Sapna Johnson, Ramakant Sahu,
Nimisha Jadon, Clara Duca
Pollution Monitoring Laboratory (PML)
Centre for Science and Environment (CSE)
New Delhi (India)
sapnajohnson06@yahoo.co.in

CONTAMINATION OF SOIL AND WATER IN AND AROUND THE UNION CARBIDE SITE AT BHOPAL

The Union Carbide India Ltd (UCIL) factory at Bhopal, abandoned after the world's worst industrial disaster that took place on December 3, 1984, is still heavily contaminated with a range of persistent pollutants. From this study it can be concluded that even after 25 years the residents of the area around UCIL factory are still exposed to chemical-laced groundwater, soil and factory wastes and perhaps will continue to be exposed until the site remains contaminated.

The city of Bhopal in Madhya Pradesh, India suffered the world's worst ever industrial disaster on December 3, 1984, when around 500,000 inhabitants were exposed to Methyl Isocyanate (MIC) released from the Union Carbide India Ltd (UCIL) pesticides factory and about 3,000 to 20,000 people died. The UCIL manufactured carbaryl, aldicarb and sevidol - a formulation of carbaryl and gamma-hexachlorocyclohexane (γ-HCH) [1-5]. The factory now closed and abandoned, still remains heavily contaminated with a range of persistent pollutants including dumped pesticides, chlorinated hydrocarbons and heavy metals etc., according to reports by NEERI, Greenpeace and others [6-10].

Organic and metallic contaminants still remain in the soil of the site and in piles of waste around the site that have leaked into the groundwater over the years and now contaminate the wells that serve thousands of people living nearby and most of these compounds are known to cause adverse effects on humans and other living organisms [11-17].
A study was therefore undertaken to assess the extent of chemical contamination of soil and water at UCIL factory and adjoining residential areas 25 years after the accident from chlorinated benzene compounds, organochlorines and carbamate pesticides and heavy metals - toxic chemicals that were either used as ingredients of the products or the wastes generated or the products of the plant.

Tab. 1 - Details of sites for collection of soil samples

S. No.	Sample Code	Site of Collection
1	S1	Waste storage shed of UCIL taken from the sack adjacent to the wall marked D/A 24
2	S2	Outside the pond in the dump site within UCIL's premises
3	S3	Inside the pond in the dump site within UCIL's premises
4	S4	From the corner plot of the dump site (now being used as playground) within UCIL's premises
5	S5	From the Sevidol formulation plant
6	S6	From the pilot plant pit (adjacent to the boundary wall) near Temik Plant
7	S7	From the ground floor of the Sevin Plant
8	S8	From Solar Evaporation Pond of UCIL, parallel to the under-construction flyover

All samples were collected in transparent polythene bags labeled and sealed. All samples were stored at 6 °C, and out of direct sunlight, from the time of collection till analysis.

Experimental

Sampling

Eight soil and twelve water samples from inside and outside the UCIL factory were collected on October 28-29, 2009. Details of the samples are given in Tab. 1 and 2 and Fig. 1 and 2.

All soil samples were taken at a depth of 20-30 cm from the surface in transparent polythene bags, labeled and sealed. All water samples were collected in polypet bottles and stored in boxes with dry ice, and out of direct sunlight, from the time of collection through analysis.

As carbamates are sensitive to alkaline hydrolysis and heat, due to the extreme instability of carbamates in alkaline media, samples of water were preserved immediately after collection by acidifying to pH 4-5 with 0.1 N chloroacetic acid. Samples for heavy metal analysis were preserved by acidifying to pH <2 with HNO_3.

Chemicals & Standards

Analytical standards of organochlorine and carbamate pesticides were obtained from Sigma Chemicals USA. Heavy metal standards were purchased from E-Merck. All the solvents used were of HPLC grade and chemicals used for the analysis were purchased from E-Merck and were A.R. grade.

Tab. 2 - Details of sites for collection of water samples

S. No.	Sample Code	Site of Collection
1	W1	From the pond in the dump site within UCIL's premises
2	W2	Hand pump in front of Leelabai's shop, Atal Ayub Nagar (10 m behind the UCIL's wall)
3	W3	Hand pump in front of Safiq Kirana store, New Arif Nagar (400 m behind UCIL's wall)
4	W4	Tube well adjacent to the Masjid (in front of Sharif Khan Bardanewale's house),Nawab Nagar
5	W5	From the pipeline connected to the Tube well near Kirana Store of Guddu Bhai, Annu Nagar
6	W6	Tube well inside the house of Dildar Khan, Blue Moon Colony
7	W7	Hand Pump near the house of Jagdish Prasad Mishra, Annu Nagar
8	W8	Hand pump near temple, Dayanand Sundar Nagar
9	W9	Tube well in front of Durga Mandir, Garib Nagar (Chand Bari)
10	W10	Hand puTube well in front of Durga Mandir, Garib Nagar (Chand Bari)mp near temple, Dayanand Sundar Nagar
11	W11	Hand pump near Chaurasia Samaj Mandir, Shiv Nagar
12	W12	Dug Well in Gali No. 2, J. P. Nagar (Near Hazra Bi house)

Samples were collected in separate bottles for organochlorines, carbamates and heavy metals.
For carbamate analysis water samples were preserved by acidifying to pH 4 - 5 with 0.1 N chloroacetic acid.
For heavy metal analysis water samples were preserved by acidifying with nitric acid to pH<2.
All samples were stored in dry ice box, and out of direct sunlight, from the time of collection till analysis.

Equipments

Thermoquest-Trace GC with the ^{63}Ni selective Electron-Capture Detector, GC column: DB-5, J&W make (30m x 0.25mm x 0.25 μm), GC-MS Model Finnigan Polaris Q Ion trap, HPLC Agilent technologies (1100 series) equipped with fluorescence detector and post column derivatization unit, HPLC column: Zorbax ODS column - 5 μm, 4.6mm x 250mm, 10 μL and 50 μL syringes from Hamilton Co., Atomic Absorption Spectrometer (Thermo) Solar M-6 Series, Rotary evaporator (Buchi type) etc.

Procedure

Samples were analyzed for 5 chlorinated benzenes, 4 organochlorines, 2 carbamate pesticides and 5 heavy metals according to United States Environment Protection Agency (USEPA) protocols.

Tab. 3 - Recovery data of chlorinated benzenes and isomers of HCH in soil and water samples

S. No.	Compound	Acronym	Retention time (R_t) min	Water *		Soil*	
				%Recovery	%RSD	%Recovery	%RSD
1	1,2-Dichlorobenzene	1,2-DCB	12.48	83	7	80	6
2	1,3-Dichlorobenzene	1,3-DCB	11.68	81	8	80	7
3	1,4-Dichlorobenzene	1,4-DCB	11.86	86	5	82	8
4	1,2,3-Trichlorobenzene	1,2,3-TCB	17.18	82	6	86	5
5	Hexachlorobenzene	HCB	21.77	85	4	82	4
6	α-Hexachlorocyclohexane	α-HCH	21.68	92	3	86	4
7	β-Hexachlorocyclohexane	β-HCH	21.92	85	3	89	2
8	γ-Hexachlorocyclohexane	γ-HCH	22.00	95	6	84	5
9	δ-Hexachlorocyclohexane	δ-HCH	22.21	90	5	90	4

*spiked at concentration of 5-10 μgL^{-1} - **spiked at concentration of 250-500 μgkg^{-1}

Sample preparation

Chlorinated benzene compounds and organochlorines - Soil samples were extracted with methylene chloride-acetone (1:1) by Soxhlet extraction (EPA Method 3540) and water samples were extracted at neutral pH with methylene chloride using separatory funnel (EPA Method 3510). Cleanup was done by Florisil column method (EPA Method 3620). After cleanup, the extract was analyzed by injecting 2 μL of aliquot into GC equipped with a narrow-bore fused-silica capillary column (DB-5)

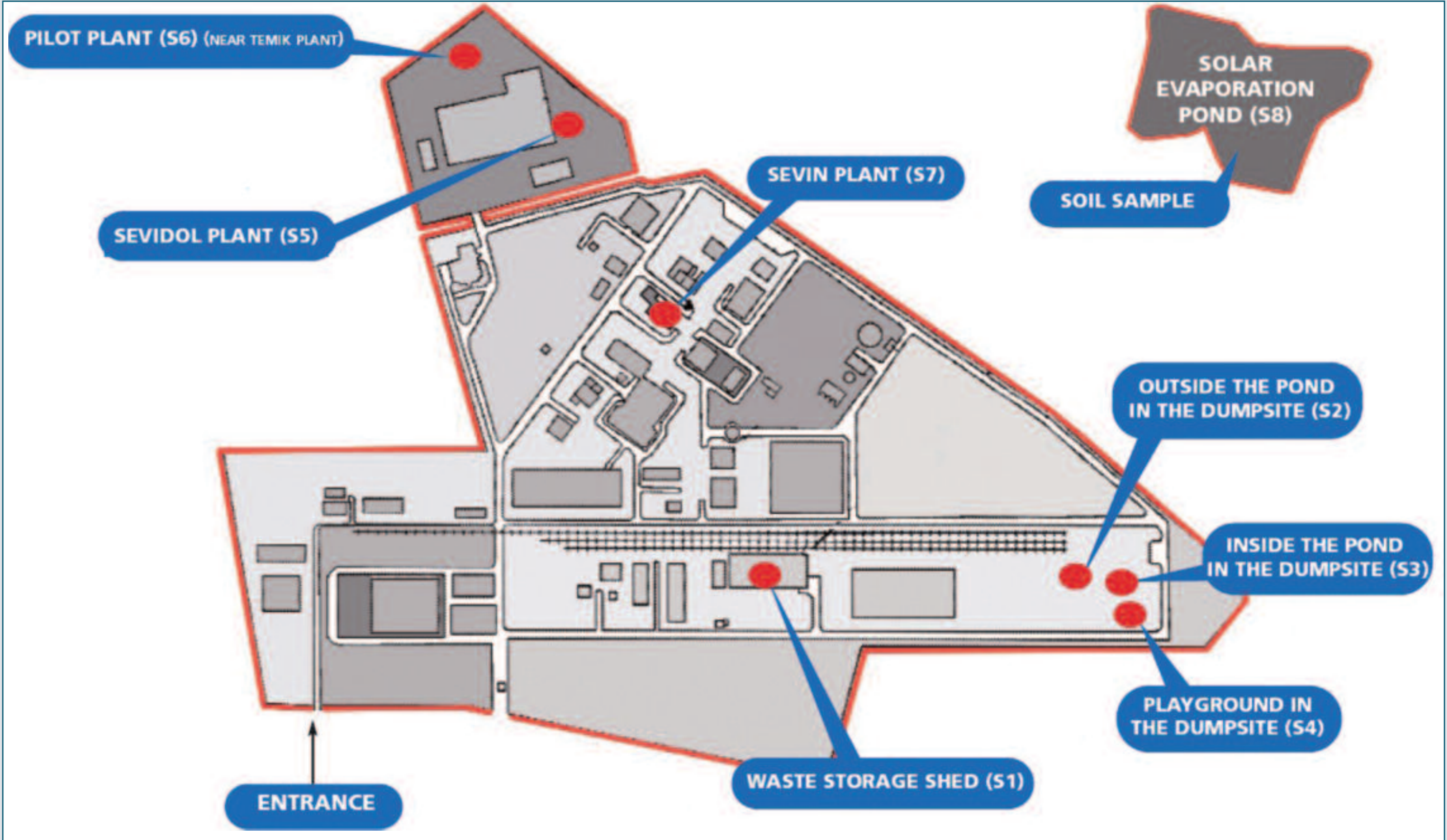


Fig. 1 - Map of the sampling sites inside the UCIL premises from where soil samples (S1 to S8) were collected

and ECD (EPA Method 8081B). Detector temperature: 300 °C, injector temperature: 250 °C, oven temperature: 50 °C (hold 4 minutes) to 120 °C at 6 °C/min; then 120 °C to 275 °C (hold 3 minute) at 25 °C/min, carrier gas: nitrogen at 1 mL/min. Peak identification was performed by the GC software (Chromcard-32 bit ver. 1.06 October 98) with calibration table set up with a relative retention time window of 0.65%. Identification of compounds was performed by comparing the retention time (R_t) of the samples' GC-peaks with the R_t of the pesticide standards (Tab. 3). The compounds present in high concentrations were analyzed after appropriate dilution of the sample extracts with hexane. The calibration curves for all chlorinated benzenes & isomers of HCH were prepared at concentration of 0.1-2.0 μg/mL and were linear (R^2 ≥0.999) in the investigated

Fig. 2 - Map of the sampling sites inside and outside the UCIL premises from where water samples (W1 to W12) were collected

Tab. 4 - Characteristic ions obtained on GC-MS for chlorinated benzenes and organochlorine pesticides

S. No.	Compound	Acronym	CAS	Molecular Weight	Primary ion	Secondary ion	Retention time (min)
1	1,2-Dichlorobenzene	1,2-DCB	95-50-1	147	180	182, 145	10.09
2	1,3-Dichlorobenzene	1,3-DCB	541-72-1	147	146	148, 111	9.33
3	1,4-Dichlorobenzene	1,4-DCB	106-46-7	147	146	148, 111	9.61
4	1,2,3-Trichlorobenzene	1,2,3-TCB	87-61-6	181.45	180	182, 145	14.8
5	Hexachlorobenzene	HCB	118-74-1	284.78	284	142, 249	20.90
6	α-Hexachlorocyclohexane	α-HCH	319-84-6	290.83	183	181, 109	20.88
7	β-Hexachlorocyclohexane	β-HCH	319-85-7	290.83	181	183, 109	21.15
8	γ-Hexachlorocyclohexane	γ-HCH	58-89-9	290.83	183	181, 109	21.24
9	δ-Hexachlorocyclohexane	δ-HCH	319-86-8	290.83	183	181, 109	21.52

concentration range. The detection limit for chlorinated benzenes and isomers of HCH was 0.5 μgL^{-1} and 0.1 μgL^{-1} respectively.

The reliability of the method (stability of the retention time, calibration range, recovery, repeatability, etc.) was checked and found to be satisfactory for the analyses. The retention times (R_t) of the compounds were stable throughout the study, with a maximum variation of 1%. Recovery studies were performed by fortifying the control soil and water samples before extraction in order to work out the efficiency of the analytical technique. The mean percentage recovery of all the chlorinated benzenes and organochlorine compounds under the experimental conditions was more than 80% (n=5) (Tab. 3). Each sample was analysed in triplicate and the relative standard deviation (RSD) for the determination of all the compounds was within 10%.

Carbamates - Two carbamates, carbaryl and aldicarb, were analysed by HPLC using the post-column fluorescence (EPA method 8318A). Carbamates were extracted from soil samples with acetonitrile on a platform shaker and clean up was done with C18 reverse phase cartridges. Water samples were extracted with methylene chloride using separatory funnel (EPA Method 3510). Final samples were filtered through 0.45 μm filters and 20 μL of the extract was injected into HPLC. After elution from the column, the analytes were hydrolyzed in a post column reaction with sodium hydroxide at 95 °C to form methyl amine. Methyl amine was reacted with *o*-phthalaldehyde (OPA) and 2-mercaptoethanol (or N,N-dimethyl-2-mercaptoethylamine) to form a highly fluorescent isoindole which is detected by a fluorescence detector. Calibration curves for carbaryl and aldicarb were prepared at the concentrations of 0.1-5 μgmL^{-1} and were found to be linear ($R^2 \geq 0.999$). Different components of the samples were compared with standards (retention time, area count) and analytes were quantitated using the external standard technique. The detection limit of carbamates was 0.05 μgmL^{-1}. Each sample was analysed in triplicate and the relative

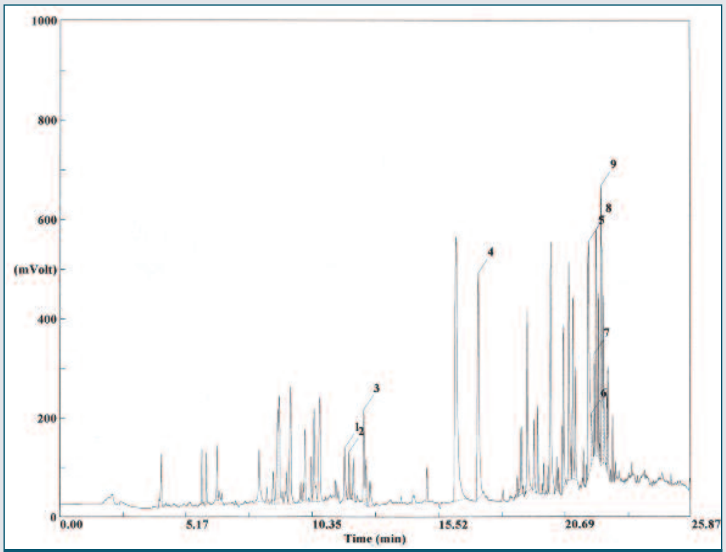


Fig. 3 - Gas chromatogram of soil sample (S-05) showing chlorinated benzenes and isomers of HCH where 1 =1,3-DCB, 2 = 1,4-DCB, 3 = 1,2-DCB, 4 = 1,2, 3-TCB, 5 = α-HCH, 6 = HCB, 7 = β-HCH, 8 = γ-HCH, 9 = δ-HCH

Tab. 5 - Chlorinated benzenes, Organochlorine and Carbamates in Soil Samples (mgkg^{-1}± SD)

S. No.	Class	Compound	Residues (mgkg^{-1}±SD)							
			S1	S2	S3	S4	S5	S6	S7	S8
1	Chlorinated Benzene	1,3-DCB	0.7±0.1	113±2	2.0±0.4	112±0.7	490±0.5	29±0.7	8.0±0.6	0.5±0.2
2	Chlorinated Benzene	1,4-DCB	0.9±0.3	64±1.8	0.6±0.15	109±0.3	542±1.2	83±2.0	8.0±0.8	0.6±0.1
3	Chlorinated Benzene	1,2-DCB	2.4±0.5	21±0.5	BDL*	16.5±0.3	1017±1.5	21±0.8	11±1.2	0.1±0.02
4	Chlorinated Benzene	1,2,3-TCB	1.3±0.3	6.5±0.3	BDL	105±1.3	508±1.2	5.0±0.6	24±1.6	0.1±0.03
5	Chlorinated Benzene	HCB	0.4±0.4	51±0.4	4.6±0.2	5.2±0.9	1.1±0.2	1.7±0.1	12±1.5	1.3±0.2
6	Organochlorine	α-HCH	0.4±0.1	130±1.5	8.7±0.3	116±0.6	114±0.5	77±1.4	72±1.0	3.4±0.2
7	Organochlorine	β-HCH	1.1±0.2	171±1.2	29.7±1.8	239±0.8	111±0.5	48±0.5	63±1.0	4.3±0.2
8	Organochlorine	γ-HCH	0.2±0.05	556±1.3	45±0.3	702±0.6	2782±0.4	264±1.4	198±0.3	10±0.8
9	Organochlorine	δ-HCH	0.7±0.1	206±1.8	15±0.4	105±0.3	112±1.8	102±1.6	80±0.4	1.7±0.2
10	Carbamate	Carbaryl	9859±1.9	BDL	BDL	BDL	191±1.5	BDL	BDL	BDL
11	Carbamate	Aldicarb	BDL	116±1.6	BDL	56±1.2	7.5±0.8	BDL	BDL	BDL

**BDL- Below Detection Limit - SD -Standard Deviation*

Tab. 6 - Heavy Metals in Soil Samples (mgkg^{-1}±SD)

S. No.	Sample Code	Arsenic	Mercury	Lead	Cadmium	Chromium
1	S1	0.7±0.1	1065±1.5	23±1.3	BDL*	86±1.4
2	S2	2.0±0.5	BDL	46±1.4	BDL	71±1.2
3	S3	1.2±0.1	BDL	17±1.2	BDL	74±1.4
4	S4	0.5±0.1	BDL	5.0±1.3	BDL	18±1.3
5	S5	3.1±0.05	BDL	BDL	BDL	108±1.9
6	S6	0.5±0.1	74±1.2	112±1.5	BDL	298±2
7	S7	2.8±0.2	8188±1.6	84±1.3	BDL	192±1.3
8	S8	1.1±0.05	18±1.4	22±1.2	BDL	1065±1.5

**BDL - Below Detection Limit - SD - Standard Deviation*

standard deviation (RSD) for the determination of all the compounds was within 10%. Recovery studies were performed by fortifying the control water and soil samples at a concentration of 300 μgL^{-1}and 1 mgkg^{-1} respectively. The mean percentage recovery of carbamates in water and soil was 87% and 85% (n=5) respectively. Analysis was done under following conditions:

- *solvents and flow rate:* solvent A: reagent water, acidified with 0.4 mL of phosphoric acid per liter of water, solvent B: methanol/acetonitrile (30:70, v/v), flow rate: 0.5 mL/min, injection volume: 20 μL;
- *hydrolysis parameters:* solution: 0.05 N aqueous sodium hydroxide, flow rate: 0.3 mL/min, temperature: 95 °C;
- *post-column derivatization parameters:* solution: *o*-phthalaldehyde/2-mercaptoethanol, flow rate: 0.3 mL/min, temperature: 37 °C;
- *fluorescence detector parameters:* excitation wavelength: 340 nm, emission wavelength: 418 nm cut off filter. The retention times of aldicarb and carbaryl were 9.36 and 9.6 min respectively.

Confirmation by GC-MS - The identity of pesticides detected in the samples by GC-ECD was confirmed by GC-MS (Method 8270C), Model Finnigan Polaris Q Ion trap GC/MS with EI ionization (70eV), in full scan mode. The analytes were identified by their: (a) characteristic retention time; (b) primary ion; and, (c) secondary ions to increase specificity. The samples were injected using a programmable temperature injector (PTV) in a capillary column DB-5 MS (30m x 0.25 mm x 0.25 μm). Injector temperature: 250 °C, oven temperature: 50 °C (hold 4 minutes) to 120 °C at 6 °C/min; then 120 °C to 275 °C (hold 3 minute) at 25 °C/min, carrier gas: helium at 1 mL/min, run time: 25.9 minute, 2.0 μL of the final extract was injected at a temperature of 250 °C keeping the ion source at 200 °C; multiplier: 1100 volts; AGC: 50, 3 microscan; default: tune parameters: autotune tune file. mass range: 50-650 m/z, solvent delay 4 minutes.

The identity of chlorinated benzenes and organochlorines detected in water and soil samples was confirmed by GC-MS. Characteristic ions - primary and secondary and the retention time for chlorinated benzenes and organochlorines detected in samples from Bhopal are given in Tab. 4.

Digestion and analysis of heavy metals by AAS - For the determination of heavy metals in soil and water samples, digestion was done according to the EPA methods and then analysed in Atomic Absorption Spectrometer (AAS). Lead, cadmium and chromium were analysed by AAS -flame technique and mercury and arsenic by AAS -vapour technique using borohydride reduction. Air-acetylene flame was used for the determination of lead and cadmium, while nitrous oxide-acetylene flame was used for the determination of chromium. The calibration curves for the determination of lead, cadmium, chromium, mercury and arsenic were prepared by using different concentrations from the stock standard solution (1000 μgml^{-1}). A calibration graph of absorbance vs. solution concentration was prepared. Aspirated the standard for every 10 samples to check the instrument drift. The standards, samples, and blanks were aspirated and absorbance recorded. The sample solution was diluted with distilled

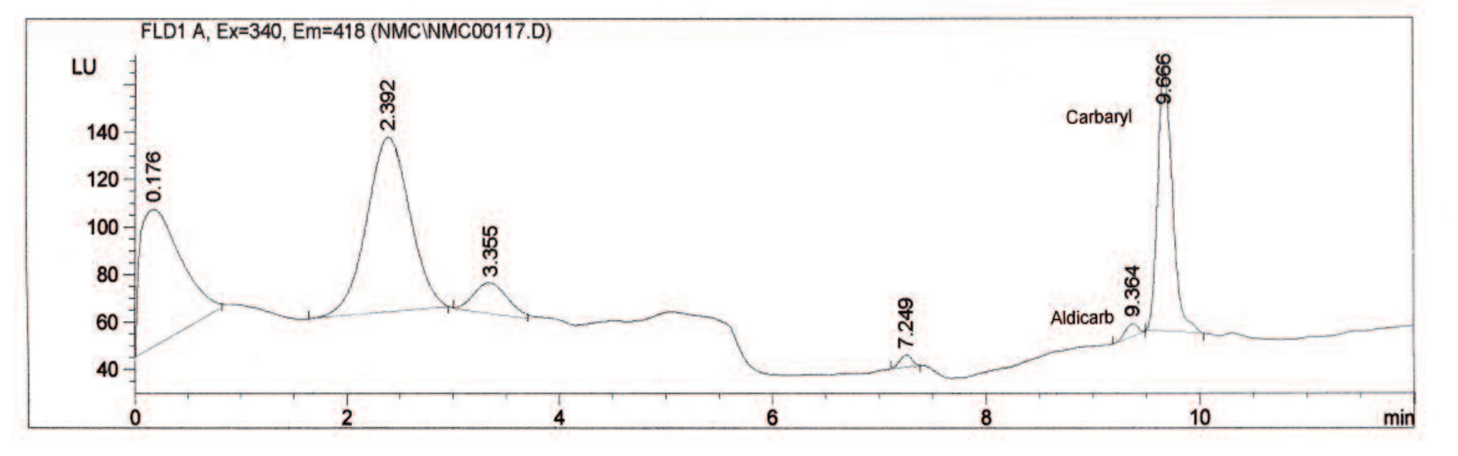


Fig. 4 - HPLC- Chromatogram of soil sample (S-05) showing the presence of carbamates

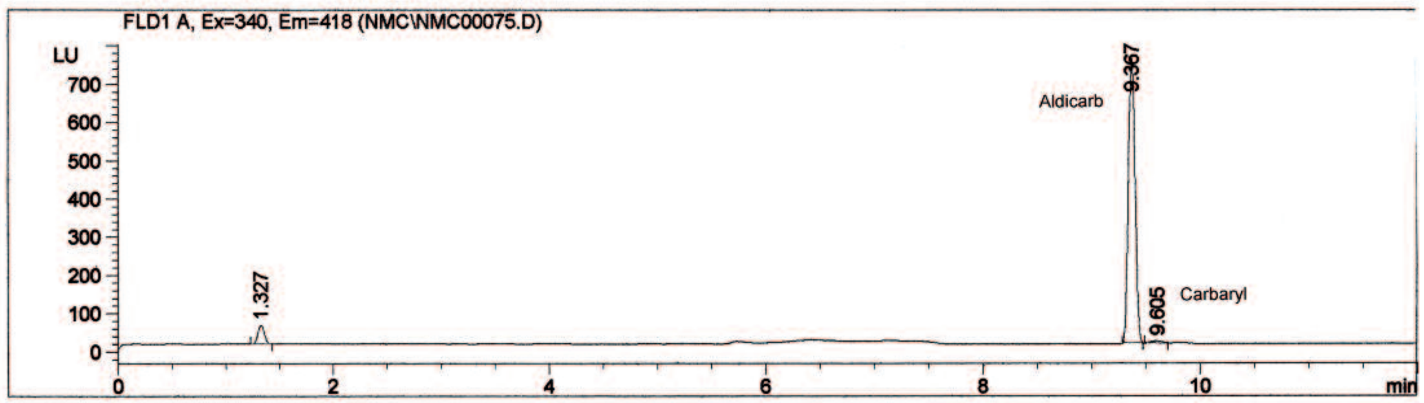


Fig. 5 - HPLC- chromatogram of water sample (W-01) showing the presence of carbamates

water appropriately to ensure that the measurements are taken within the equipment linear dynamic range. Linearity was found to be good (R^2=0.99) for all five heavy metals by calibration curve method. The detection limit for heavy metals - arsenic and mercury by AAS - Cold Vapor technique was 0.002 mgL^{-1} and for lead, cadmium and chromium by AAS -flame technique was 0.5, 0.04 and 0.25 mgL^{-1}, respectively . Recovery studies were carried out for heavy metals by 5 independent measurements and found to be more than 90% in both soil and water samples.

Results and discussion

The results show a widespread contamination of the plant site and the groundwater of the surrounding areas.

Contamination within the factory premises

One stored waste sample, six soil samples and one surface water sample within the factory premises and one soil sample from the waste disposal site (solar evaporation pond) clearly show that the land within the UCIL factory and the waste disposal site is highly contaminated with pesticides, chlorinated benzenes and heavy metals.

Waste sample from Waste storage Shed (S1)

The waste stored within the UCIL-premises contained all chlorinated benzene compounds investigated and all organochlorine pesticides tested. The carbaryl content in this sample was as high as 9859 mgkg^{-1}. Among chlorinated benzenes 1,2-dichlorobenzene was detected at a concentration of 2.4 mgkg^{-1}. γ-HCH was detected at a concentration of 0.2 mgkg^{-1}. β-HCH the most persistent isomer was detected at a concentration of 1.1 mgkg^{-1} (Tab. 5). This sample also had 4 out of the 5 heavy metals tested. The mercury content was as high as 1065 mgkg^{-1} (Tab. 6).

Soil samples from within the factory premises (S2-S7)

HCH and its isomers, HCB, 1,3-dichlorobenzene and 1,4-dichlorobenzene were detected in all soil samples. In five soil samples 1,2-dichlorobenzene and 1,2,3-trichlorobenzene were found. Aldicarb was detected in three and carbaryl in one soil sample (Tab. 5). γ-HCH (lindane) was detected in the soil sample within the premises ranging from 45 mgkg^{-1} (S3 - outside the pond in the dump site within UCIL's

Tab. 7 - Chlorinated benzenes, organochlorine and carbamate pesticides in water samples (µgL^{-1}±SD).

Class	Compound	Residues (µgL^{-1})											
		W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12
Chlorinated Benzene	1,3-DCB	0.4±0.05	0.2±0.1	0.2±0.01	0.1±0.03	BDL*	0.2±0.01	0.2±0.02	0.2±0.03	0.2±0.02	0.2±0.02	0.8±0.03	0.2±0.02
Chlorinated Benzene	1,4-DCB	0.4±0.03	0.3±0.1	BDL	0.2±0.02	BDL	0.3±0.05	0.2±0.01	0.2±0.02	0.3±0.01	0.2±0.01	2.5±0.2	0.4±0.01
Chlorinated Benzene	1,2-DCB	BDL	BDL	BDL	BDL	BDL	0.2±0.08	BDL	BDL	0.4±0.02	0.1±0.02	0.2±0.02	0.2±0.03
Chlorinated Benzene	1,2,3-TCB	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.2±0.02	0.1±0.01	0.2±0.01	0.2±0.01
Chlorinated Benzene	HCB	1.3±0.2	BDL	0.1±0.02	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.1±0.01	BDL
Organochlorine	α-HCH	6.4±0.9	0.2±0.03	0.1±0.02	BDL	0.1±0.01	BDL	BDL	0.1±0.02	0.1±0.01	0.1±0.02	0.2±0.02	0.6±0.1
Organochlorine	β-HCH	6.0±0.5	0.3±0.08	0.2±0.03	BDL	BDL	BDL	1.0±0.08	0.1±0.03	0.1±0.02	0.4±0.1	0.1±0.01	0.4±0.03
Organochlorine	γ-HCH	0.3±0.1	0.4±0.1	0.1±0.01	0.3±0.02	0.3±0.01	0.5±0.1	0.3±0.01	0.5±0.02	1.1±0.1	1.0±0.2	3.8±0.02	1.9±0.1
Organochlorine	δ-HCH	3.0±0.2	0.2±0.05	0.8±0.1	0.1±0.03	0.1±0.02	0.1±0.01	0.4±0.02	0.1±0.01	0.1±0.03	0.2±0.05	0.1±0.03	0.2±0.05
Carbamate	Carbaryl	3.0±0.1	0.8±0.2	28±1.2	BDL	BDL	0.2±0.02	BDL	BDL	BDL	BDL	11.3±0.4	BDL
Carbamate	Aldicarb	260±1.8	BDL	0.5±0.1	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL

**BDL - Below Detection Limit - SD - Standard Deviation* premises) to 2782 mgkg^{-1} (S 5- sevidol formulation plant). Among chlorinated benzenes - 1,2-dichlorobenzene in the soil sample from the sevidol formulation plant (S5) was 1017 mgkg^{-1} (Fig. 3).

Among the carbamates highest concentration was detected in the soil sample collected from sevidol formulation plant (S5). Aldicarb was detected at a concentration of 7.5 mgkg^{-1} and carbaryl at 191 mgkg^{-1} (Fig. 4).

Arsenic and chromium were found in all soil samples whereas mercury was present in two samples and lead in five out of six samples. Cadmium was not detected in any sample. Chromium was found in the range of 18 mgkg^{-1} - 298 mgkg^{-1}. The highest concentration of chromium was found in the pilot plant pit near temik plant (S6) (Tab. 6). Though mercury was found in only two samples, its concentration was quite high. In the soil sample collected from the floor of the sevin plant (S7), the concentration of mercury was 8188 mgkg^{-1}. Even at the time of sample collection the droplets of elemental mercury could be seen in the Sevin plant. 3.1.3 Soil Sample from Solar Evaporation Pond (S8). This sample contained all chlorinated benzene compounds and organochlorine pesticides. It also had four out of five heavy metal tested. The chromium content in this sample was 1065 mgkg^{-1}. UCIL was using a chromium coolant and was throwing the cooling water in the solar evaporation pond (Tab. 6).

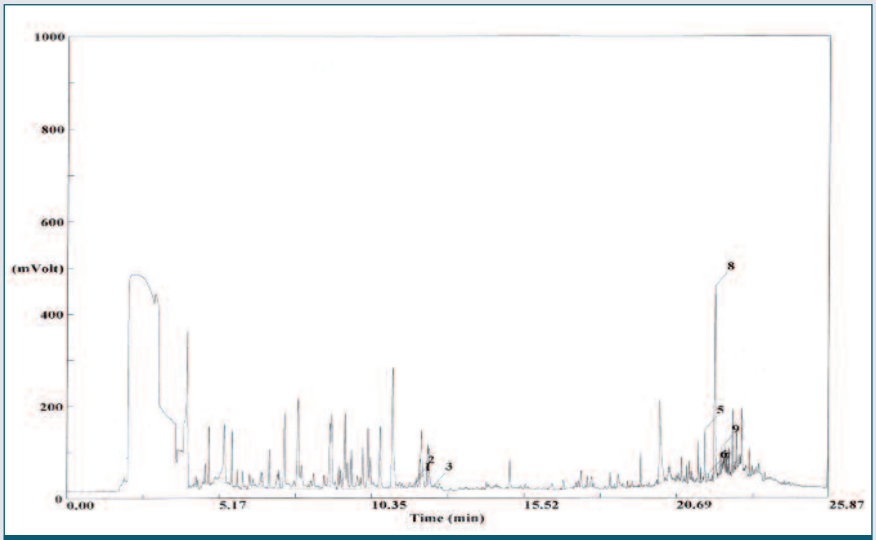


Fig. 6 - Gas chromatogram of water sample (W-11) showing chlorinated benzenes and isomers of HCH where 1 =1,3-DCB, 2 = 1,4-DCB, 3 = 1,2-DCB, 4 = 1,2, 3-TCB, 5 = α-HCH, 6 = HCB, 7 = β-HCH, 8 = γ-HCH, 9 = δ-HCH

Surface Water sample from within the factory premises (W1)

The surface water sample collected within the factory premises had the highest level of contamination of the entire water samples tested. Three chlorinated benzenes and all organochlorines and both carbamate pesticides were detected in this sample. HCH and its isomers were detected at a concentration of 15 μgL^{-1}. α and β isomer were detected at a concentration of 6.4 μgL^{-1} and 6.0 μgL^{-1} respectively (Tab. 7). Aldicarb was detected at a high concentration of 260 μgL^{-1} (Fig. 5).

Water contamination in adjoining areas (W2-W12)

Groundwater samples collected from colonies around the UCIL factory were contaminated with chlorinated benzene compounds and organochlorine pesticides. Carbaryl was found in four ground water samples in the range of 0.2-28 μgL^{-1} (2-280 times the individual pesticide limit of IS: 14543). Aldicarb was detected in only one hand pump sample in front of Safiq Kirana store, New Arif Nagar (400 m behind UCIL's wall) (W3) at a concentration of 0.5 μgL^{-1}.

The concentration of total pesticides found in all water samples was 1.1 to 59.3 times the total limit (0.5 μgL^{-1}) only mandatory water standard in India fixed by the Bureau of Indian Standard (IS:14543). The average concentration in all groundwater samples was 6 μgL^{-1}.The water sample collected from the hand pump near Chaurasia Samaj Mandir in Shiv Nagar (W11) was the most contaminated. It has highest concentration of carbaryl (11.3 μgL^{-1}), lindane (3.8 μgL^{-1}) and mercury (20 μgL^{-1}) (Tab. 7 and 8) and this place is more than 3 km away from the UCIL factory. Fig. 6 shows the presence of pesticide residue in this sample.

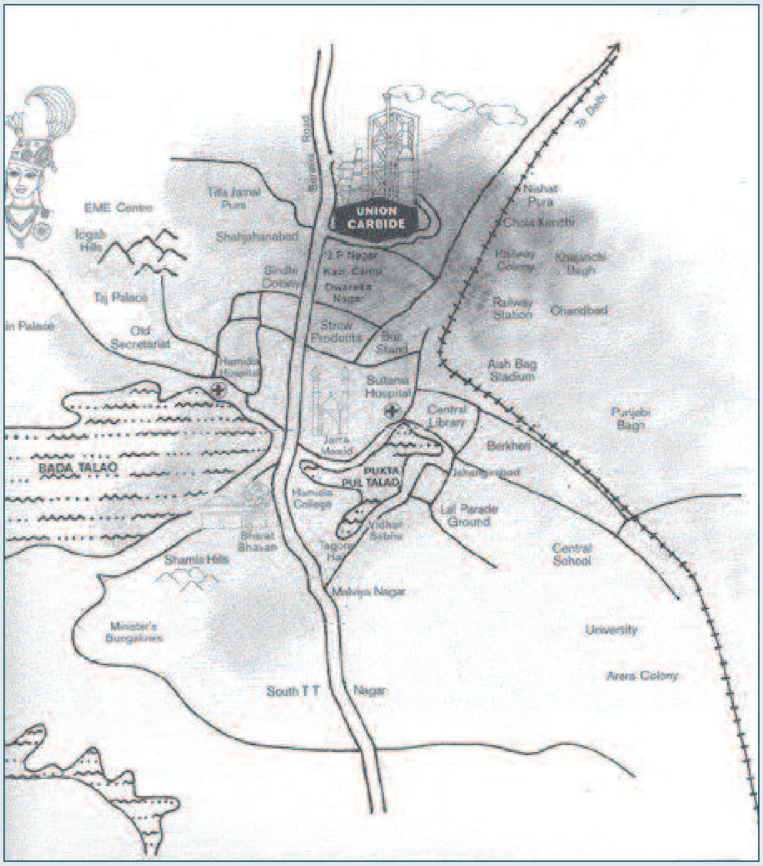
Conclusions

The results clearly show that the area within the UCIL factory and the waste disposal site is highly contaminated with pesticides, chlorinated benzenes and heavy metals. Contaminations as high as 9859 mgkg^{-1} of carbaryl, 2782 mgkg^{-1} of lindane, 8188 mgkg^{-1} of mercury and 1065 mgkg^{-1} of chromium were found in different samples. The average total pesticide concentration in ground water of surrounding areas

Tab. 8 - Heavy metals in water samples (μgL^{-1}±SD)

S. No	Sample Code	Arsenic	Mercury	Lead	Cadmium	Chromium
	Indian Drinking water standard (IS 10500)	50	1	50	10	50*
1	W1	BDL	BDL	BDL	BDL	BDL
2	W2	BDL*	BDL	1200±1.8	100±1.4	BDL
3	W3	BDL	BDL	BDL	BDL	BDL
4	W4	BDL	BDL	BDL	BDL	BDL
5	W5	BDL	BDL	BDL	BDL	BDL
6	W6	BDL	BDL	BDL	BDL	BDL
7	W7	BDL	BDL	BDL	BDL	BDL
8	W8	BDL	BDL	BDL	BDL	BDL
9	W9	BDL	BDL	BDL	BDL	BDL
10	W10	BDL	BDL	BDL	BDL	BDL
11	W11	BDL	20±1.5	BDL	BDL	BDL
12	W12	BDL	BDL	BDL	BDL	BDL

**Standard for hexavalent chromium - *BDL- Below Detection Limit - SD -Standard Deviation*



was 6 μgL^{-1} which is 12 times the permissible levels. The profile of chemicals found within the UCIL factory and in the waste disposal site of UCIL matches the chemicals found in the groundwater sample in the colonies outside the factory premises. Apparently there is no other source of these chlorinated benzene compounds and pesticides then UCIL. The topography of the area also points towards contamination of the groundwater due to the UCIL. The plant is located at a slightly higher altitude than the residential colonies with a gently sloping terrain. Carbamate pesticides, as a general group, are considered to be moderately-persistent in the environment. But finding carbamates in groundwater, 25 years since the plant shut down, clearly means that the elevated UCIL plant contaminated site is acting as a continuous source of groundwater contamination. For more than 25 years (even before the accident took place and just a few years after manufacturing began) the residents of the area have been exposed to chemical-laced groundwater and they will continue to be exposed till the site remains contaminated.

Acknowledgements: The authors are thankful to Ms. Sunita Narain, Director of CSE for providing facilities, valuable advice and encouragement and Mr. Chandra Bhushan (Associate Director of CSE) for help in planning and execution of the work. We also thankfully acknowledge Professors H.B. Mathur, H.C. Agarwal for their technical guidance and encouragement during the investigation.

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RIASSUNTO

Contaminazione del suolo e dell'acqua all'interno e attorno all'area della Union Carbide a Bhopal

Il sito della Union Carbide a Bophal, abbandonato dopo il disastro avvenuto nel dicembre del 1984, è stato oggetto di studio circa la contaminazione del suolo e delle acque. Da questa ricerca si può concludere che a distanza di venticinque anni l'area è tuttora fortemente inquinata.