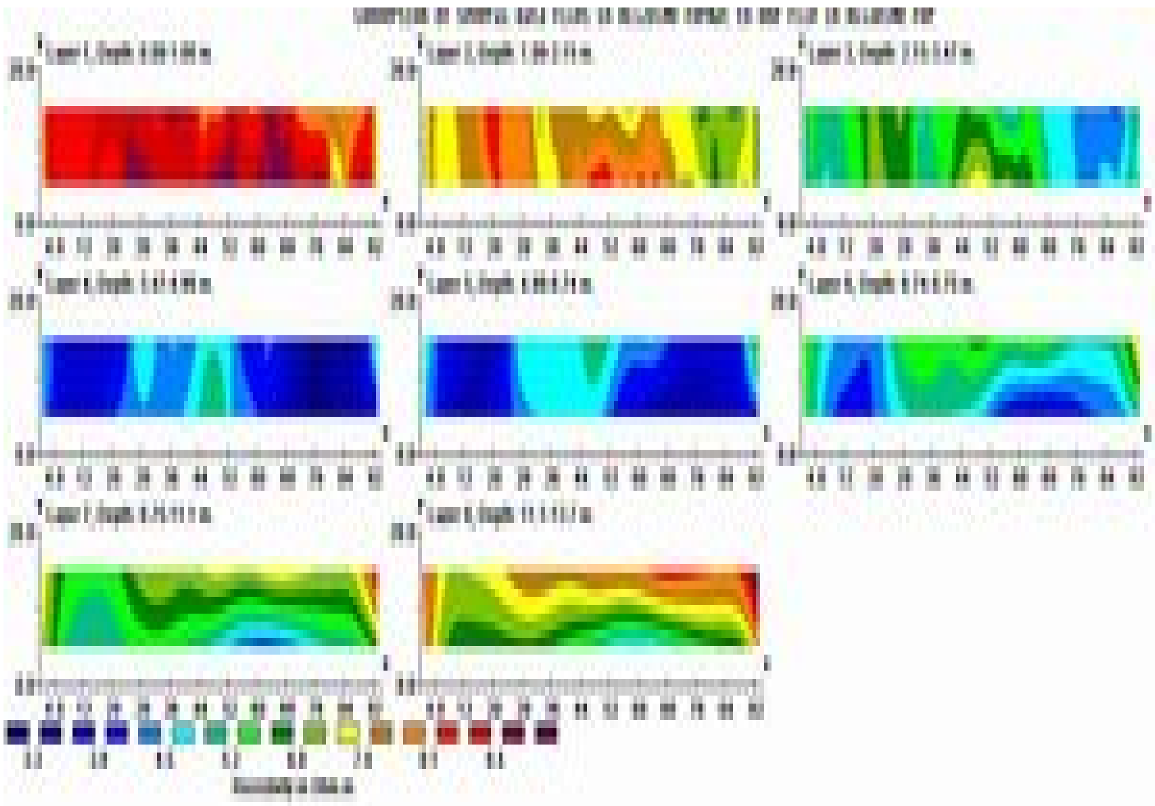

Fig. 28: 3D geo-electrical profile

Site VII : This site is selected in the eastern part of premises and north of SEP as shown in Fig. 11. The eastern part of this open land was waterlogged where as many parts are covered with bushes. After clearing some of the bushes we were able to take a profile in EW direction with 2m electrode spacing and keeping 1st electrode in the E. The 2D data was corrected and interpreted with RES2DINV. The obtained result with minimum

. In this profile too the dump was not seen, although there are tarry dump in the south of this profile as shown in Fig 3f.

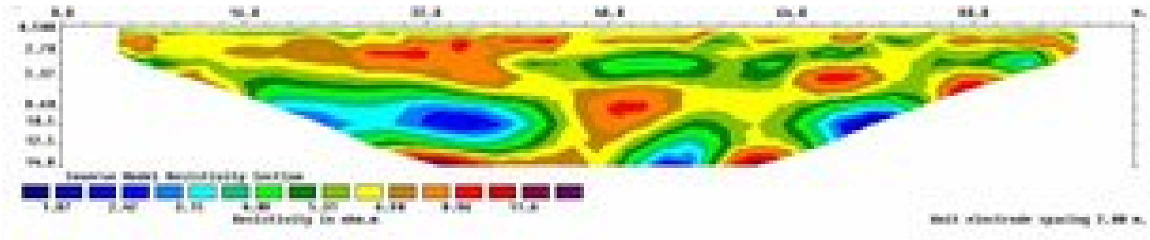

Fig. 29: 2D geo-electrical profile

Site VIII : The site is selected in the close vicinity of the plant in the eastern direction. Part of this area was also water logged and some are covered with bushes. The profile was taken in N70^{0}E as shown in Fig. 11. A 2D profile was taken and the processed data was interpreted for resistivity profile which is shown in Fig. 30.

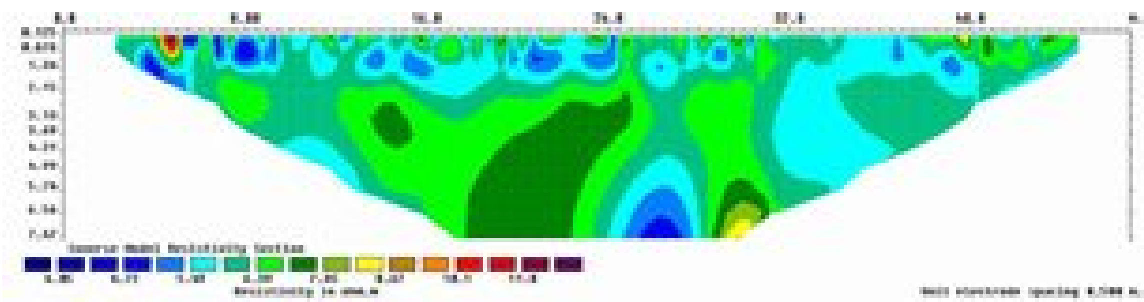

Fig. 30: 2D geo-electrical profile

There was no indication of any dump in this part of premises. Further three more profiles were taken parallel to it at the separation of 4m, 5m and 3m respectively. An area of 48mx12m was covered by these profiles. The interpreted data after correction is shown in Fig. 31a, b and c. There was no indication of any dump, although an anomaly was seen in one of the profile and it was found to be pot-hole. A 3D profile was also generated from s inferred that there was no dump in the area covered by the profiles.

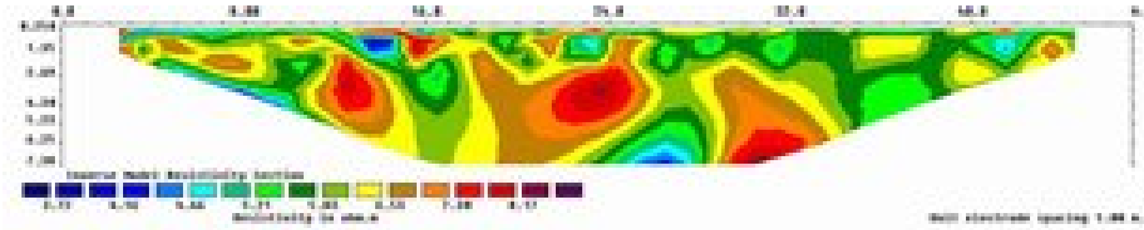

Fig. 31a: 2D geo-electrical profile

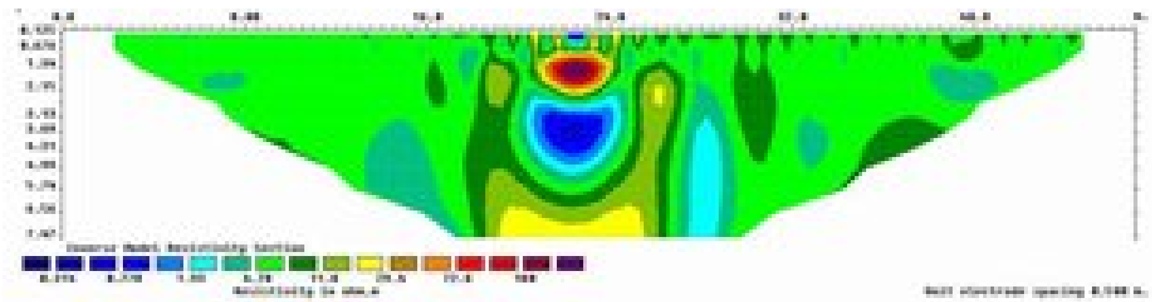

Fig. 31b: 2D geo-electrical profile

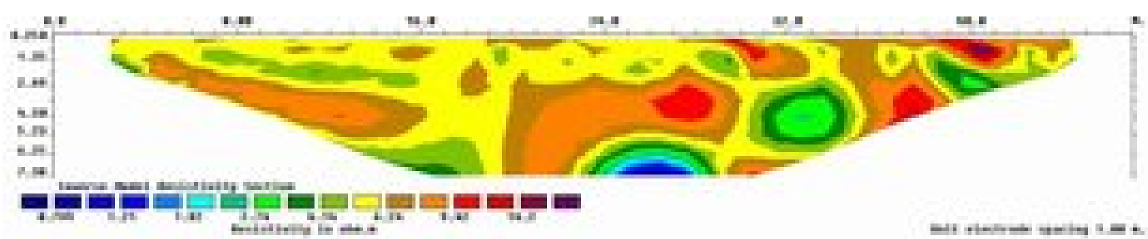

Fig. 31c: 2D geo-electrical profile

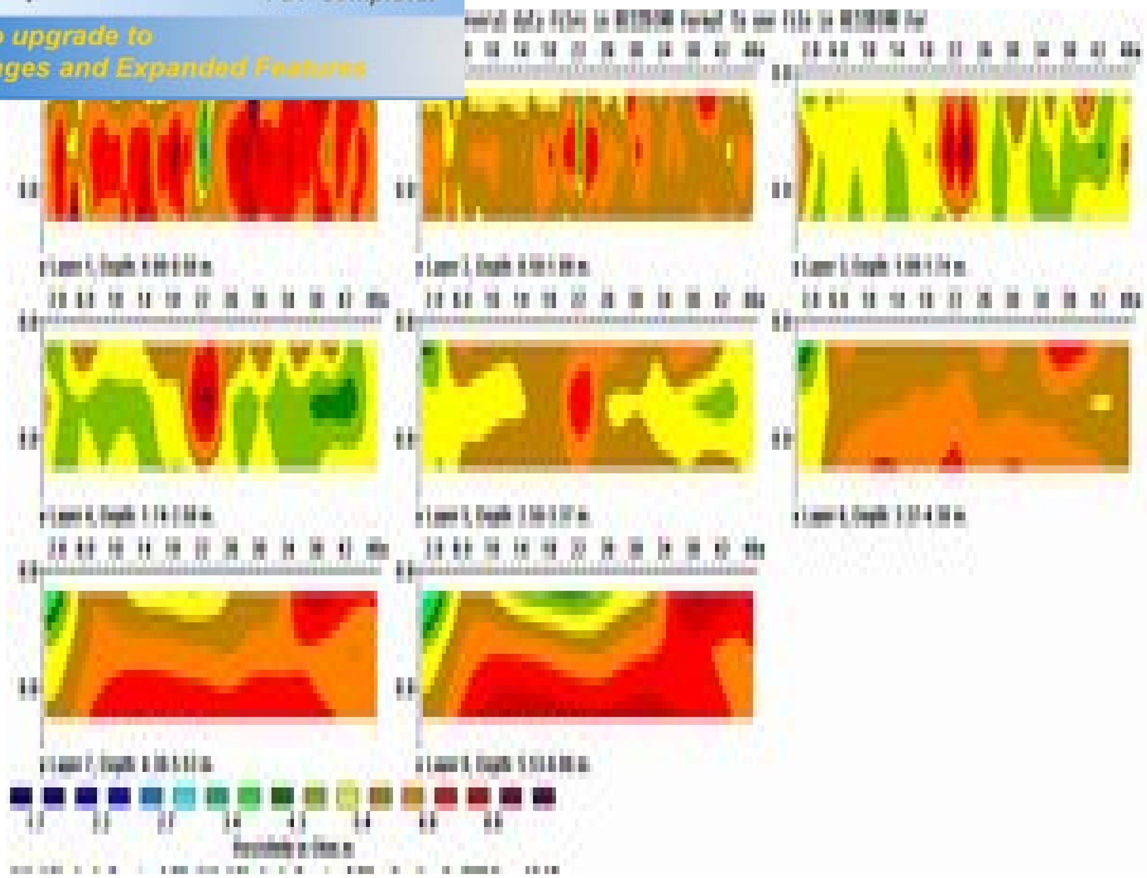

Fig. 32: 3D geo-electrical profile

Site IX : The site has been selected at the open space available at the main entrance, on the western side of road as shown in Fig. 11. The electrode separation was selected as 2m and 2D profile was obtained. The data was corrected and interpreted using RES2DINV. The obtained result is shown in Fig. 33.

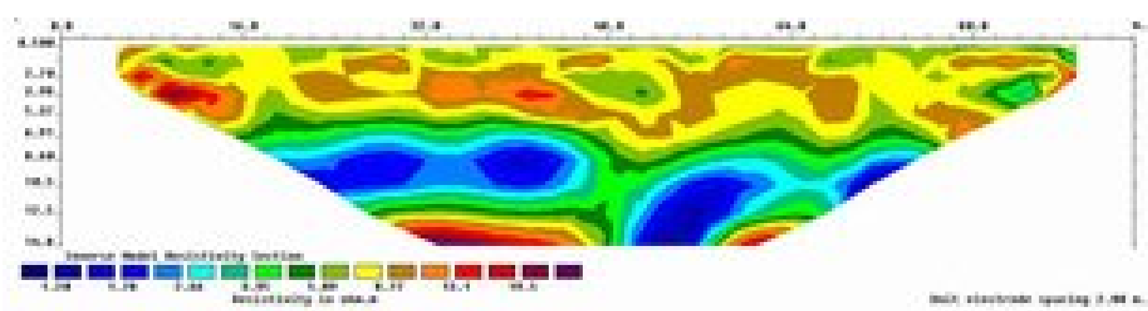

Fig. 33: 2D geo-electrical profile

cation of any dump. We took another two profiles parallel to it at the separation of 5m each. The geo-electrical profiles are shown in Fig. 34a and b.

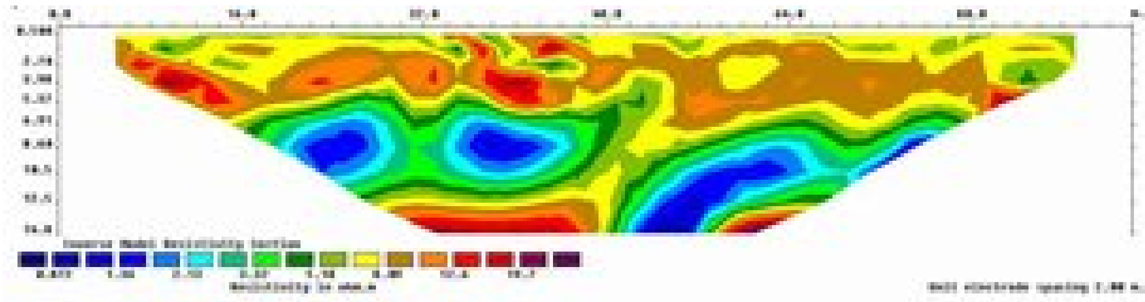

Fig. 34a: 2D geo-electrical profile

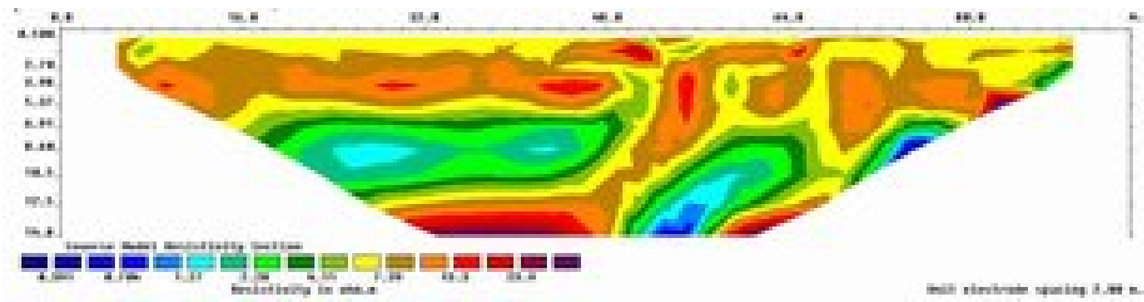

Fig. 34b: 2D geo-electrical profile

A 3D profile was generated with the software RES3DINV and using these 2D data to obtain a 3D picture at various depth. The profile is shown in Fig. 35. It does not appear that there is any dump in the patch covered by the profiles.

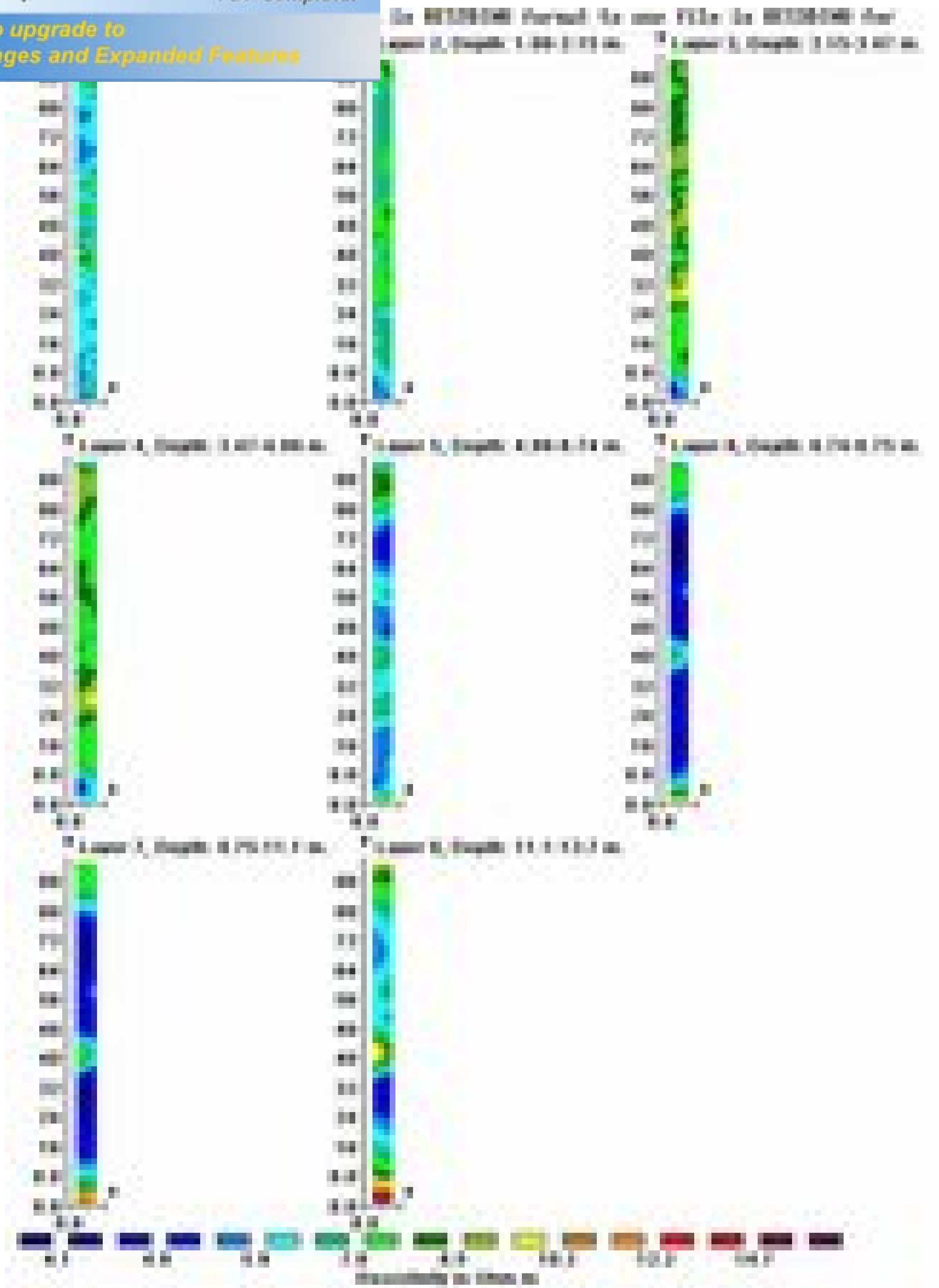

Fig. 35: 3D geo-electrical profile

HERT was carried out across the selected area based on the previous studies and reports to ascertain the extent and depth of dumps in the premises of UCIL. Total nine sites were covered as the technique requires continuous open space without concrete, bushes; waterlog (ponds) and roads which are very limited in the premises. Out of nine sites, dumps are located at three sites (Fig. 36) namely :

Site I : North of Formulation Plant

Site III : South of Storage tank and Police Post, and

Site V : Between Neutralization tank and SEP including Terry dump in northern part.

Most of the dumps are limited to about 2m in depth except one that may be deeper (4-8m). These dumps are limited to few spots. These high resistivity zones need to be ascertain through detailed chemical examination for their toxicity.

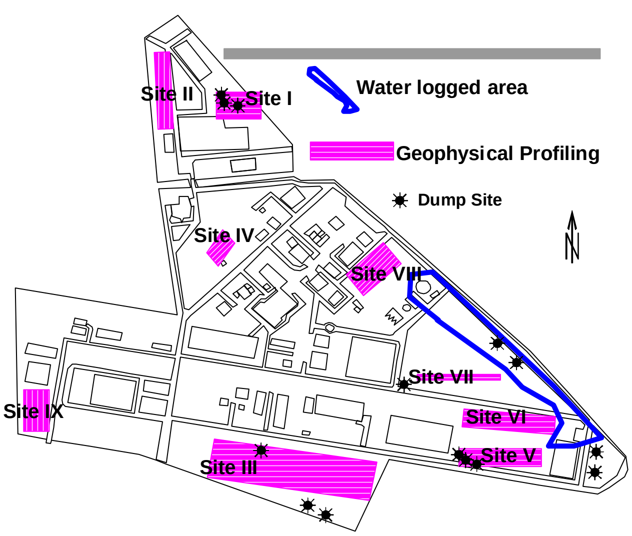

Fig. 36: Dump sites

anced the investigation and officials from BGRD have helped during the investigations. Director NGRI has encouraged carrying out investigations. Authors are thankful to them.

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Rapid 3D Resistivity & IP inversion using the least-squares method (For 3-D surveys using the pole-pole, pole-dipole, dipole-dipole, rectangular, Wenner, Wenner-Schlumberger and non-conventional arrays) On land, underwater and borehole surveys
Geoelectrical Imaging 2D & 3D, GEOTOMO SOFTWARE, MALAYSIA

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.

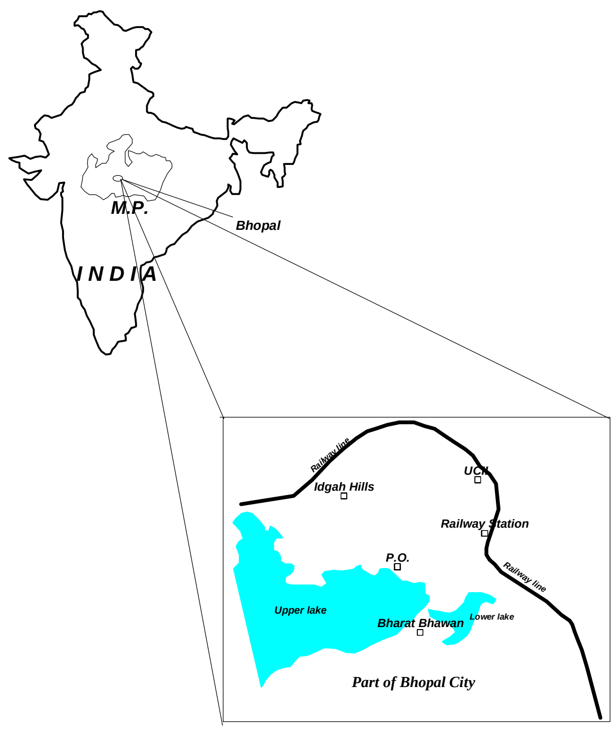

Fig. 1 Location map of study area

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.

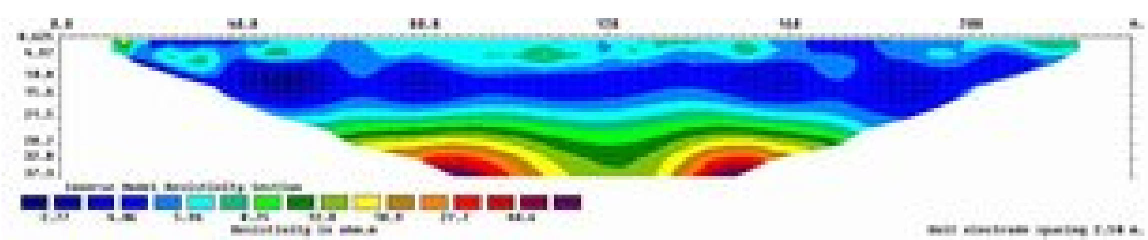

Fig. 2: 2D geo-electrical Profile

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.

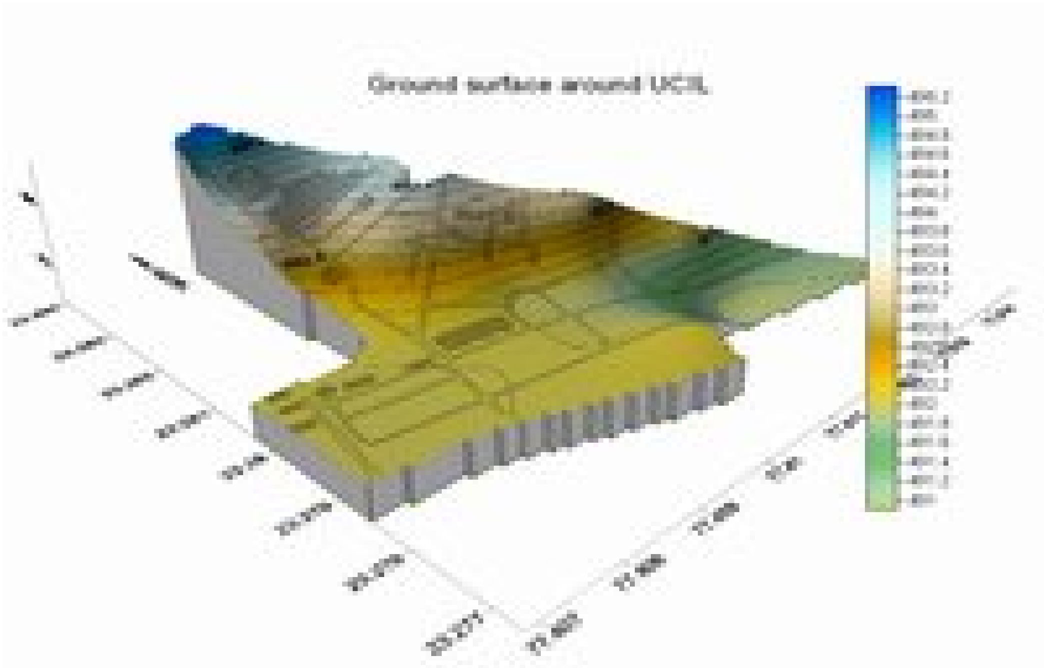

Fig. 3 Ground elevation map of area

Fig. 4 Well Location map

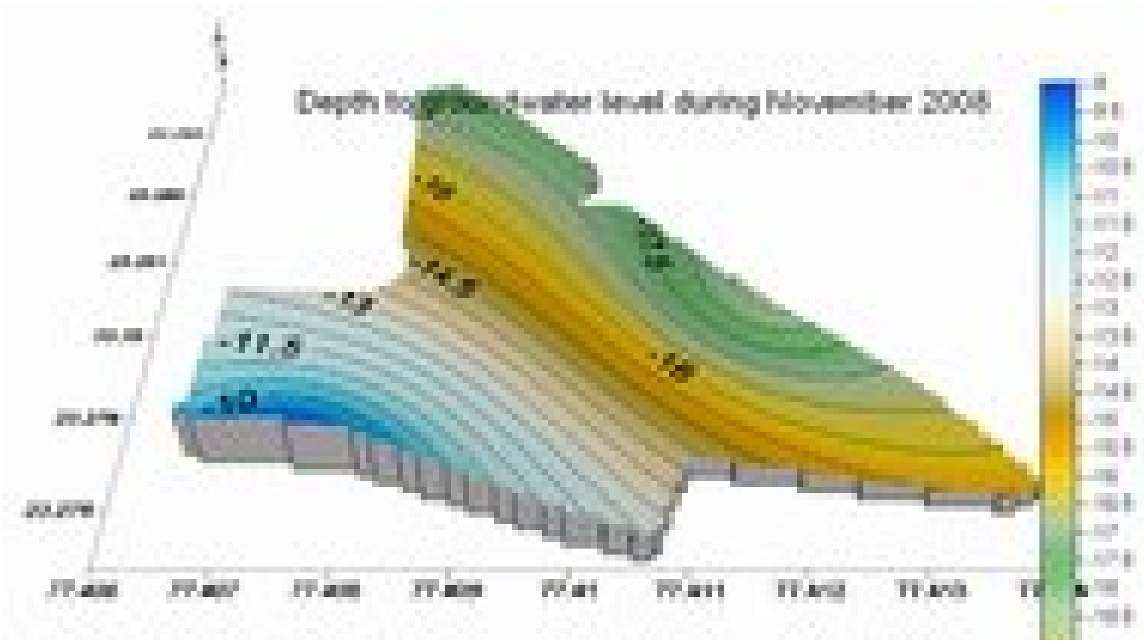

Fig. 5 Depth to water level during November 2008

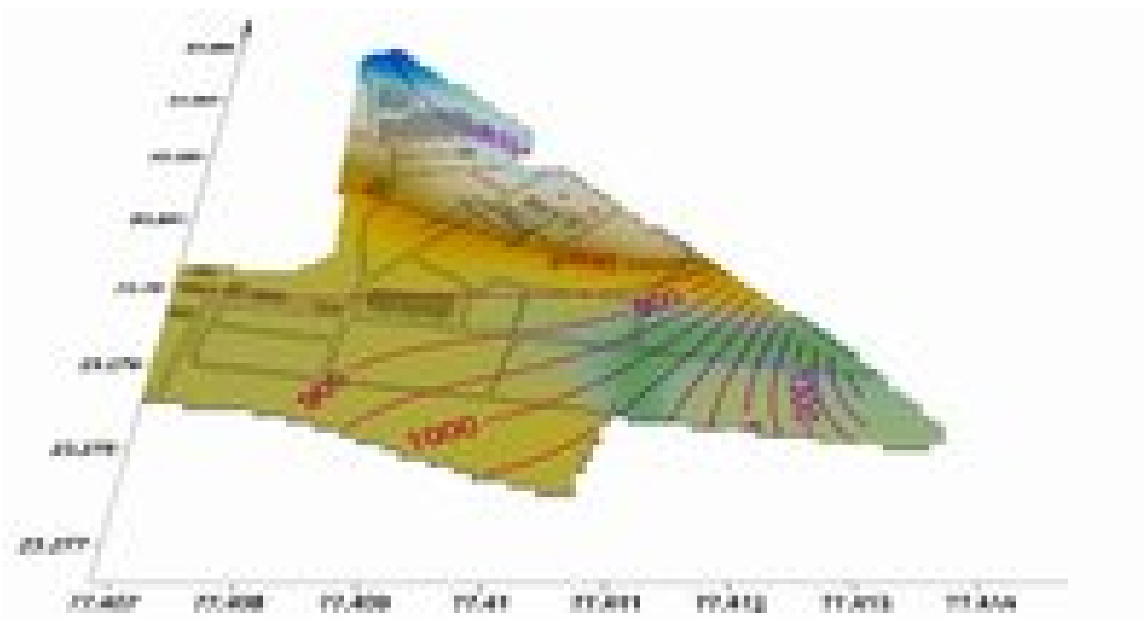

Fig. 6 EC value during November 2008

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).

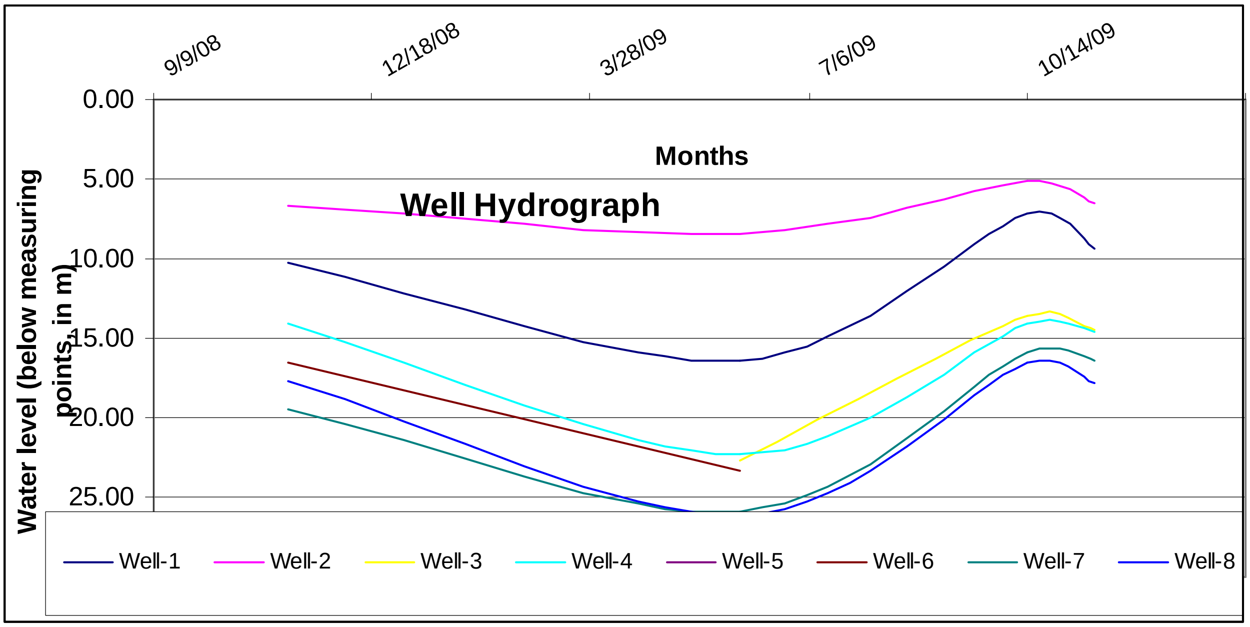

Fig. 7 Well Hydrograph of wells at the periphery of area

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.

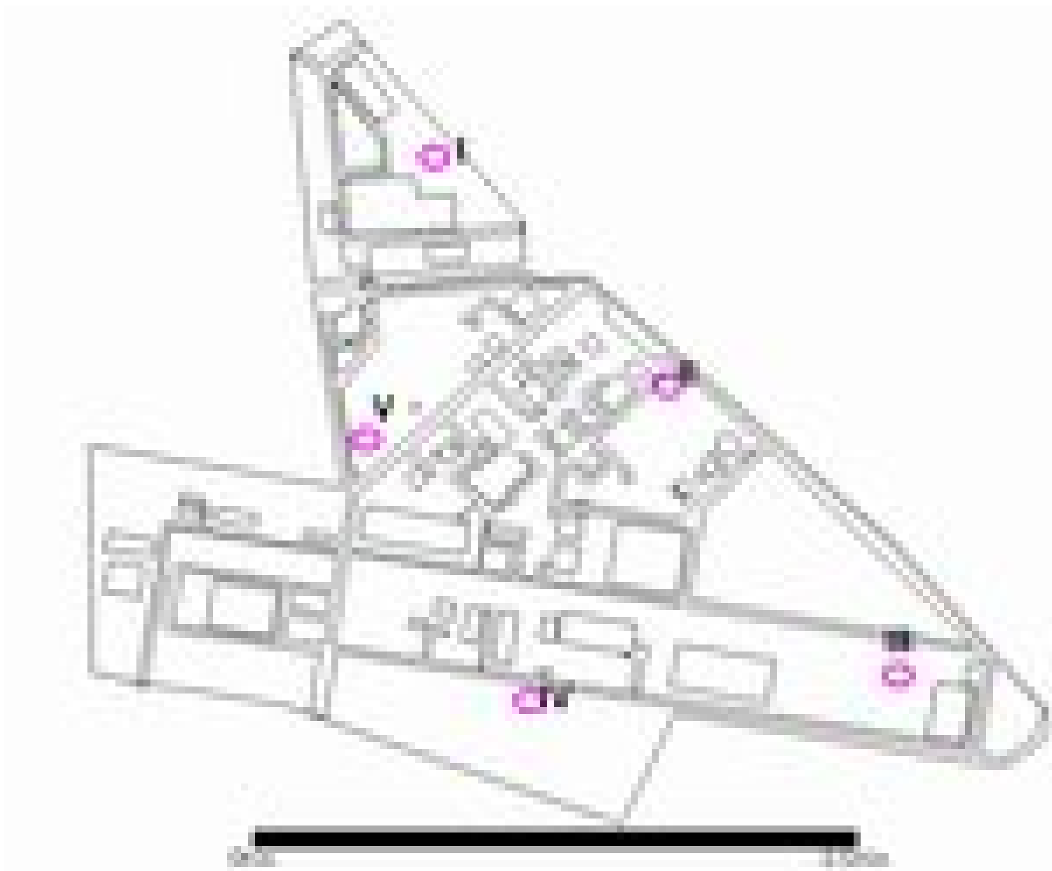

Fig. 8 Location of Drilling sites

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.

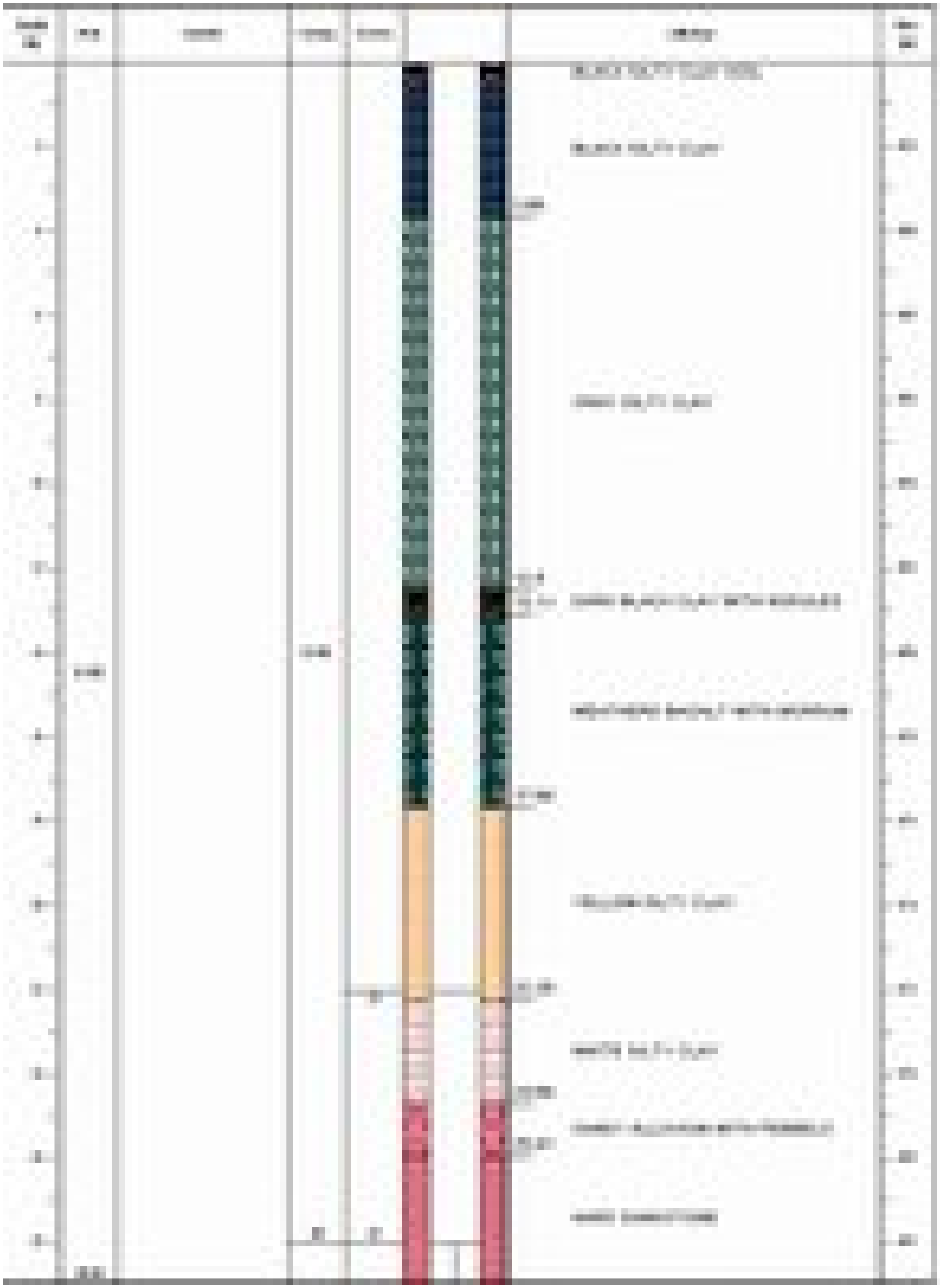

Fig. 9 : Litholog and drill time log.

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.

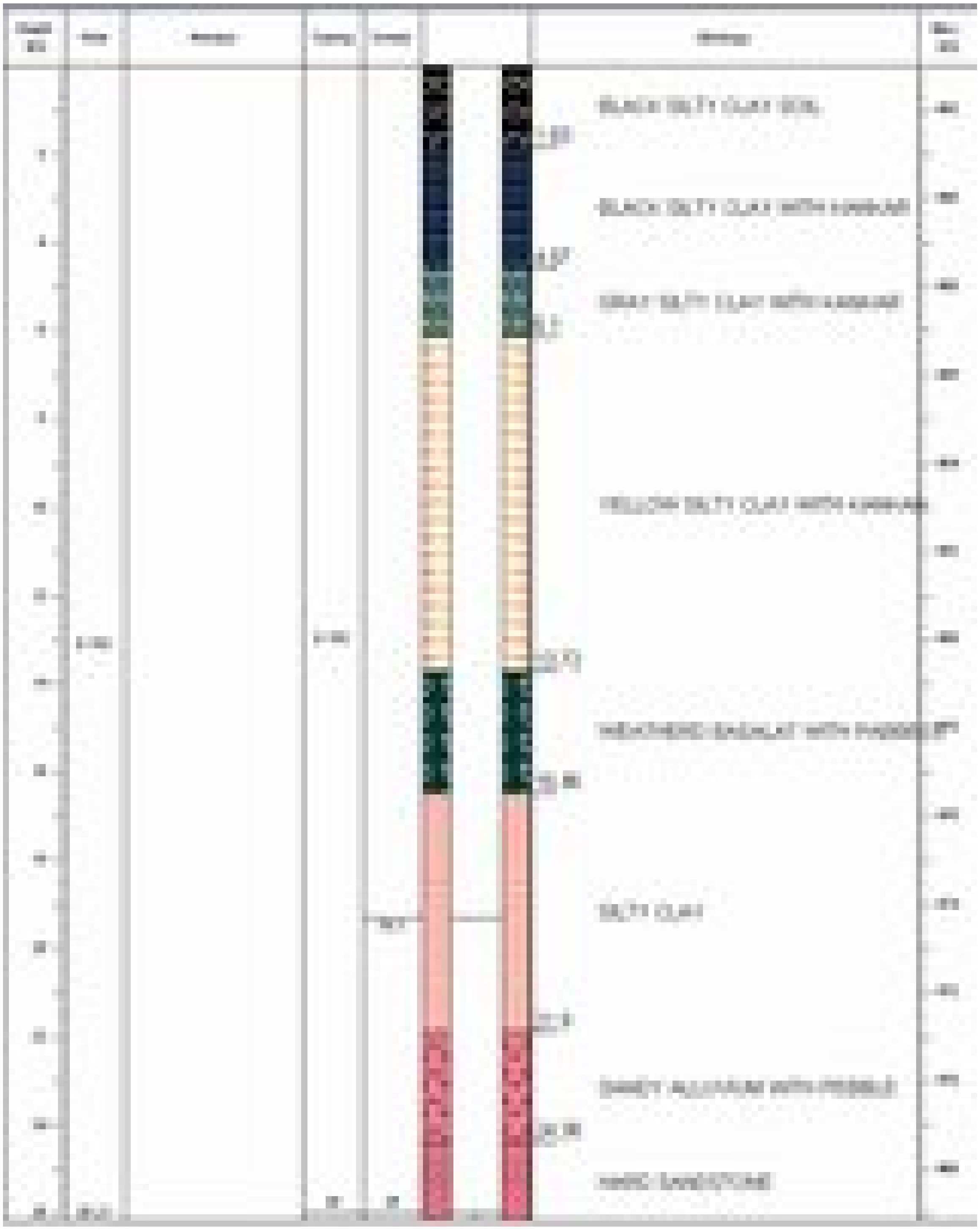

Fig. 10 Litholog and drill-time log at site II

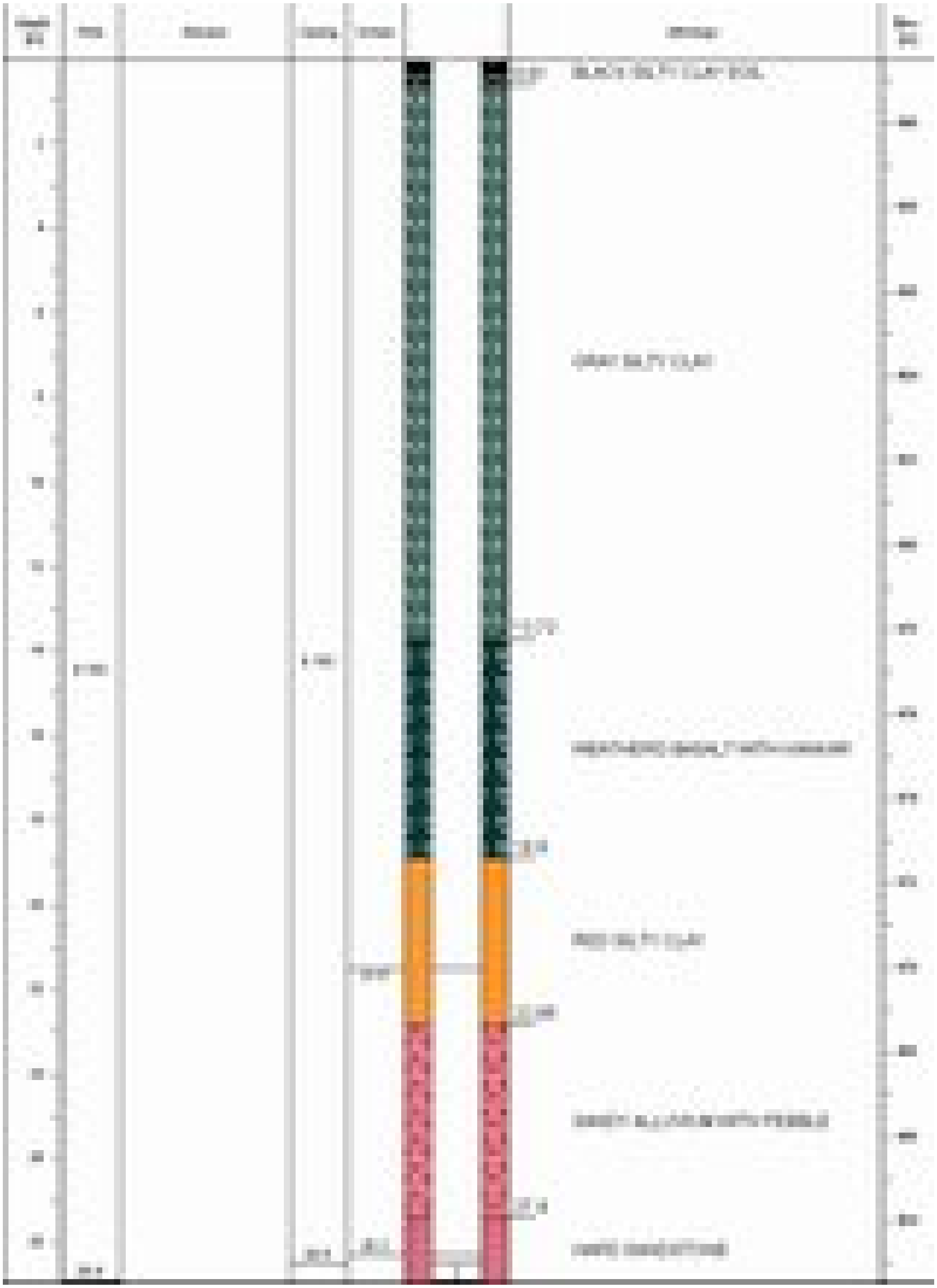

Fig. 11 Litholog and drill-time log at site III

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.

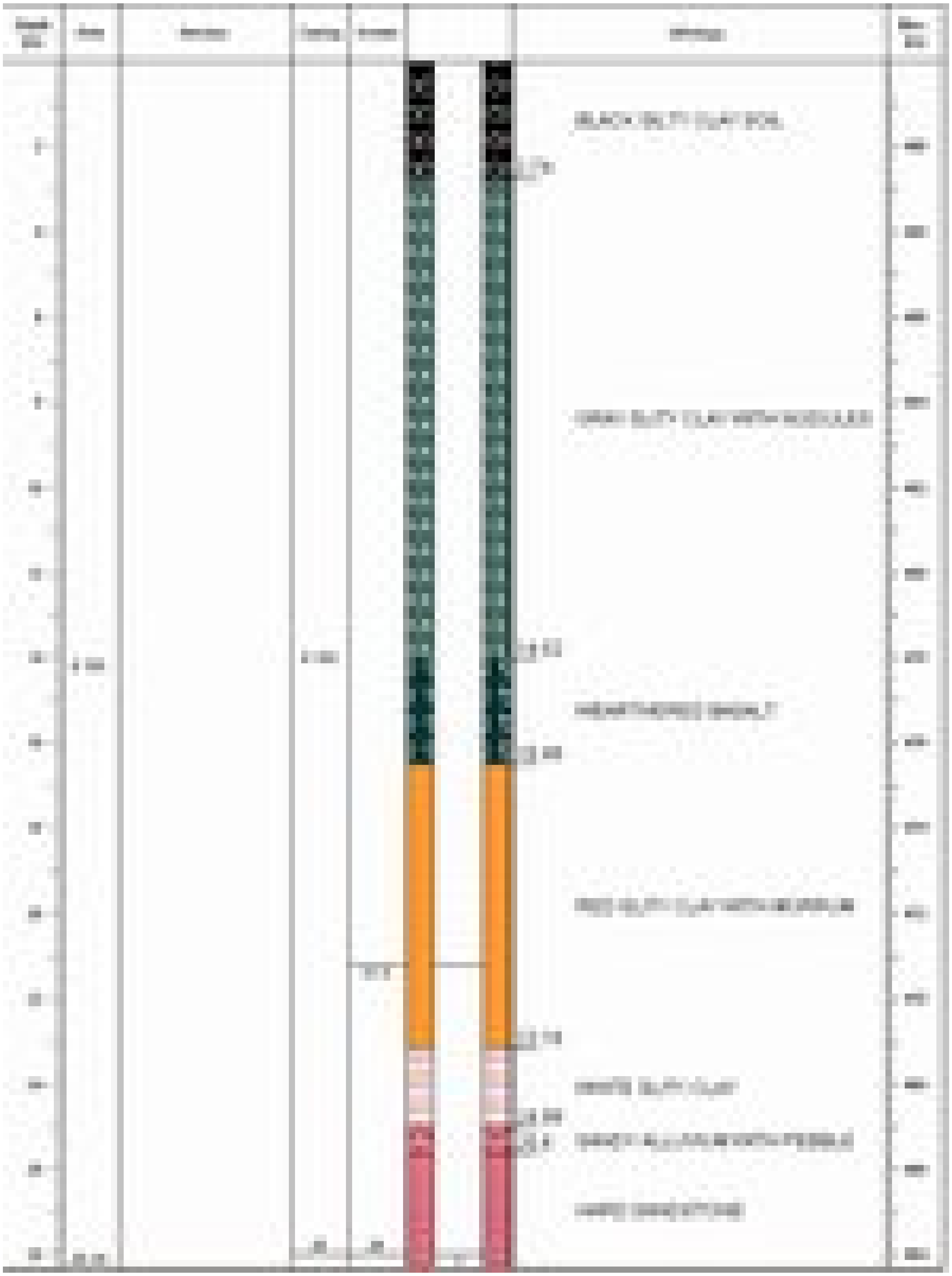

Fig. 12 Litholog at site IV

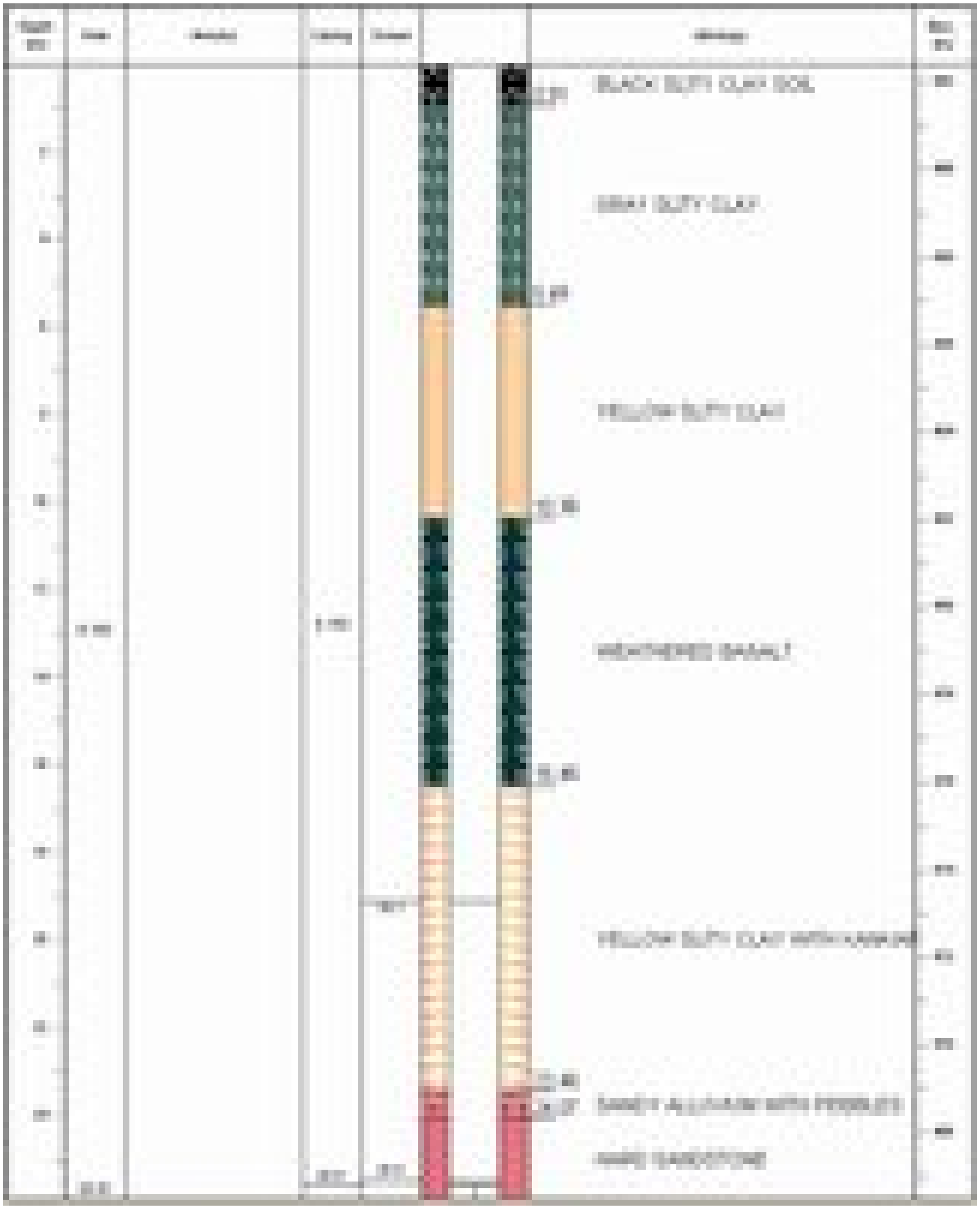

Fig. 13 Litholog at site V

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.

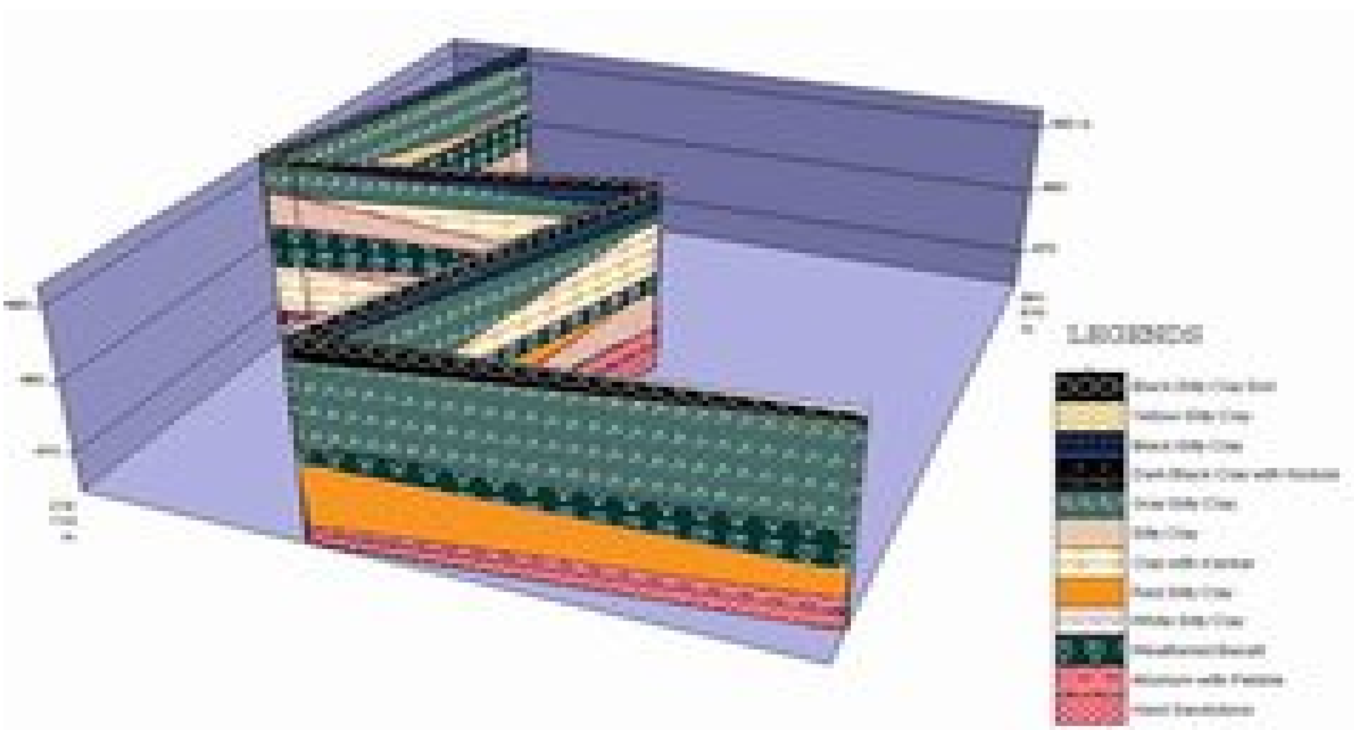

Fig 14 Fence diagram showing geological strata

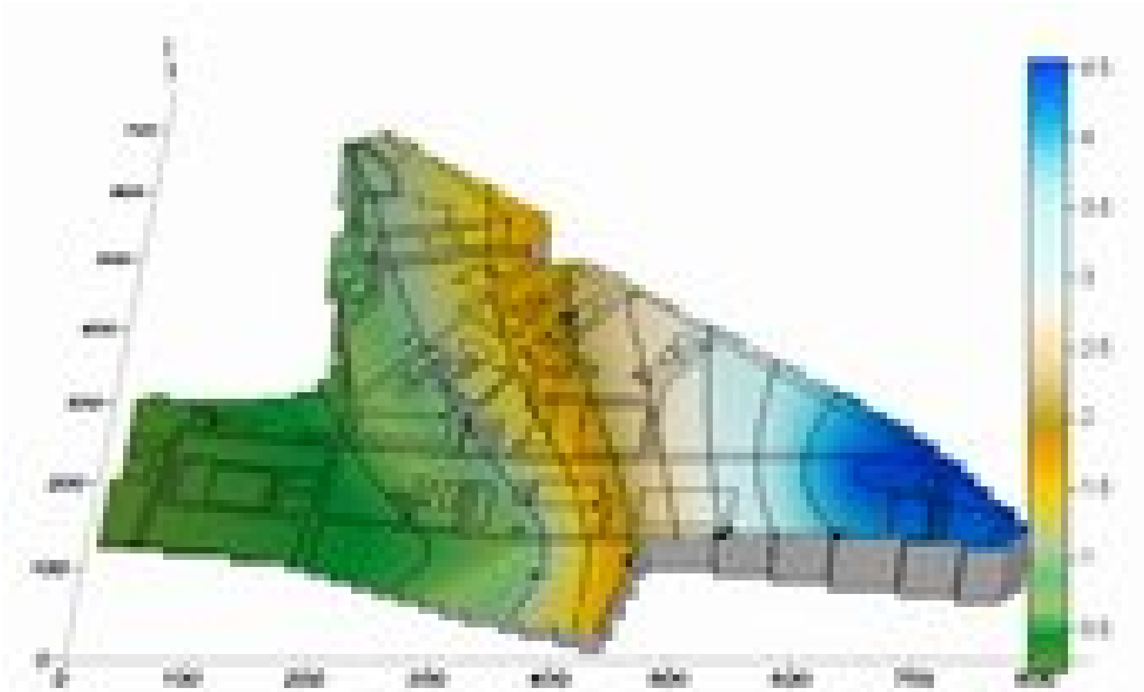

Fig. 15 Aquifer thickness distribution

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).

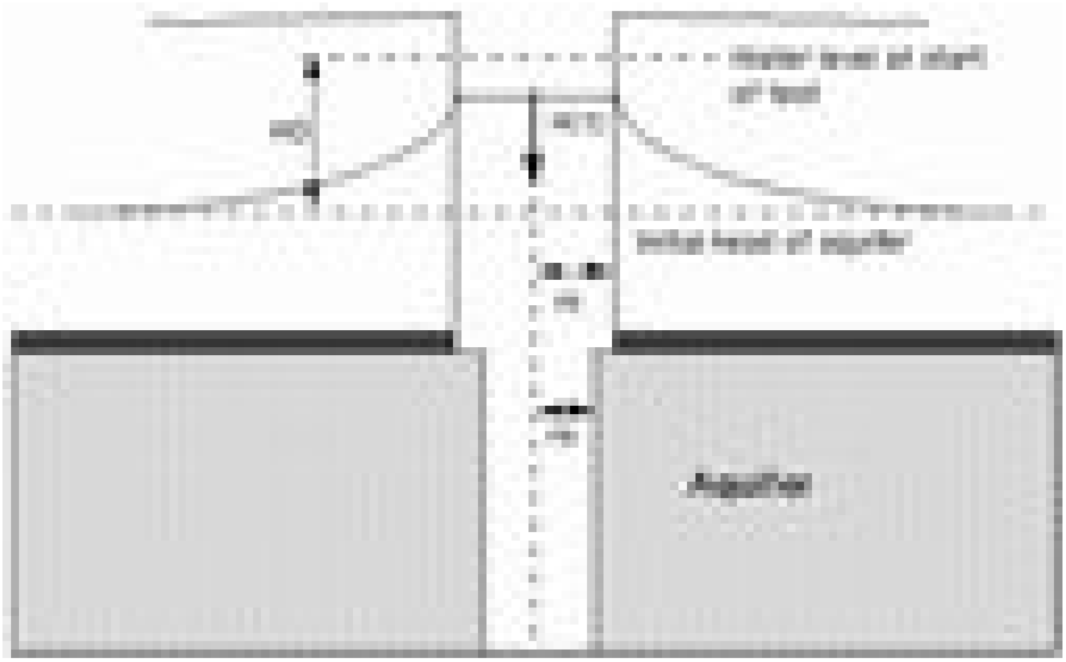

Fig.16 Slug Test (after Cooper et al 1967)

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 Darcyôs 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.

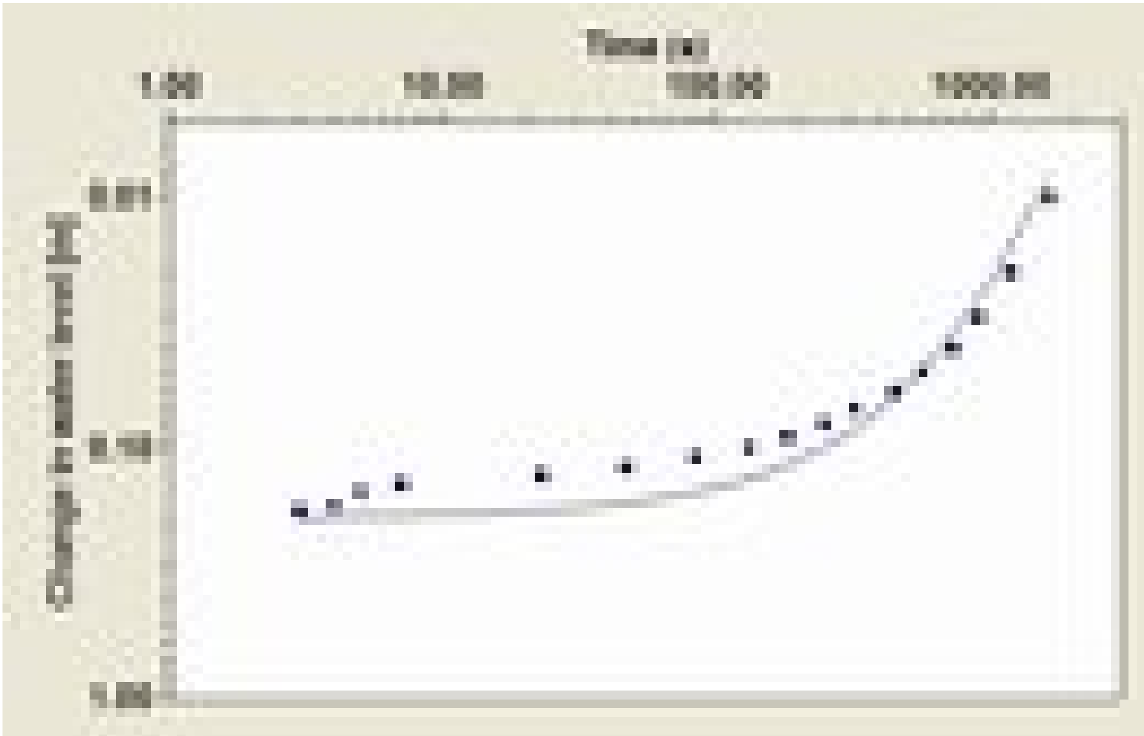

Fig. 17 Match with type curve at Well 1

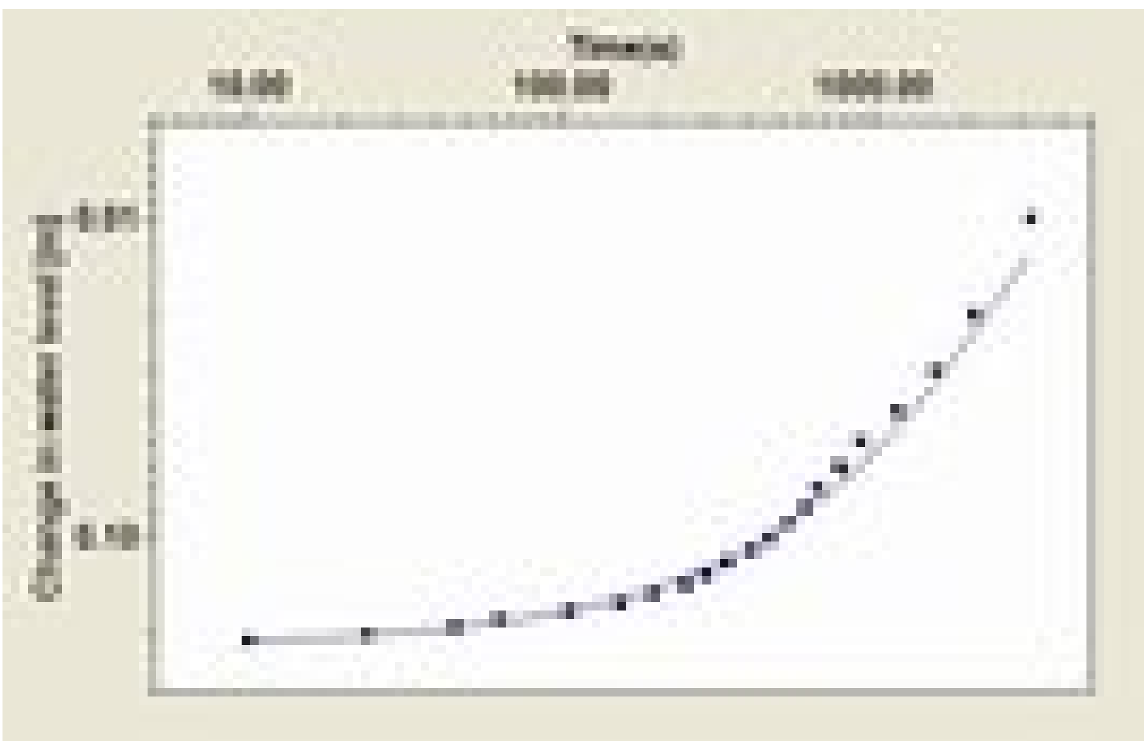

Fig. 18 Match with type curve at Well 2

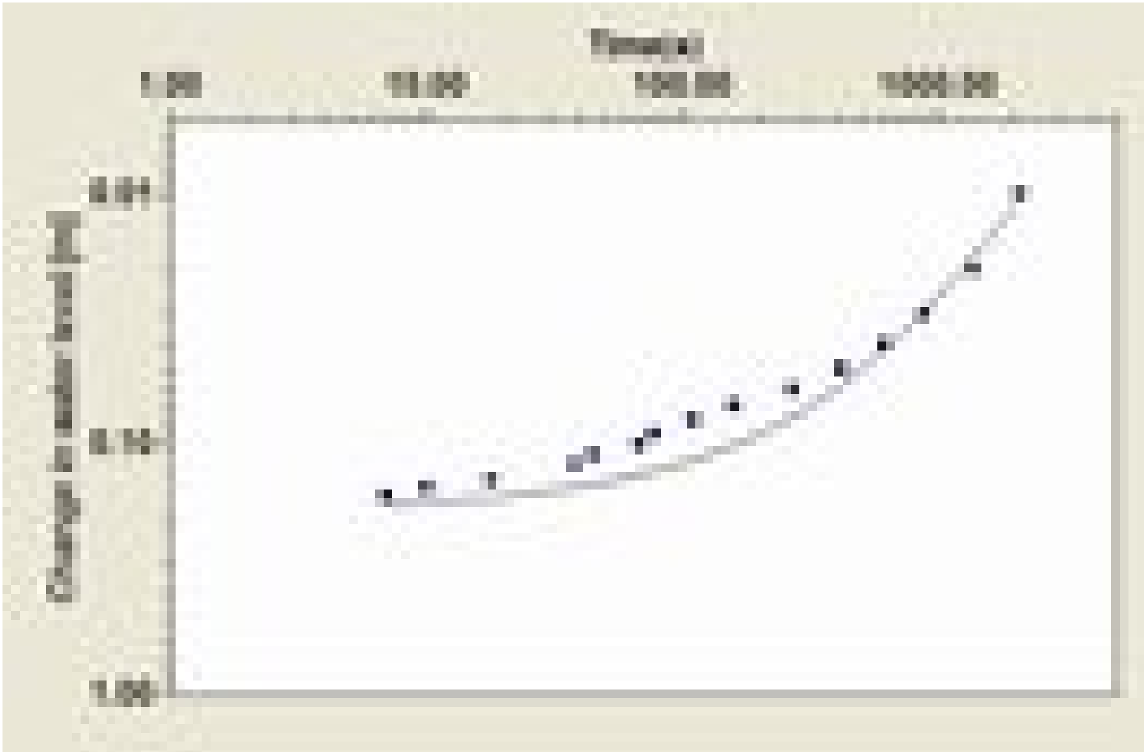

Fig. 19 Match with type curve at Well 3

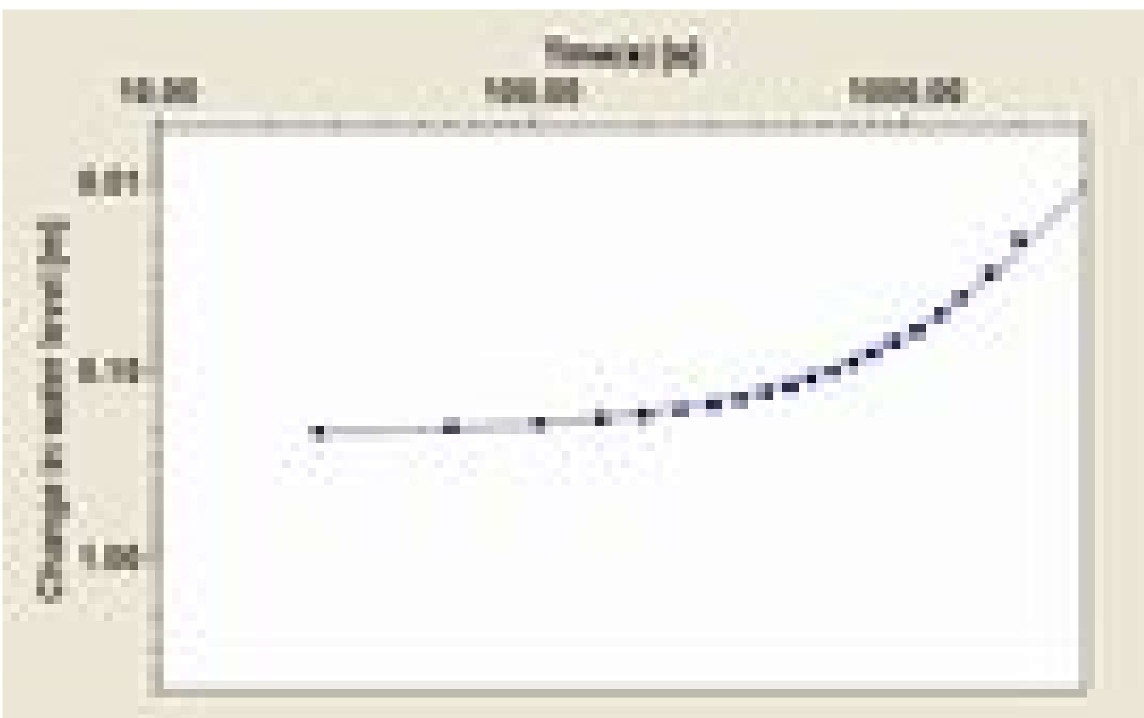

Fig. 20: Match with type curve at Well 4

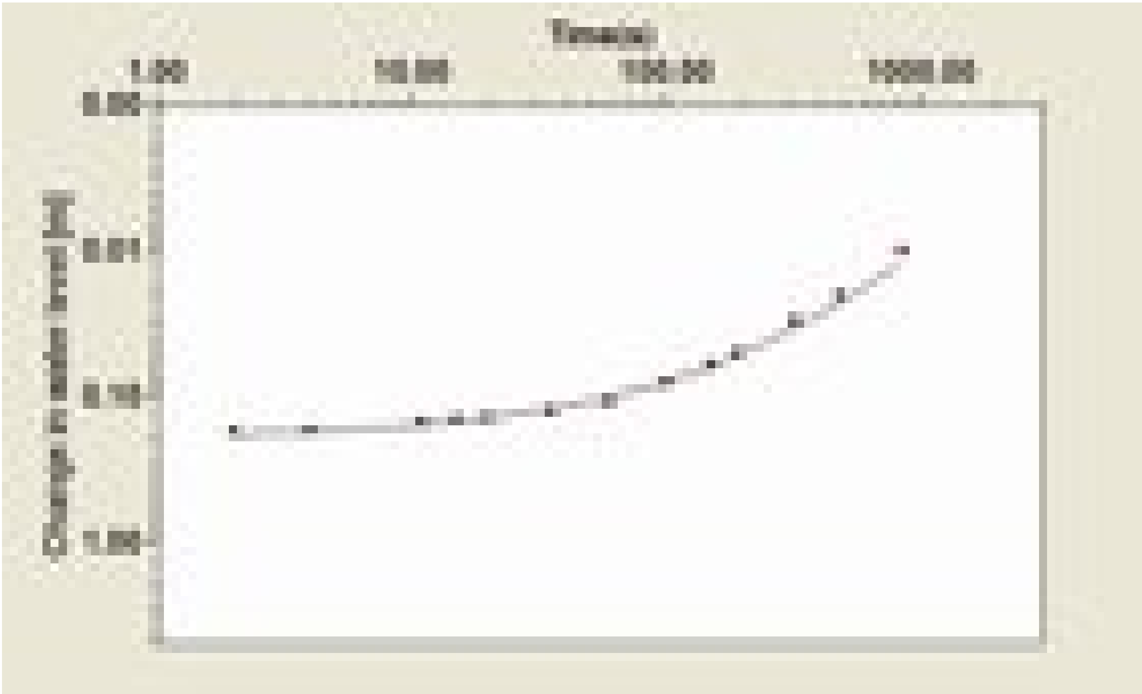

Fig. 21: Match with type curve at Well 5

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

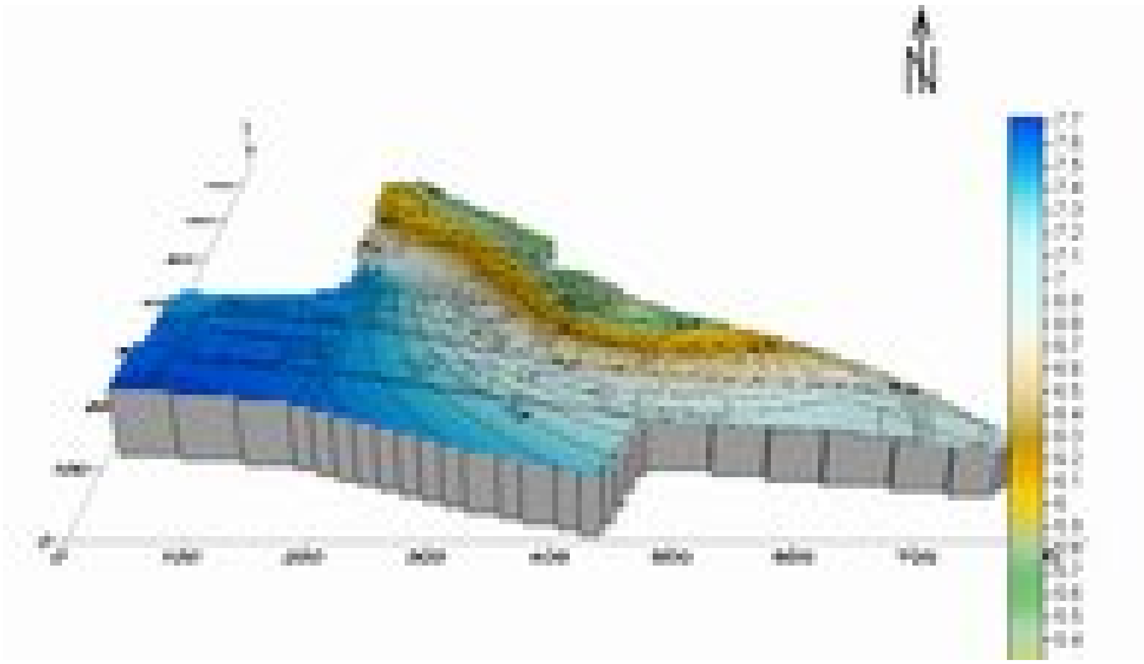

Fig.22: Permeability distribution map

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.

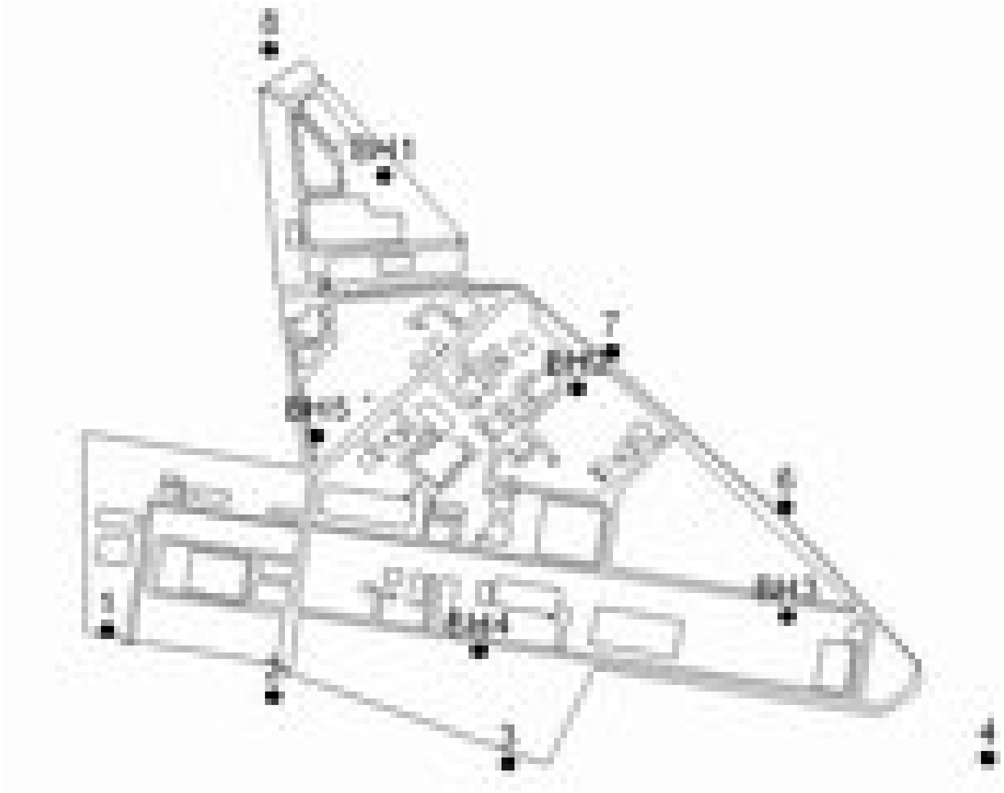

Fig. 23 Location of monitoring wells during Feb. 2010

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.

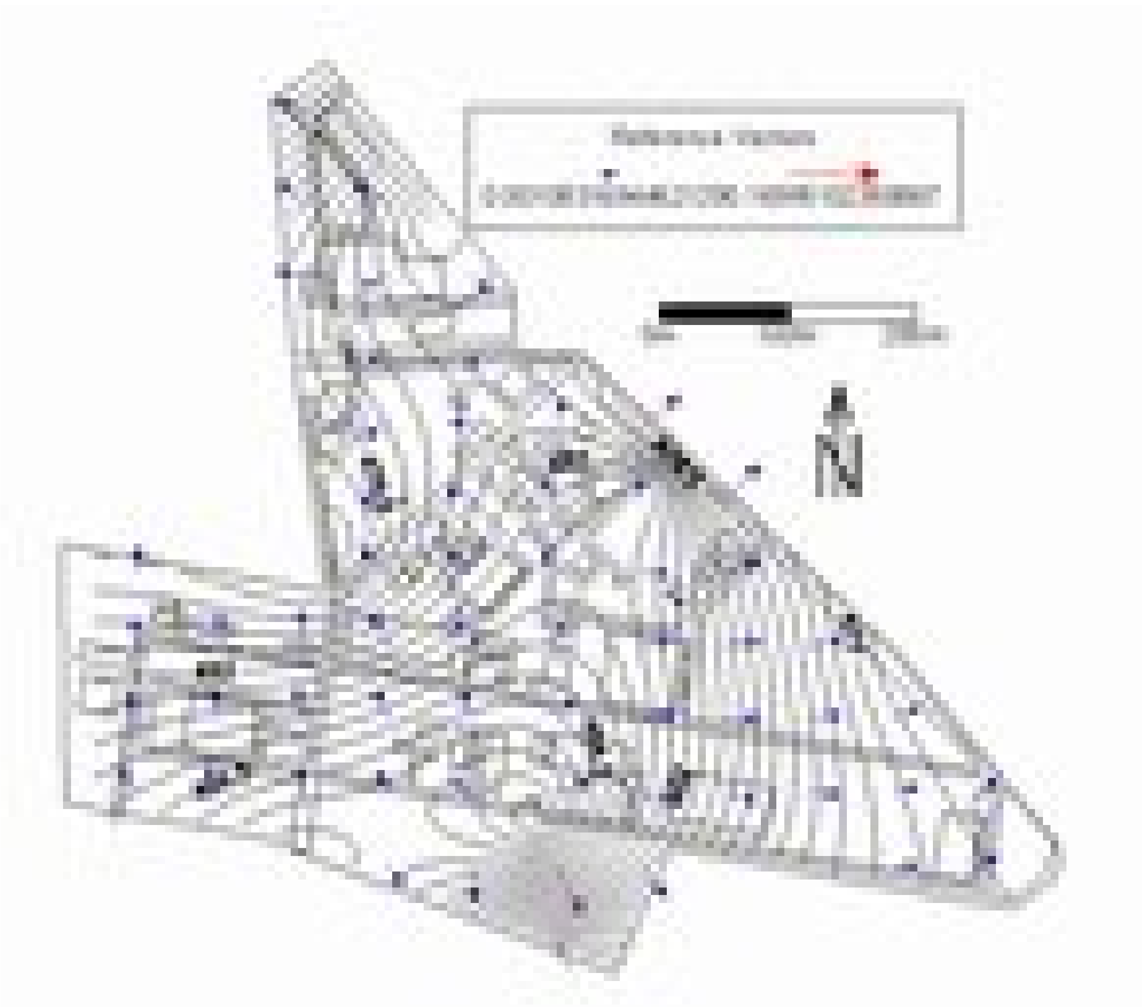

Fig. 25: Hydraulic gradient map for February 2010

SIMULATION OF GROUNDWATER 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

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

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.

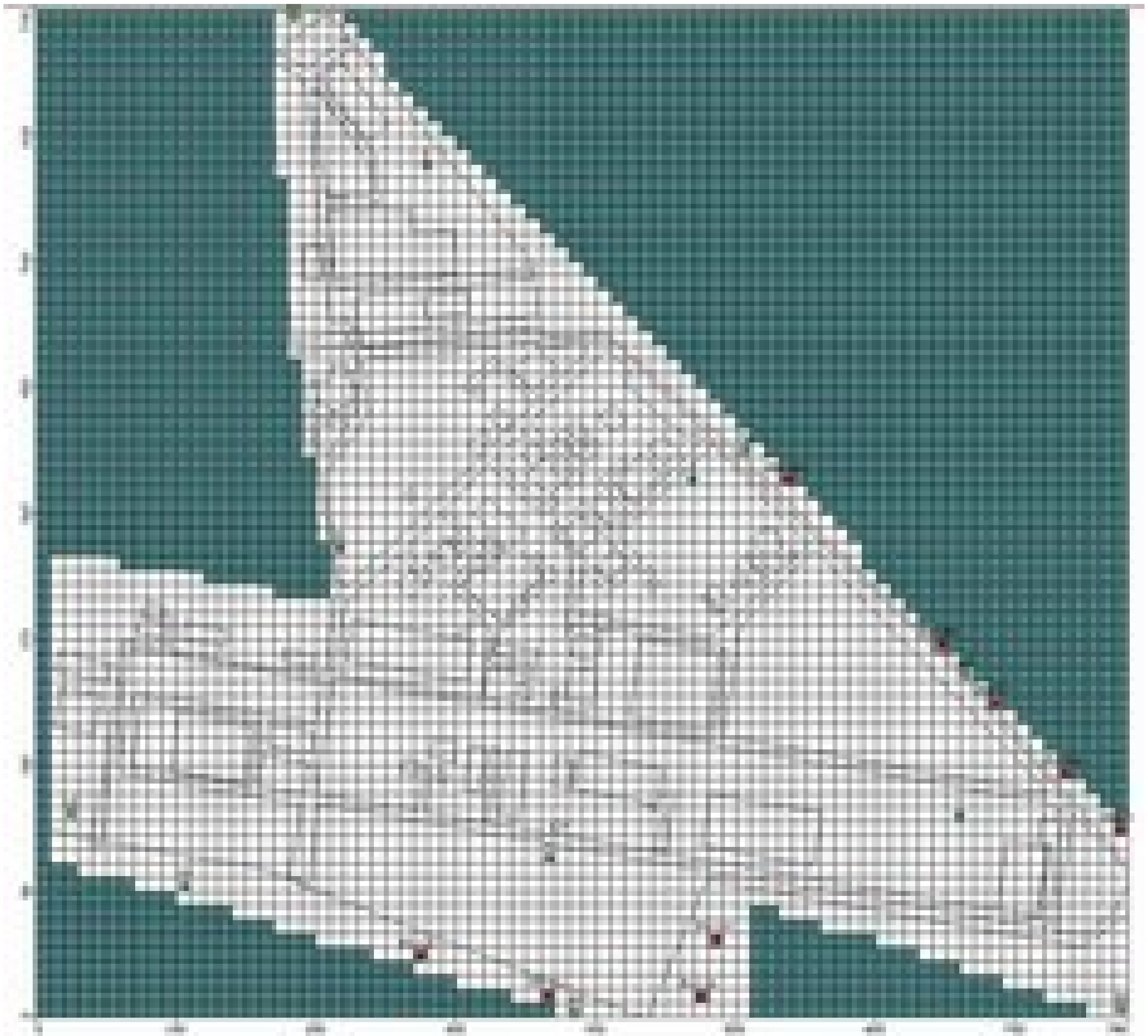

Fig. 26 : Discritization of study area.

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.

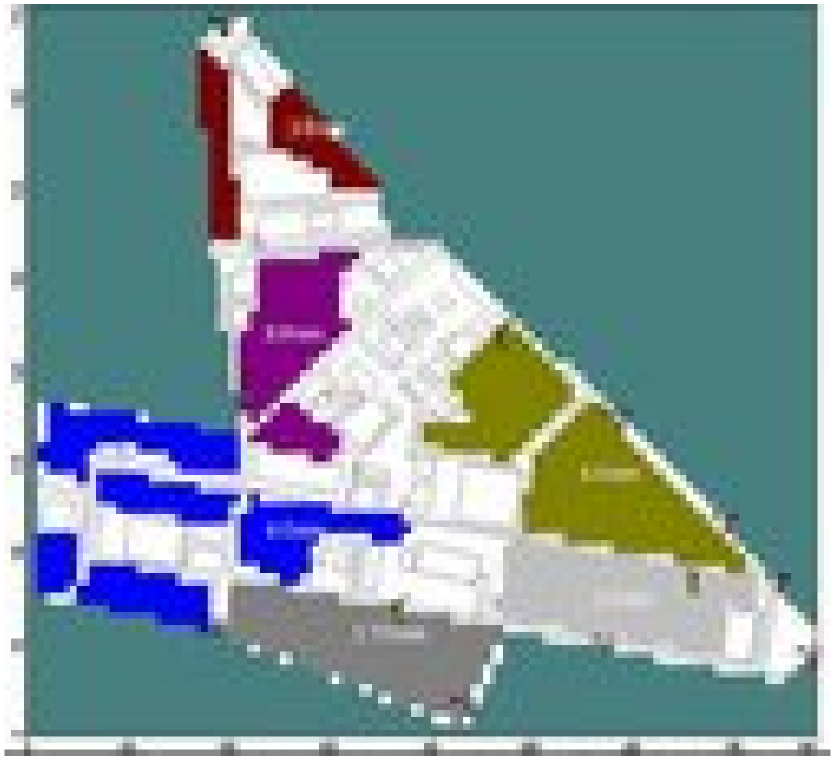

Fig 27: Initial recharge distribution

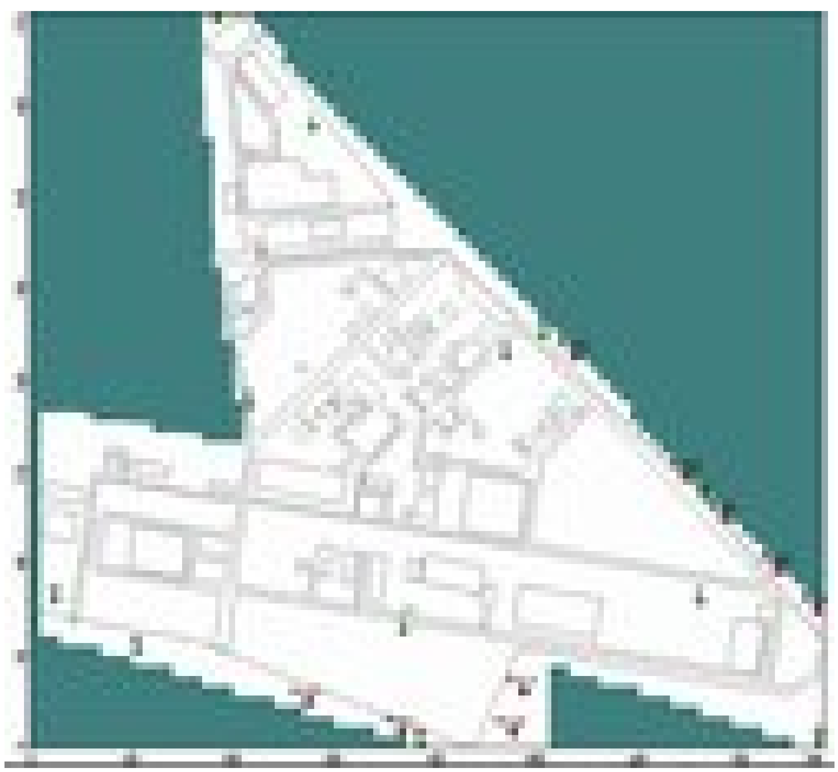

Fig. 28 Observation and Abstraction wells

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.

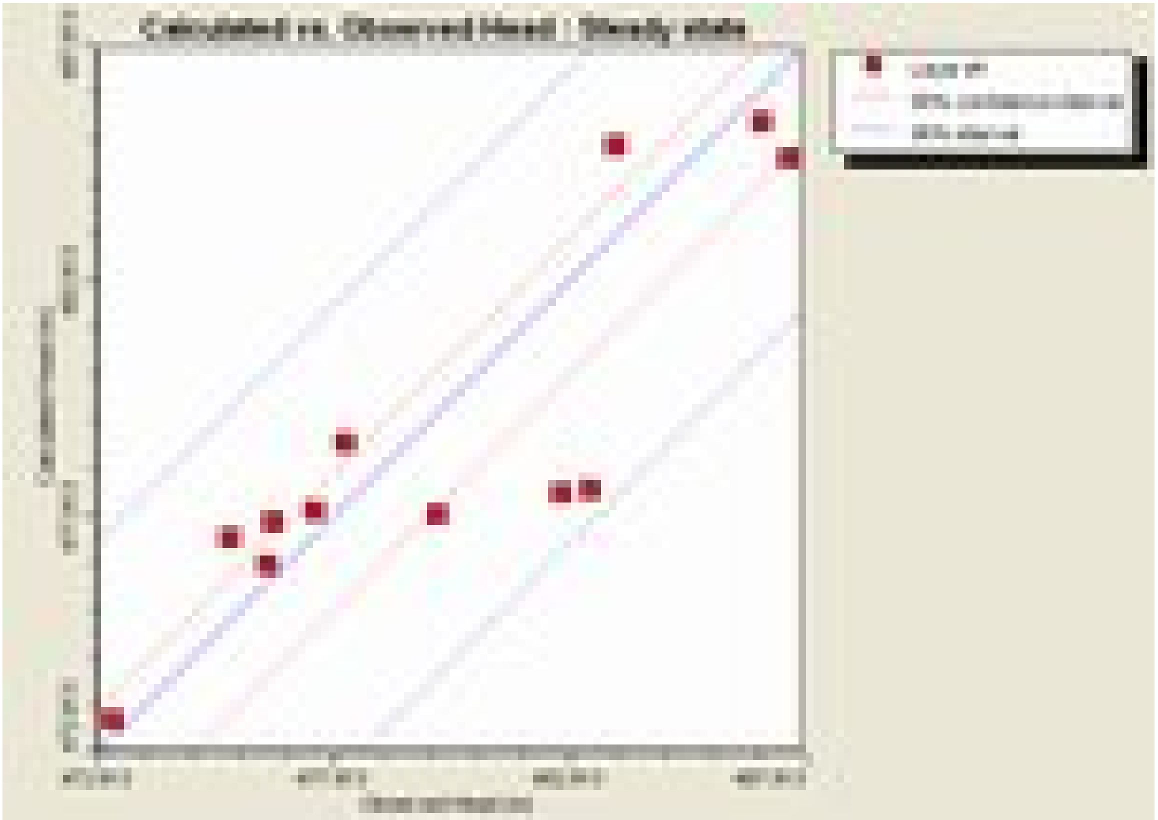

Fig. 29: Comparison between the computed and observed water levels

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

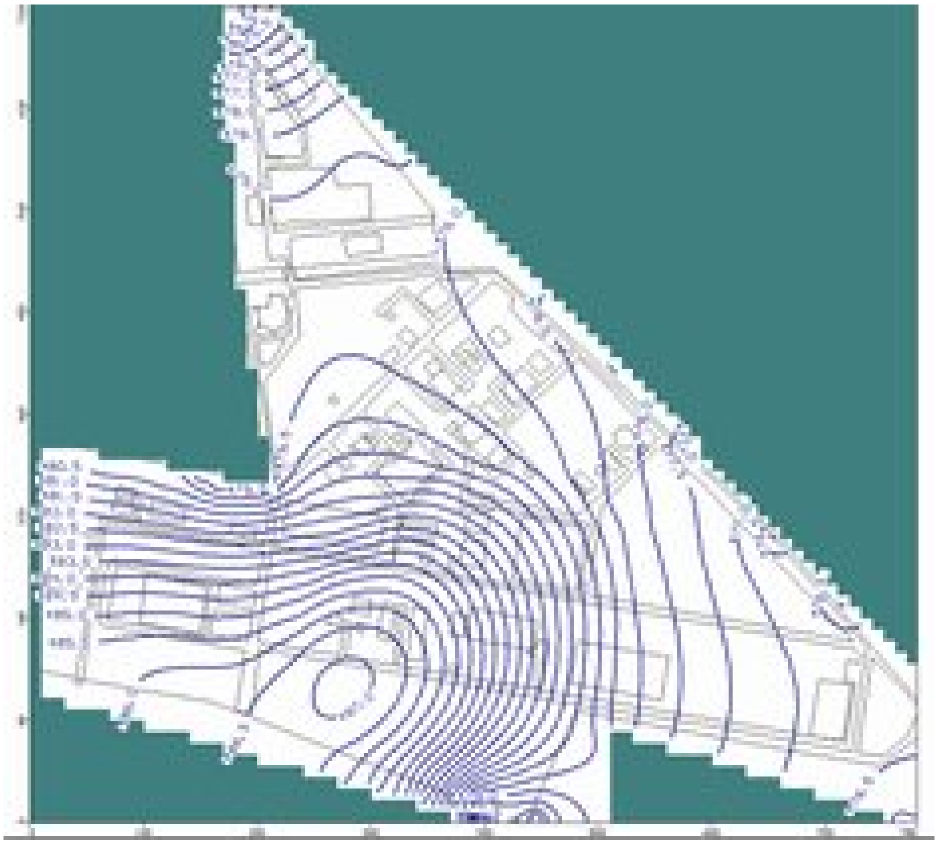

Fig. 30 Simulated potential lines

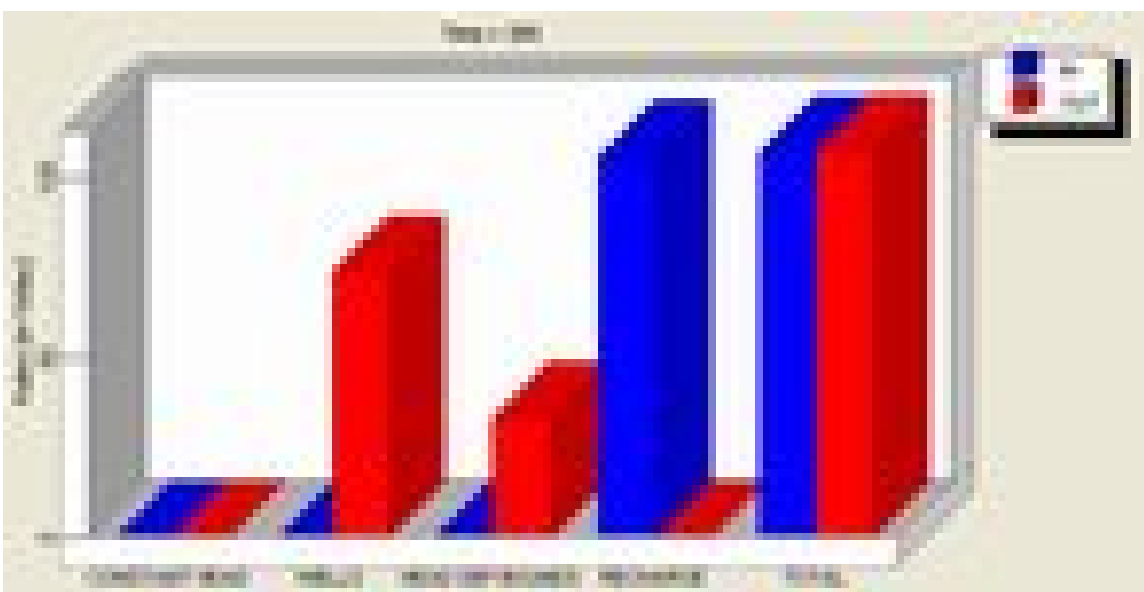

Fig. 31 Mass budget for the model

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.

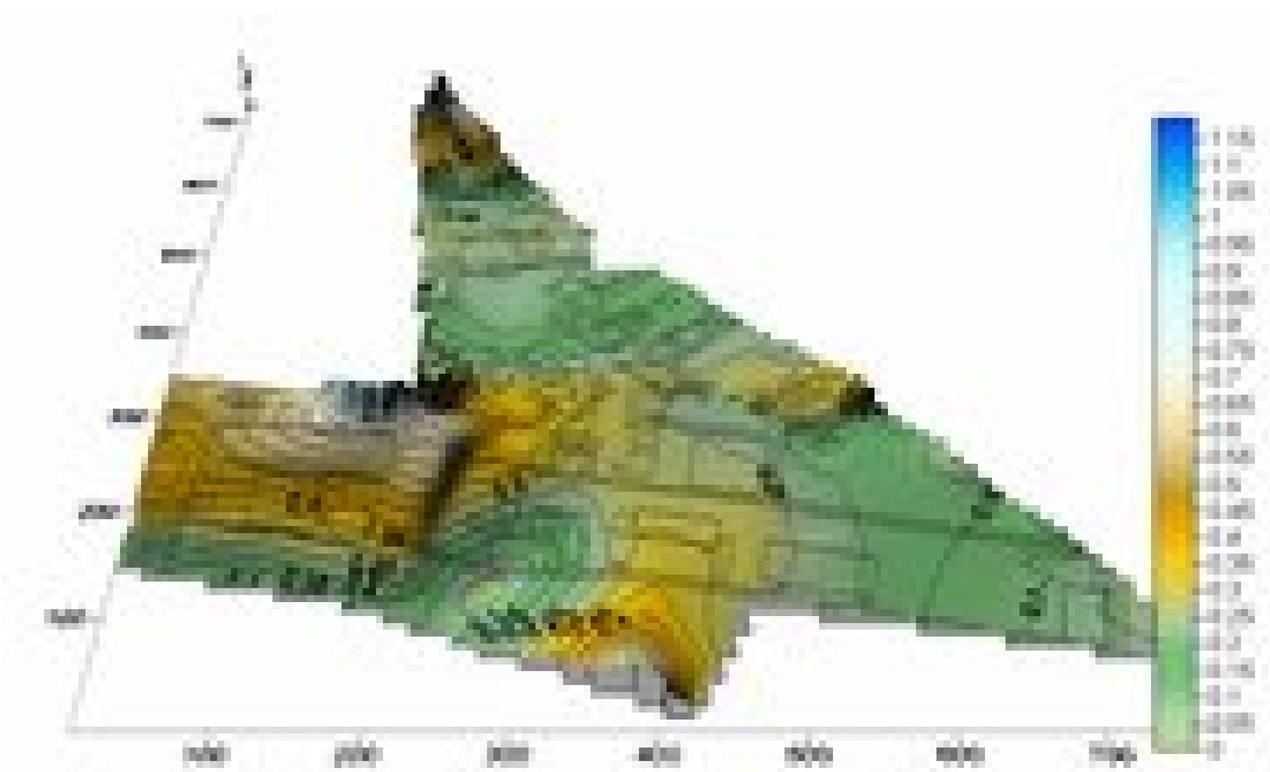

Fig. 32: Groundwater velocity for the month of February 2010.

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.

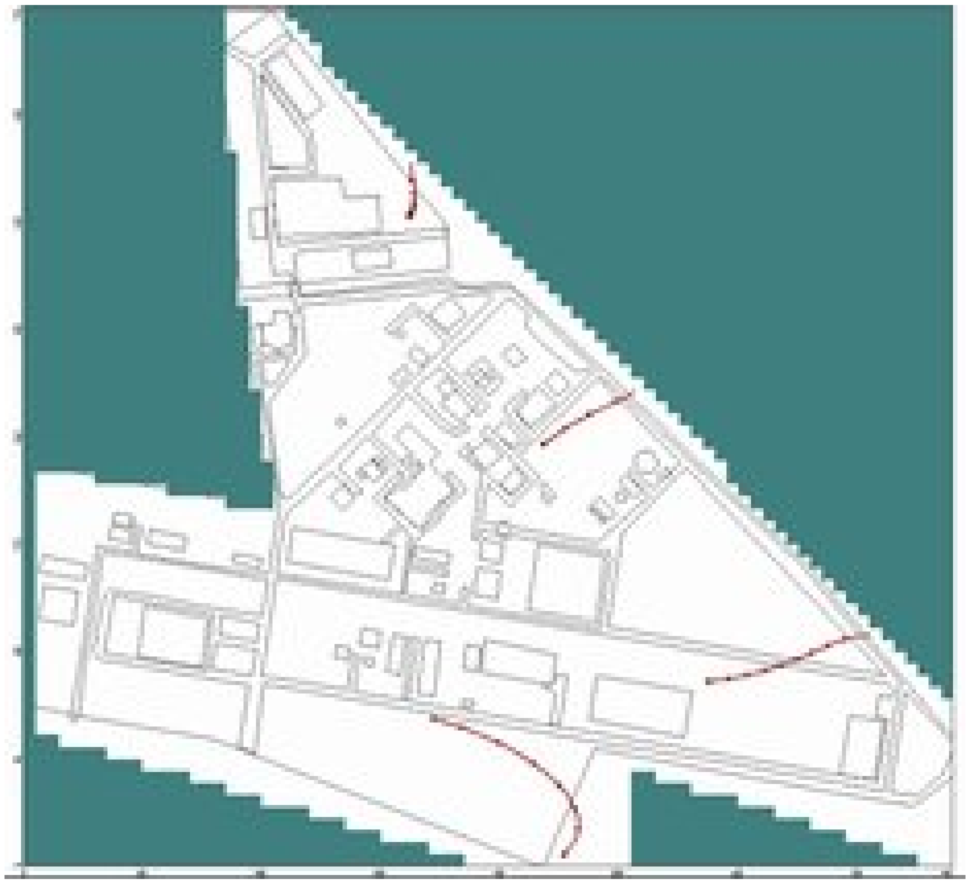

Fig. 33 Particle tracking in different zones

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.

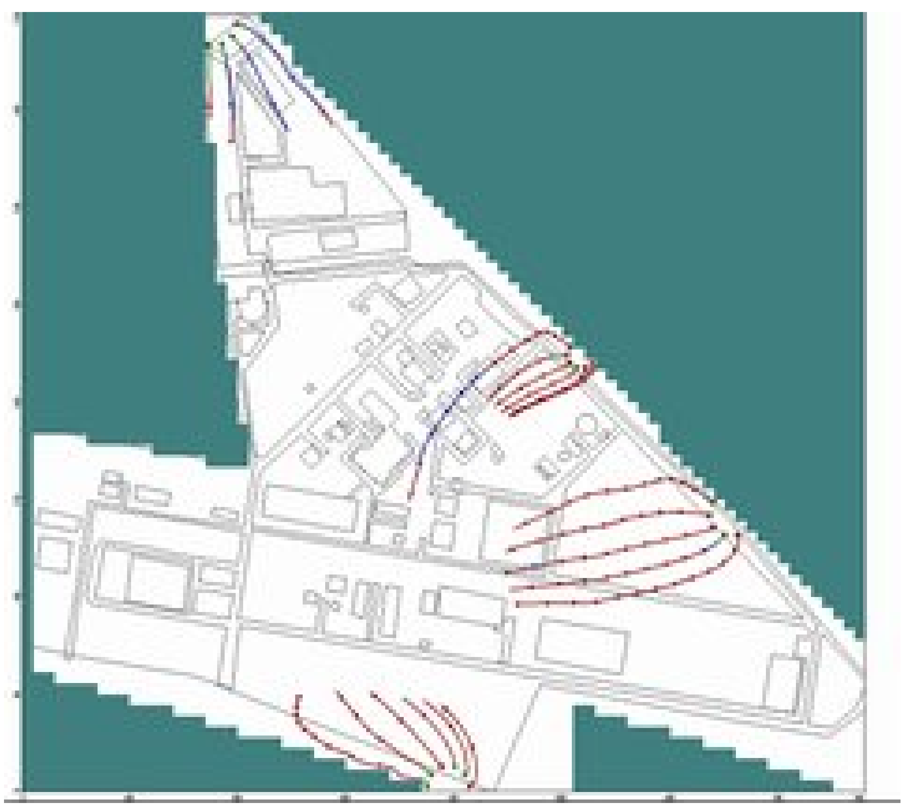

Fig. 34 Well head capture zone at 4 locations

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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