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Characterization of Volatile Organic Compounds (VOCs) at an Industrial Lagoon in North-West of England, UK

Nwachukwu, Arthur Nwachukwu*

Williamson Research Centre for Molecular Environmental Sciences, School of Earth, Atmospheric and Environmental Sciences, The University of Manchester, UK (M13 9PL)

Corresponding author

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ABSTRACT

Volatile Organic Compounds (VOCs) are among the most common air pollutants emitted from chemical, petrochemical and allied industries. VOCs are one of the main sources of photochemical reaction in the atmosphere leading to various environmental hazards. Growing environmental awareness has put up stringent regulations to control VOC emissions. To heed to these regulations, there is often a requirement to monitor VOC concentrations. In this study we measured and analysed aggregate concentrations of VOC and their individual components at an industrial lagoon in North-West of England. Measurements were conducted at various boreholes on the site; however, for the purpose of this paper only two boreholes were considered, the one closest to the chemical company and one at some distance from it. The aggregate concentrations of VOCs were obtained using an in-borehole gas monitor called *Gasclam* whilst a *Tenax TA* sorbent tube incorporated into and to work in parallel with this instrumentation was used to adsorb bulk concentration of VOCs and subsequently desorbed (for characterisation) using thermal desorption/gas chromatography-mass spectroscopy (TD/GC-MS) technique. Gasclam results show VOCs in the borehole closer to the chemical company to exhibit a broader range and have higher average concentrations. The values range from 169 ppm to 1964 ppm for the former borehole and 168 ppm–3974 ppm in the latter borehole. Whilst the former has average VOCs concentration of 846 ppm; the latter has 2241 ppm as its average over the monitoring period. The total concentration of adsorbed VOCs in Borehole 1 is 2.38x 10^2mg/m^3 whilst in Borehole 2; it is 2.42x 10^2mg/m^3. Among the identified VOCs are those considered to be hazardous to health such as tetrachloroethylene, trichloroethylene, chloroethylene, toluene, chlorofluorobenzene, benzene, xylene, and ethylbenzene. However, this site does not constitute an immediate health risk as there is no available exposure pathway and a receptor.

Introduction

Volatile organic compounds (VOCs) are a group of organic compounds containing one or more carbon atoms and whose vapour pressures are high enough to cause them to readily volatilise into the atmosphere conditions (Pankow, 1987; U.S. EPA, 1992). VOC emissions result from natural and anthropogenic (man-made) sources. Natural sources of VOCs include vegetation, forest fires and animals (Lemieux *et al.*, 2004; Buzcu and Fraser, 2006). Although natural sources of VOC emissions are more overall (Guenther *et al.*, 1995), there are anthropogenic sources in populated and industrialized areas that are another contributors to air quality. The major anthropogenic sources of VOCs are vehicles, the use of solvents and solvent containing products, and industrial and agricultural sources (Fenger, 1999; Schiffman *et al.*, 2001; Klemp *et al.*, 2002; Folsom and Allen, 2005).

The major symptoms linked to exposure to some VOCs with adverse effects for humans and animals comprise conjunctive irritation, nose and throat discomfort, headache, allergic skin reaction, nausea, emesis, epistaxis, fatigue and dizziness (Jones, 1999). The potency of organic chemicals to cause health effects varies greatly from those that are highly toxic, to those with no known health effect (Eljarrat and Barcelo, 2003). As with other pollutants (such as persistent, bioaccumulative and toxic substances /PBTs/), the extent and nature of the health effect will depend on many factors including time and intensity of exposure. Eye and respiratory tract irritation, headaches, and memory impairment are among the immediate symptoms that some people have soon after exposure to some volatile organics (Guo *et al.*, 2004). At present, little is known about what health effects occur from the levels of organics usually found in the indoor and outdoor atmosphere. Many organic compounds are known to cause cancer in animals; some are suspected human carcinogens (IARC, 1987, 1999a, b, 2004).

Among the VOCs that are significant in impacted environmental systems are chlorinated solvents such as carbon tetrachloride, tetrachloroethylene, and trichloroethylene (TCE), and their degradation compounds), fuel hydrocarbons such as benzene, toluene, ethylbenzene and *o,m,p*-xylenes as well as volatile pesticides such as chlordane, aldrin and lindane (Tillman and Weaver, 2005). The U.S Environmental Protection Agency lists 107 compounds whose toxicity and volatility produce a potentially unacceptable inhalation risk to receptors (Environmental Quality Management 2003). These VOCs can be released into the subsurface environment from leaking landfill liners, improper disposal, accidental spillage, or leaking underground storage tanks (LUSTs) (Tillman and Weaver, 2005).

Once in the subsurface, these compounds can become bound to the soil matrix, dissolved in groundwater (or soil water) and/or exist as a separate, residual phase known as a non-aqueous phase liquid (NAPL). Soil, aqueous, and NAPL-phase organics may all be sources of organic vapours in the subsurface. Therefore, organic vapour transport in the unsaturated zone requires understanding of interphase mass-transfer processes as the contaminant can be distributed between soil gas, water, soil, and NAPL phases.

The aim of this work is to characterised volatile organic compounds within an industrial lagoon site in the North-West of England in order to determine their specificity and quantity. Whilst specific VOCs would help to determine whether they are amongst the ones considered to be hazardous to health, their quantity on the other hand would determine if they have passed the regulatory limits.

Site description

Construction of the lagoons began in 1958 and they stopped receiving waste in 1998, so they were operational for about 40yrs. The site was used for the disposal of waste materials which contained chlorinated hydrocarbons in accordance with a Waste Management Licence. The site is now closed. It covers an area of about 16ha and is bounded to the south by a river and to the north by a canal. The adjacent chemical manufacturing site has been in operation for over 100yrs. It has been owned by a different company since 2000.

Materials and Methods

The Gasclam was designed to operate remotely; specifically in 50 mm ID monitoring wells. It monitors and records the following: CH_4, CO_2, O_2, CO, H_2S, VOC, atmospheric pressure, borehole pressure, pressure differential, temperature and water level. It is made from stainless steel and is also intrinsically safe. It is environmentally sealed and has ingress protection rated IP-68. The Gasclam is battery operated and can be powered for up to three months whilst operating on an hourly sampling frequency. Target applications for the Gasclam ground gas monitor include landfill for long term profiling, brown field sites for development issues, monitoring for coal mine fires, leakage of crude/petroleum, solvent storage and filling stations, oil refineries for local compliance/regulation, and for below ground carbon capture and storage monitoring regime (Pankow, 1987).

The Gasclam has the following technical information: (i) it has a memory which can record and store 65,000 time/date stamped readings, (ii) it weighs 7kg (13.2 lbs), (iii) It has overall length of 85cm (33.5 inches), (iv) the head diameter is 10.8 cm (4.25 inches), (v) its operation temperature range is –5 to +50 °C or 41°F to 122°F, (vi) it is powered by Duracell 1.5v LR20 MN1300 cells or a rechargeable battery pack.

Two Gasclam units with PID sensors were modified by incorporating a sorption tube containing Tenax TA (poly-2, 6-diphenyl-p-phenylene oxide) adsorbent (Markes International). This particular sorbent was chosen based on its outstanding selective properties in adsorption and desorption of VOCs over others gases (Kroupa *et al.*, 2004). These properties include high thermal stability (Brown, 1996), high hydrophobicity and rapid desorption kinetics (Barro *et al.*, 2009; Lee *et al.*, 2006; Singer *et al.*, 2007; Schripp *et al.*, 2007; Barro *et al.*, 2005; Saba *et al.*, 2001), high breakthrough volume (Baya and Siskos, 1996; Rothweiler and Wager, 1991; Borusiewicz and Zięba-Palus, 2007; Camel and Caude, 1995; Ras and Borrull, 2009; Gallego *et al.*, 2010), inertness towards most pollutants, high mechanical strength, and a good adsorption range of VOCs (Woolfenden, 2010). It has a surface area of 35m^2 g^{-1} and a pore volume of 2.4 cm^3 g^{-1} (Kroupa *et al.*, 2004).

VOCs adsorbed on Tenax TA sorbent tube are analysed by thermal desorption /gas chromatography mass spectroscopy (TD/GC-MS); a method which has already been standardised internationally (ISO 16000-6, 2004).

In-situ VOC sample collection

The two units were installed to monitor continuously on hourly sampling intervals for up to one month. The in-situ continuous data from the PID was downloaded while the sorbent tube was removed from the Gasclam and sealed for subsequent GC-MS analysis. The summation of the *in-situ* PID data from the Gasclam shows that the total VOC concentration adsorbed onto the sorbent material during the entire monitoring period 138780 ppm and 118020 ppm for boreholes 1 and 2 respectively. The sorbent tubes were subsequently analysed ex-situ for specific VOCs by thermal desorption Gas Chromatography/Mass Spectrometry (TD/GC-MS).

Ex-situ sample analysis

Analyses of the samples were conducted by heating the sorbent tube to 300°C. The volatile components were then trapped on a cold trap, held at -10°C, prior to desorption onto the GC column. Desorption of the TD tubes was carried out using a Markes International 50:50 TD system coupled to an Agilent GC/MS. Data acquisition in scanning mode was via a PC running Agilent Chemstation software.

The mass of each of the identified VOCs was calculated relative to the standard by assuming that the area of their peaks on the chromatogram is proportional to their masses. The relationship is shown below:

$A_{is}/Q_{is} = A_x/Q_x$ ………………………(1).

Where A_{is} is the area of internal standard on the chromatogram, Q_{is} is the amount of internal standard = 500ng, A_x is the area of specific VOC on the chromatogram and Q_x is the amount of specific VOC =? The VOCs analytical result is shown in the appendix.

Results and Discussion

The multi-parameter time series data obtained from the studied site. The figures represent datasets collected from boreholes 1 and 2 respectively. As observed, they showed changes in VOCs concentrations which are in the ranges of 169 ppm to 1964 ppm in borehole 1 and 168 ppm to 3974 ppm in borehole 2. The aggregate concentration of VOCs over the monitoring period is 846 ppm and 2241 ppm in boreholes 1 and 2 respectively. This shows that the concentration of VOCs in borehole 2 is about 3 times that in borehole 1.

The total concentration of adsorbed VOCs in Borehole 1 is 2.38 x 10^2 mg/m^3 whilst in Borehole 2; it is 2.42x 10^2mg/m^3. Tetrachloroethylene and 3,5-dimethyloctane have the highest and lowest concentrations of 28.8 mg/m^3 (12.1%) and 7.97 x 10^{-2} mg/m^3 (0.034%) respectively among the identified VOCs in Borehole 1; whilst in Borehole 2, the highest concentration of 43.4 mg/m^3 (17.9%) was recorded for tetrachloroethylene and the lowest concentration of 2.06 x 10^{-2} mg/m^3 (0.009%) for chloroethylene.

Most of the identified VOCs are among USEPA list of 107 compounds whose toxicity and volatility produce a potentially unacceptable inhalation risk to receptors. However, the risk of anyone being exposed to a significant amount of the contaminant is very low/negligible. This is because; the potential for exposure is during sampling which is a controlled and managed process. Therefore, it cannot be concluded that these wells are potentially dangerous. The result also shows that the total concentration of VOCs adsorbed from Borehole 1 is approximately 0.5 times higher than that from Borehole 2. This implies that although the 2 boreholes contain hazardous VOCs, Borehole 1 is actually more dangerous on the basis of the quantity of these VOCs it is contaminated with. This type of information can be helpful during risk assessment in understanding the regime and distribution of VOCs at different locations on a given site.

Table.1 Volatile organic compounds analytical results sample: H 148953 (Borehole 1)

S/N	Name of compounds	Individual TIC peak Area	Total mass (mg)	Total concentration (mg/m^3)	% of the total area	Cumulative % of total area
1	Tetrachloroethylene	3.94E+09	1.41E-01	2.88E+01	1.21E+01	1.21E+01
2	Trichloroethylene	2.50E+09	8.96E-02	1.83E+01	7.69E+00	1.98E+01
3	1,2-Dichloroethane	2.18E+09	7.81E-02	1.59E+01	6.70E+00	2.65E+01
4	Undecane	7.77E+08	2.78E-02	5.68E+00	2.39E+00	2.89E+01
5	Dichloromethylene	5.86E+08	2.10E-02	4.29E+00	1.80E+00	3.07E+01
6	1,1-Dichloroethylene	4.61E+08	1.65E-02	3.37E+00	1.42E+00	3.21E+01
7	Toluene	4.53E+08	1.63E-02	3.32E+00	1.39E+00	3.35E+01
8	1,1-Dichloroethane	4.19E+08	1.50E-02	3.07E+00	1.29E+00	3.48E+01
9	trans-1,2-Dichloroethylene	4.15E+08	1.49E-02	3.04E+00	1.28E+00	3.61E+01
10	1,2-Dichloroethylene	3.92E+08	1.41E-02	2.87E+00	1.21E+00	3.73E+01
11	1-Methyldecahydronaphthalene	3.57E+08	1.28E-02	2.61E+00	1.10E+00	3.84E+01
12	2-Methyldecahydronaphthalene	3.30E+08	1.18E-02	2.41E+00	1.01E+00	3.94E+01
13	Trichloromethane	3.05E+08	1.09E-02	2.23E+00	9.38E-01	4.03E+01
14	2-Methyldecane	2.49E+08	8.93E-03	1.82E+00	7.66E-01	4.11E+01
15	Decane	2.42E+08	8.68E-03	1.77E+00	7.45E-01	4.18E+01
16	3-Butyl-cyclohexanone	2.32E+08	8.33E-03	1.70E+00	7.14E-01	4.26E+01
17	3-Methyldecane	2.26E+08	8.12E-03	1.66E+00	6.96E-01	4.32E+01
18	trans-Decahydronaphthalene	2.01E+08	7.20E-03	1.47E+00	6.18E-01	4.39E+01
19	Dodecane	2.00E+08	7.16E-03	1.46E+00	6.14E-01	4.45E+01
20	2-Piperidinone, N-[4-bromo-n-butyl]-	1.95E+08	7.00E-03	1.43E+00	6.00E-01	4.51E+01
21	2-Ethyl-1-dodecanol	1.95E+08	6.99E-03	1.43E+00	6.00E-01	4.57E+01
22	Chloroethylene	1.81E+08	6.51E-03	1.33E+00	5.58E-01	4.62E+01
23	1-Methyl-2-propylcyclohexane	1.76E+08	6.31E-03	1.29E+00	5.41E-01	4.68E+01
24	3,3-Dimethyloctane	1.75E+08	6.26E-03	1.28E+00	5.37E-01	4.73E+01
25	Methylcyclohexane	1.74E+08	6.25E-03	1.28E+00	5.36E-01	4.79E+01
26	p-Xylene	1.68E+08	6.02E-03	1.23E+00	5.17E-01	4.84E+01

27	2,6-Dimethyloctane	1.58E+08	5.65E-03	1.15E+00	4.84E-01	4.89E+01
28	Tetradecana	1.56E+08	5.58E-03	1.14E+00	4.78E-01	4.93E+01
29	3,5-Dimethylheptane	1.55E+08	5.57E-03	1.14E+00	4.78E-01	4.98E+01
30	2-Butyl-1-octanol	1.52E+08	5.46E-03	1.11E+00	4.68E-01	5.03E+01
31	3-Methyloctane	1.49E+08	5.33E-03	1.09E+00	4.57E-01	5.07E+01
32	2-Methylundecane	1.44E+08	5.16E-03	1.05E+00	4.42E-01	5.12E+01
33	2-Tetradecyloxirane	1.42E+08	5.10E-03	1.04E+00	4.38E-01	5.16E+01
34	Carbon Tetrachloride	1.40E+08	5.02E-03	1.03E+00	4.31E-01	5.20E+01
35	3-Ethylhexane	1.31E+08	4.71E-03	9.61E-01	4.04E-01	5.24E+01
36	Phytol	1.29E+08	4.62E-03	9.44E-01	3.97E-01	5.28E+01
37	1,1,1,2-Tetrachloroethane	1.29E+08	4.62E-03	9.43E-01	3.96E-01	5.32E+01
38	4-Methyldecane	1.25E+08	4.48E-03	9.14E-01	3.84E-01	5.36E+01
39	2-Methylheptane	1.22E+08	4.39E-03	8.95E-01	3.76E-01	5.40E+01
40	2,5-Dimethylheptane	1.18E+08	4.24E-03	8.64E-01	3.63E-01	5.44E+01
41	2-Hexyl-1-octanol	1.18E+08	4.23E-03	8.63E-01	3.63E-01	5.47E+01
42	1,5-Diisopropyl-2,3-dimethylcyclohexane	1.15E+08	4.11E-03	8.40E-01	3.53E-01	5.51E+01
43	cis-1,3-Dimethylcyclohexane	1.14E+08	4.09E-03	8.35E-01	3.51E-01	5.54E+01
44	4-Chloroheptane	1.07E+08	3.82E-03	7.80E-01	3.28E-01	5.58E+01
45	Ethylcyclohexane	1.06E+08	3.81E-03	7.77E-01	3.26E-01	5.61E+01
46	1,2-Diethyl-1-methylcyclohexane	1.06E+08	3.79E-03	7.73E-01	3.25E-01	5.64E+01
47	3-Methylundecane	1.05E+08	3.76E-03	7.67E-01	3.22E-01	5.67E+01
48	Nonane	1.02E+08	3.66E-03	7.47E-01	3.14E-01	5.70E+01
49	1-Ethyl-2-propylcyclohexane	9.84E+07	3.53E-03	7.20E-01	3.03E-01	5.73E+01
50	1,2-Dipropylcyclopentane	9.77E+07	3.50E-03	7.15E-01	3.01E-01	5.76E+01
51	3-Ethyl-2-methylheptane	9.77E+07	3.50E-03	7.15E-01	3.00E-01	5.80E+01
52	4-Methyloctane	9.74E+07	3.49E-03	7.13E-01	2.99E-01	5.82E+01
53	2,3-Dimethyldecane	9.52E+07	3.41E-03	6.96E-01	2.93E-01	5.85E+01
54	sec-Butylcyclohexane	9.06E+07	3.25E-03	6.63E-01	2.79E-01	5.88E+01
55	3-Butyl-cyclohexanone	8.88E+07	3.19E-03	6.50E-01	2.73E-01	5.91E+01
56	1-Methyl-2-propylcyclopentane	8.82E+07	3.16E-03	6.45E-01	2.71E-01	5.94E+01
57	2-Butyl-1-octanol	8.79E+07	3.15E-03	6.43E-01	2.70E-01	5.96E+01
58	2-Methyloctane	8.52E+07	3.06E-03	6.24E-01	2.62E-01	5.99E+01
59	4-Ethyl-2,3-dimethyl-2-hexene	8.37E+07	3.00E-03	6.13E-01	2.57E-01	6.02E+01

60	2-Octyldecan-1-ol	8.32E+07	2.99E-03	6.09E-01	2.56E-01	6.04E+01
61	2,6,10-Trimethyldodecane	8.30E+07	2.98E-03	6.08E-01	2.55E-01	6.07E+01
62	4-Methylheptane	7.88E+07	2.82E-03	5.76E-01	2.42E-01	6.09E+01
63	trans-1-Ethyl-3-Methylcyclopentane	7.44E+07	2.67E-03	5.45E-01	2.29E-01	6.11E+01
64	4-Methyl-1-heptene	7.30E+07	2.62E-03	5.34E-01	2.24E-01	6.14E+01
65	1,1,4-Trimethylcyclohexane	7.12E+07	2.55E-03	5.21E-01	2.19E-01	6.16E+01
66	4-Methylnonane	6.98E+07	2.50E-03	5.11E-01	2.15E-01	6.18E+01
67	3-Methylhexane	6.57E+07	2.35E-03	4.81E-01	2.02E-01	6.20E+01
68	3-Methylnonane	6.44E+07	2.31E-03	4.71E-01	1.98E-01	6.22E+01
69	cis-1-Ethyl-3-methylcyclohexane	6.31E+07	2.26E-03	4.62E-01	1.94E-01	6.24E+01
70	1-Methyl-3-propylcyclooctane	6.29E+07	2.25E-03	4.60E-01	1.93E-01	6.26E+01
71	Propylcyclohexane	6.12E+07	2.20E-03	4.48E-01	1.88E-01	6.28E+01
72	1-Nonadecanol	6.12E+07	2.19E-03	4.48E-01	1.88E-01	6.30E+01
73	cis-1-Ethyl-4-methylcyclohexane	6.08E+07	2.18E-03	4.45E-01	1.87E-01	6.31E+01
74	4,5-Diethyloctane	6.02E+07	2.16E-03	4.41E-01	1.85E-01	6.33E+01
75	6,10,13-Trimethyl-1-tetradecanol	6.00E+07	2.15E-03	4.39E-01	1.85E-01	6.35E+01
76	2-Octyldecan-1-ol	5.85E+07	2.10E-03	4.28E-01	1.80E-01	6.37E+01
77	Ethylbenzene	5.84E+07	2.09E-03	4.27E-01	1.79E-01	6.39E+01
78	Cyclohexanepropanol-	5.36E+07	1.92E-03	3.93E-01	1.65E-01	6.40E+01
79	Diisooctyl phthalate	5.11E+07	1.83E-03	3.74E-01	1.57E-01	6.42E+01
80	1-Ethyl-2,3-dimethylcyclohexane	4.77E+07	1.71E-03	3.49E-01	1.47E-01	6.43E+01
81	2,7-Dimethyloctane	4.57E+07	1.64E-03	3.34E-01	1.41E-01	6.45E+01
82	1-Bromo-4-chloro-2-fluorobenzene	4.45E+07	1.60E-03	3.26E-01	1.37E-01	6.46E+01
83	1-Ethyl-2-propylcyclohexane	4.38E+07	1.57E-03	3.20E-01	1.35E-01	6.48E+01
84	2,5-Dimethyloctane	4.36E+07	1.57E-03	3.19E-01	1.34E-01	6.49E+01
85	1-Ethyl-2-methylcyclohexane	4.16E+07	1.49E-03	3.04E-01	1.28E-01	6.50E+01
86	2,4,6-Trimethylheptane	4.02E+07	1.44E-03	2.94E-01	1.24E-01	6.51E+01
87	1,2,3-Trimethylcyclohexane	3.97E+07	1.42E-03	2.90E-01	1.22E-01	6.53E+01
88	2-Bromomethyl-3,4-dihydro-2H-pyran	3.87E+07	1.39E-03	2.83E-01	1.19E-01	6.54E+01
89	1,2-Dimethyl-1-cyclooctene	3.84E+07	1.38E-03	2.81E-01	1.18E-01	6.55E+01

90	trans-1,2,3-Trimethylcyclohexane	3.76E+07	1.35E-03	2.75E-01	1.16E-01	6.56E+01
91	1-Pentyl-2-propylcyclopentane	3.75E+07	1.34E-03	2.74E-01	1.15E-01	6.57E+01
92	1,2,4-Trimethylcyclopentane	3.66E+07	1.31E-03	2.68E-01	1.13E-01	6.58E+01
93	2-Ethyl-1,3-dimethylcyclohexane	3.56E+07	1.28E-03	2.61E-01	1.10E-01	6.60E+01
94	1-Isopropyl-3-methylcyclohexane	3.52E+07	1.26E-03	2.57E-01	1.08E-01	6.61E+01
95	2-Hexyl-1-decanol	3.50E+07	1.25E-03	2.56E-01	1.07E-01	6.62E+01
96	1,2,4-Trimethylcyclohexane	3.44E+07	1.23E-03	2.52E-01	1.06E-01	6.63E+01
97	trans-1-Isopropyl-4-methylcyclohexane	3.15E+07	1.13E-03	2.31E-01	9.70E-02	6.64E+01
98	1,2-Epoxyoctadecane	2.90E+07	1.04E-03	2.12E-01	8.91E-02	6.65E+01
99	cis-9-Octadecen-1-ol	2.50E+07	8.95E-04	1.83E-01	7.68E-02	6.65E+01
100	1-Isopropyl-2,3-dimethylcyclopentane	2.45E+07	8.80E-04	1.80E-01	7.55E-02	6.66E+01
101	(2-Methylbutyl)cyclohexane	2.43E+07	8.70E-04	1.78E-01	7.47E-02	6.67E+01
102	3,7,11-Trimethyl-1-dodecanol	2.09E+07	7.48E-04	1.53E-01	6.42E-02	6.68E+01
103	1,1,2,3-Tetramethylcyclohexane	1.87E+07	6.69E-04	1.37E-01	5.74E-02	6.68E+01
104	Butylcyclopentane	1.78E+07	6.38E-04	1.30E-01	5.47E-02	6.69E+01
105	1-Butyl-2-propylcyclopentane	1.59E+07	5.71E-04	1.16E-01	4.90E-02	6.69E+01
106	3-Ethylheptane	1.52E+07	5.46E-04	1.11E-01	4.68E-02	6.70E+01
107	1-Isobutyl-3-methylcyclopentane	1.29E+07	4.63E-04	9.46E-02	3.97E-02	6.70E+01
108	3,5-Dimethyloctane	1.09E+07	3.91E-04	7.97E-02	3.35E-02	6.70E+01
109	Unidentified compounds	1.07E+10	3.84E-01	7.84E+01	3.30E+01	1.00E+02

∑ PID VOCs signal (ppm)	**∑ VOC mass (mg)**	**Total vol. (m^3)**	**∑VOCs conc.(mg/m3)**
138780	1.17E+00	4.90E-03	2.38E+02

Table.2 Volatile organic compounds analytical results sample: H 148954 (Borehole 2)

S/N	Name of compounds	Individual TIC peak Area	Total mass (mg)	Total concentration (mg/m^3)	% of the total area	Cumulative % of total area
1	Tetrachloroethylene	4.89E+09	2.13E-01	4.34E+01	1.79E+01	1.79E+01
2	Trichloroethylene	3.06E+09	1.33E-01	2.72E+01	1.12E+01	2.91E+01
3	1,2-Dichloroethane	1.19E+09	5.16E-02	1.05E+01	4.34E+00	3.34E+01
4	cis-1,2-Dichloroethylene	9.76E+08	4.24E-02	8.66E+00	3.56E+00	3.70E+01
5	1,3-Dimethylbenzene	8.51E+08	3.70E-02	7.55E+00	3.11E+00	4.01E+01
6	1,1-Dichloroethane	6.11E+08	2.65E-02	5.42E+00	2.23E+00	4.23E+01
7	trans-2-Dodecen-1-ol	5.43E+08	2.36E-02	4.82E+00	1.98E+00	4.43E+01
8	1,3-Dimethylbenzene	4.63E+08	2.01E-02	4.11E+00	1.69E+00	4.60E+01
9	Toluene	4.47E+08	1.94E-02	3.97E+00	1.63E+00	4.76E+01
10	1-(4-Bromobutyl)-2-piperidinone	2.66E+08	1.16E-02	2.36E+00	9.71E-01	4.86E+01
11	1,2,4-Trimethylbenzene	2.23E+08	9.68E-03	1.98E+00	8.14E-01	4.94E+01
12	Phytol	2.21E+08	9.62E-03	1.96E+00	8.08E-01	5.02E+01
13	trans-1,2-Dichloroethylene	2.20E+08	9.58E-03	1.95E+00	8.05E-01	5.10E+01
14	1-Ethyl-3-methylbenzene	2.03E+08	8.81E-03	1.80E+00	7.40E-01	5.17E+01
15	2-Methyldecane	1.95E+08	8.47E-03	1.73E+00	7.12E-01	5.24E+01
16	3-Methyldecane	1.64E+08	7.14E-03	1.46E+00	6.00E-01	5.30E+01
17	Ethylbenzene	1.51E+08	6.57E-03	1.34E+00	5.52E-01	5.36E+01
18	Dodecane	1.51E+08	6.55E-03	1.34E+00	5.50E-01	5.41E+01
19	1-Ethyl-4-methylbenzene	1.47E+08	6.39E-03	1.30E+00	5.36E-01	5.47E+01
20	4-Methyl-1-undecene	1.31E+08	5.67E-03	1.16E+00	4.77E-01	5.52E+01
21	4-Methyldecane	1.25E+08	5.42E-03	1.11E+00	4.55E-01	5.56E+01
22	1-Ethyl-2-methylbenzene	1.19E+08	5.16E-03	1.05E+00	4.33E-01	5.61E+01
23	2-Methylundecane	1.18E+08	5.14E-03	1.05E+00	4.32E-01	5.65E+01
24	1-Methyl-2-pentylcyclohexane	1.16E+08	5.05E-03	1.03E+00	4.24E-01	5.69E+01
25	5-Methyldecane	1.16E+08	5.04E-03	1.03E+00	4.24E-01	5.73E+01
26	4-Methylnonane	1.15E+08	5.02E-03	1.02E+00	4.21E-01	5.78E+01
27	2-Hexyl-1-decanol	1.13E+08	4.93E-03	1.01E+00	4.14E-01	5.82E+01
28	1,1-Dichloroethylene	1.10E+08	4.77E-03	9.74E-01	4.01E-01	5.86E+01
29	Methylcyclohexane	9.32E+07	4.05E-03	8.27E-01	3.41E-01	5.89E+01
30	4-Methyldecane	9.27E+07	4.03E-03	8.23E-01	3.39E-01	5.92E+01

31	2-Thiophenethiol	9.22E+07	4.01E-03	8.18E-01	3.37E-01	5.96E+01
32	trans-Decahydronaphthalene	9.20E+07	4.00E-03	8.17E-01	3.36E-01	5.99E+01
33	3-Methyloctane	9.10E+07	3.96E-03	8.08E-01	3.33E-01	6.03E+01
34	2-Methylheptane	8.94E+07	3.89E-03	7.94E-01	3.27E-01	6.06E+01
35	Pentylcyclohexane	8.52E+07	3.70E-03	7.56E-01	3.11E-01	6.09E+01
36	2-Butyl-1-octanol	8.29E+07	3.60E-03	7.35E-01	3.03E-01	6.12E+01
37	1,2-Dipropylcyclopentane	7.98E+07	3.47E-03	7.08E-01	2.92E-01	6.15E+01
38	2-Hexyl-1-decanol	7.82E+07	3.40E-03	6.94E-01	2.86E-01	6.18E+01
39	3-Methylundecane	7.50E+07	3.26E-03	6.65E-01	2.74E-01	6.20E+01
40	2,3-Dimethyldecane	7.46E+07	3.24E-03	6.62E-01	2.72E-01	6.23E+01
41	Dodecane	7.36E+07	3.20E-03	6.54E-01	2.69E-01	6.26E+01
42	2,6,10-Trimethyldodecane	7.28E+07	3.17E-03	6.46E-01	2.66E-01	6.29E+01
43	1,1,3,4-Tetrachloro-1,3-butadiene	6.99E+07	3.04E-03	6.20E-01	2.55E-01	6.31E+01
44	Undecane	6.98E+07	3.04E-03	6.19E-01	2.55E-01	6.34E+01
45	2,5-Dimethylheptane	6.42E+07	2.79E-03	5.70E-01	2.35E-01	6.36E+01
46	2-Methyloctane	6.37E+07	2.77E-03	5.65E-01	2.33E-01	6.38E+01
47	3-Methylnonane	6.28E+07	2.73E-03	5.57E-01	2.29E-01	6.41E+01
48	4-Methyloctane	5.93E+07	2.58E-03	5.26E-01	2.16E-01	6.43E+01
49	4-Ethyloctane	5.46E+07	2.37E-03	4.84E-01	1.99E-01	6.45E+01
50	3-Ethylhexane	4.98E+07	2.16E-03	4.41E-01	1.82E-01	6.47E+01
51	2,6-Dimethyloctane	4.60E+07	2.00E-03	4.08E-01	1.68E-01	6.48E+01
52	4-Formyl-3,5-di-t-butylbenzoic acid	4.12E+07	1.79E-03	3.65E-01	1.50E-01	6.50E+01
53	Benzene	4.10E+07	1.78E-03	3.64E-01	1.50E-01	6.51E+01
54	Bis(chloromethyl) sulfide	4.09E+07	1.78E-03	3.63E-01	1.49E-01	6.53E+01
55	Decane	4.07E+07	1.77E-03	3.62E-01	1.49E-01	6.54E+01
56	1-Chloro-4-fluorobenzene	4.06E+07	1.77E-03	3.61E-01	1.48E-01	6.56E+01
57	1-Chloro-3-fluorobenzene	3.87E+07	1.68E-03	3.44E-01	1.42E-01	6.57E+01
58	2-Methyl-1-decanol	3.81E+07	1.66E-03	3.38E-01	1.39E-01	6.59E+01
59	3-Ethyl-2-methylheptane	3.70E+07	1.61E-03	3.29E-01	1.35E-01	6.60E+01
60	Ethylcyclohexane	3.62E+07	1.58E-03	3.21E-01	1.32E-01	6.61E+01
61	cis-1-Ethyl-3-methyl-cyclohexane	3.53E+07	1.54E-03	3.13E-01	1.29E-01	6.62E+01
62	2,6-Dimethylundecane	3.48E+07	1.51E-03	3.09E-01	1.27E-01	6.64E+01
63	Cyclooctanecarbaldehyde	3.48E+07	1.51E-03	3.08E-01	1.27E-01	6.65E+01

64	1,2,4-Trimethylcyclohexane	3.47E+07	1.51E-03	3.08E-01	1.27E-01	6.66E+01
65	7-Methyl-1-undecene	3.35E+07	1.46E-03	2.97E-01	1.22E-01	6.68E+01
66	Benzene, 1,3,5-trimethyl	3.07E+07	1.34E-03	2.73E-01	1.12E-01	6.69E+01
67	3-Ethylhexane	3.02E+07	1.31E-03	2.68E-01	1.10E-01	6.70E+01
68	cis-1,4-Dimethylcyclohexane	2.96E+07	1.29E-03	2.63E-01	1.08E-01	6.71E+01
69	trans-1-Ethyl-4-Methylcyclohexane	2.95E+07	1.28E-03	2.62E-01	1.08E-01	6.72E+01
70	Cyclohexanepropanol-	2.84E+07	1.24E-03	2.52E-01	1.04E-01	6.73E+01
71	Propylcyclohexane	2.83E+07	1.23E-03	2.51E-01	1.03E-01	6.74E+01
72	2-Propylheptanol	2.75E+07	1.19E-03	2.44E-01	1.00E-01	6.75E+01
73	Diisooctyl phthalate	2.12E+07	9.21E-04	1.88E-01	7.74E-02	6.76E+01
74	1-Butyl-2-propylcyclopentane	1.47E+07	6.38E-04	1.30E-01	5.36E-02	6.76E+01
75	1-Chloro-2-fluorobenzene	1.11E+07	4.84E-04	9.88E-02	4.07E-02	6.77E+01
76	Hexanedioic acid, dioctyl ester	4.38E+06	1.90E-04	3.89E-02	1.60E-02	6.77E+01
77	Ethyl iso-allocholate	4.01E+06	1.74E-04	3.56E-02	1.46E-02	6.77E+01
78	Chloroethylene	2.33E+06	1.01E-04	2.06E-02	8.50E-03	6.77E+01
79	Unidentified compounds	8.84E+09	3.84E-01	7.84E+01	3.23E+01	1.00E+02

∑ PID VOCs signal (ppm)	**∑ VOC mass (mg)**	**Total vol. (m^3)**	**∑VOCs conc.(mg/m^3)**
118020	1.19E+00	4.90E-03	2.43E+02

Conclusions

The concentrations of VOC in the borehole closer to the chemical company displayed a broader range and have higher average concentrations. The values range from 169 - 1964 ppm for the former borehole and 168 ppm - 3974 ppm in the latter borehole. Also whilst the former has average VOCs concentration of 846 ppm; the latter has 2241 ppm as its average over the monitoring period. The identified VOCs comprise of those recognised to be significantly hazardous to health and the environment. They include tetrachloroethylene, trichloroethylene, chloroethylene, toluene, benzene, chlorofluorobenzene, xylene, and ethylbenzene. A comparison of the individual concentrations of VOCs in this site with the international standard shows that they have passed the set limits. However, the presence of contaminants does not immediately constitute a risk. There need to be an exposure pathway and a receptor; but at the site, there is neither of these. The use of a PID/Tenax enabled Gasclam enables robust sub-surface VOC gas/vapour monitoring data enabling site zoning and a more effective targeting of remedial efforts on those zones of actual concern leading to savings in both time and money and helping to ensure that the remedial works are more sustainable in line with current guidance. They also save frequent "snapshot" monitoring visits enabling a more accurate representation of sub-surface conditions to be obtained.

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