90568
(8)

The Science of the Total Environment, 50 (1986) 87—101
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

MEASUREMENT OF MOBILITY OF ORGANIC COMPOUNDS IN SOILS

HANS M. SEIP[1], JOROLF ALSTAD[1], GEORG E. CARLBERG[2], KARI MARTINSEN[2] and RUNE SKAANE[1]

[1]*Department of Chemistry, University of Oslo, P.O. Box 1033 Blindern, 0315 Oslo 3 (Norway)*
[2]*Center for Industrial Research, P.O. Box 350 Blindern, 0314 Oslo 3 (Norway)*

(Received May 8th, 1985; accepted August 2nd, 1985)

ABSTRACT

The leachability of chlorinated hydrocarbons, chlorophenols and "light aromatic compounds" has been studied for three typical Norwegian soils. A simple column equipment for studying the leachability of organic compounds in soil is described. Concentration profiles for the compounds are compared with those of tritiated water. Good correlations between soil adsorption constants (K_{oc}) and water solubility were obtained for the chlorinated hydrocarbons and some of the "light aromatic hydrocarbons". Soil adsorption constants for the chlorophenols varied significantly between the soils, probably due to a varying degree of dissociation and hydrogen bonding.

INTRODUCTION

The adsorption of organic compounds by soil or soil components is of importance because strong adsorption may prevent pollutants from entering surface or groundwater. If the rate of degradation of the organic compounds in the soil is slow, a reservoir is built up from which leaching may occur later. A wide range of compounds, such as hydrocarbons (including aromatic hydrocarbons), ethers, phenols and many chlorinated compounds have been found in groundwater (Zoeteman et al., 1981; van Duijvenbooden et al., 1981, Burmaster, 1982). The adsorption of organic water pollutants onto particles or dissolved humic substances is also of major importance in relation to the distribution, sedimentation and bioavailability of the compounds to aquatic organisms.

Groundwater is becoming of increasing importance as a source of drinking water; the behaviour of contaminants as the water percolates through the soil is therefore of great interest. Many waterworks place wells close to a river in order to use bank infiltration as a first step in the treatment of river water for public supplies. In a natural river water — groundwater infiltration system the behaviour of organic pollutants is determined by many physical, biological and chemical processes. In a field study it is often difficult to assess the importance of each of these processes in determining the net

0048-9697/86/$03.50 © 1986 Elsevier Science Publishers B.V.

RECEIVED NOV 23 2005 By

14589

mobility of a particular compound in the ground. In the laboratory, however, experimental conditions can be controlled so that the effect of individual transport phenomena can be observed.

The adsorption of organic pollutants onto soil is often studied in batch experiments (e.g. Means et al., 1980; Boyd, 1982) which certainly give useful information, but the conditions are very different from those found in the field and the results cannot be used directly to estimate the fate of pollutants under field conditions. Studies with soil columns are somewhat more realistic. A comparison between batch and column methods for assessing the leachability of hazardous wastes has recently been published by Jackson et al. (1984). They conclude that batch extraction is more reproducible, whereas the column method is more realistic in simulating leaching processes under field conditions. Several types of equipment for soil column experiments have been described (e.g. Rao et al., 1979; Schwarzenbach and Westall, 1981; Wilson et al., 1981).

The aim of the present investigation was to study how selected organic pollutants would penetrate typical Norwegian soil samples. The pollutants chosen include chlorinated hydrocarbons and "light aromatic compounds", both of which are frequently found in both surface and groundwaters (van Duijvenbooden et al., 1981), and chlorinated phenols, which are frequently found in surface water.

EXPERIMENTAL

Requirements

Our main considerations in designing the experiments were:

— the "rain" (input solution) should be distributed evenly onto the soil surface;

— the "rain" intensity should be easy to vary and fairly realistic compared to field conditions;

— it should be possible to study volatile compounds;

— it should be possible to add the compounds to be studied to the "rain" solution or to the top of the soil column;

— the water movement should be studied simultaneously with the movement of the organic compounds;

— as little as possible of the organic compounds should be adsorbed onto the surface of tubings and containers.

Equipment

We decided to use one type of equipment for volatile compounds such as haloforms and light aromatic hydrocarbons and a somewhat simpler arrangement for non-volatile compounds, e.g. high-molecular-weight polycyclic aromatic hydrocarbons (PAH). A sketch of the equipment used in the former case is shown in Fig. 1. The soil column is placed in a stainless steel cylinder (G) with copper netting in the bottom, below which there is a small

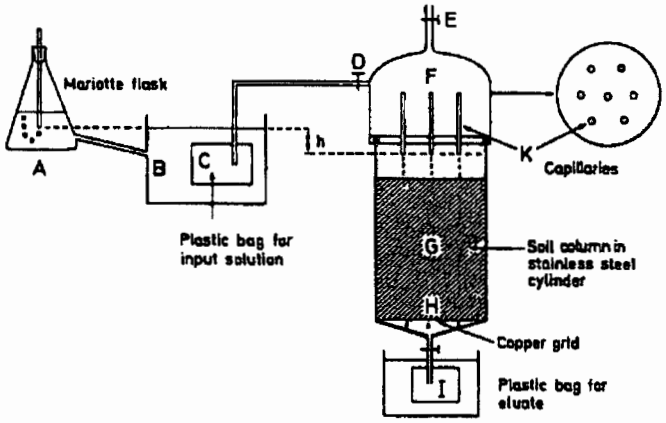

Fig. 1. Schematic illustration of the equipment used for volatile compounds. The inner diameter of the column (G) is 8.3 cm and the height of packed soil is about 9.5 cm. The inner diameter of the capillaries (K) is 0.175 mm.

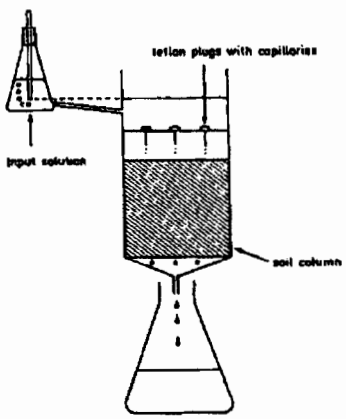

Fig. 2. Schematic illustration of the equipment used for leaching experiments with PAHs.

air-filled space. The eluate is collected in a plastic bag (I) (polyvinylfluoride, produced by Alltech Assoc.). The solution serving as "rain" is kept in another, similar bag (C) with a connection to a glass-bell (F) above the soil column. The solution is distributed through capillaries (K). The bag (C) is immersed in water, and the water level in (B) is kept constant through connection with a Mariotte flask (see Fig. 1). The difference in height (h) determines the "rain" intensity, and it was adjusted to give about 17.3 mm h^{-1}; the variation was less than ± 10%.

The simpler equipment used for the less volatile compounds (polycyclic aromatic hydrocarbons) is shown in Fig. 2. The glass bell (F in Fig. 1) is replaced by an open metal cup containing seven holes fitted with Teflon plugs with thin capillaries in the bottom. The eluate is collected in an aluminium container. The equipment was used to study the movement of

PAHs in road dust through various soils. The results of the experiment are given elsewhere (Gjessing et al., 1984).

Procedure

Before starting the experiments the soil column was saturated with tap water (pH ≈ 6.5) to field capacity. Then "rain", tap water containing the compounds to be studied and tritiated water, was supplied for 2—3 days, followed by tap water at the same rate for a further 4—9 days. The compounds studied were added to the water as a methanol or acetone solution.

Some 20—25 samples were taken from bag (I) for determination of the concentrations of organic compounds in the eluate. The sampling frequency was gradually reduced during the experiment. Samples of the input solution in bag (C) were taken just before starting the experiment and when switching over to tap water. The samples were stored at 5°C and analyzed by standard methods within 1 week. Samples for measuring the concentration of tritiated water were taken more frequently. It was assumed that H_2O moved through the column at the same rate as HTO.

For comparison with the column experiments a few batch experiments were also carried out. A mixture of 5 g of soil and 25 ml of tap water containing the compounds to be studied was equilibrated for 5 h. The water was separated from the soil by filtration and the concentration of organic compounds in the filtrate were determined.

Compounds and soils

The mobility of 15 organic compounds in three different soil types was studied with the equipment shown in Fig. 1. The compounds were divided into three groups: (1) "chlorinated hydrocarbons"; (2) "chlorophenols"; and (3) "light aromatic compounds" (see Table 1, which also gives the concentrations of the compounds used in the "rain"). The concentration of tritiated water corresponded to 5000 Bq ml^{-1}.

Some characteristics of the soils used are given in Table 2. Soil A consists mostly of sand and has a very low organic carbon content and a low cation exchange capacity. Soils B and C contain more organic carbon; a major difference is found in pH values.

Parameters characterizing 10 experiments are shown in Table 3. To check the reproducibility, the experiment with compound group 3 and soil C was performed in duplicate.

In our experiments the soil was dried at room temperature, sifted through a 3 mm grid and packed as homogeneously as possible in the steel cylinder.

Analytical methods

Soil. Soil pH was measured in suspension (water/soil = 2.5:1 by volume) after 24-h equilibration.

Cation exchange capacity. The cations were extracted by adding 25 ml of 1 *M* CH_3COONH_4 to 5 g of air-dried soil. The suspension was filtered after 24 h, and the filtrate analyzed for K^+ (atomic absorption spectroscopy,

TABLE 1

THE COMPOUNDS[a] STUDIED AND THEIR CONCENTRATIONS IN THE "PRECIPITATION"

Group 1: chlorinated hydrocarbons		Group 2: chlorophenols		Group 3: light aromatic compounds	
Compound	Concentration ($mg\ l^{-1}$)	Compound	Concentration ($mg\ l^{-1}$)	Compound	Concentration ($mg\ l^{-1}$)
1,1,2-Trichloroethane	0.5	2,4-Dichlorophenol	0.025	Benzene	1.0
Trichloroethene	0.5	2,4,6-Trichlorophenol	0.0125	Toluene	1.0
Tetrachloroethene	0.5	2,3,4,6-Tetrachlorophenol	0.0125	*m*-Xylene	1.0
1,3,5-Trichlorobenzene	0.5	Pentachlorophenol	0.0125	Nitrobenzene	1.0
		4,5,6-Trichloroguaiacol	0.0125	Dimethylphthalate	2.5
		Tetrachloroguaiacol	0.0125		

[a] Elsewhere in this paper the names are simplified by omitting the numbers.

TABLE 2
SOME PROPERTIES OF THE SOILS USED

Soil type	pH	Organic carbon (%)	CEC[a] (meq kg^{-1})	Sand (%)	Silt (%)	Clay (%)
A (forest soil)	5.6	0.2	4.8	97.3	2.2	0.5
B (agricultural soil)	7.4	2.2	90	65.2	25.6	9.2
C (forest soil)	4.2	3.7	29	69.5	20.5	10.1

[a] Cation exchange capacity measured at pH ≈ 7.

TABLE 3
IMPORTANT EXPERIMENTAL PARAMETERS

Experiment No.[a]	Amount of solution used (mm)	Amount of distilled water used (mm)	Average "rain" intensity (mm h^{-1})	Density of soil (g cm^{-3})	Interstitial fraction
1,A	333	532	7.2	1.54	0.35
1,B	512	604	7.3	1.21	0.48
1,C	521	676	7.0	1.02	0.57
2,A	356	543	7.6	1.59	0.35
2,B	520	624	7.5	1.22	0.49
2,C	526	1040	7.3	1.01	0.55
3,A	366	633	7.5	1.54	0.34
3,B	484	1240	7.2	1.24	0.50
3,C (I)	520	1404	7.3	1.00	0.57
3,C (II)	530	1259	7.5	0.99	0.57

[a] The digit corresponds to the group of compounds (Table 1), the letter to the soil type (Table 2). I and II are two replicates.

AAS), NH_4^+, Ca^{2+}, Mg^{2+} (inductively coupled argon plasma spectroscopy, ICP) and H^+ (titration).

Organic compounds. The analyses of the chlorinated phenols were based on derivatisation by direct acetylation of the compounds in the water phase (50 ml) with acetic anhydride (Voss et al., 1981). Dibromophenol was used as internal standard. The samples were then extracted with cyclohexane and derivatized chlorinated phenols were analysed using a Hewlet Packard 5730A gas chromatograph (GC) equipped with a glass-capillary column (SE 54) and electron capture detector.

The quantification was based on standard curves using four standard concentrations.

Chlorinated hydrocarbons were extracted from the water (100 ml) by n-pentane (5 ml) and analysed by GC as for the chlorinated phenols with trichlorobromomethane as internal standard (Eklund et al., 1978).

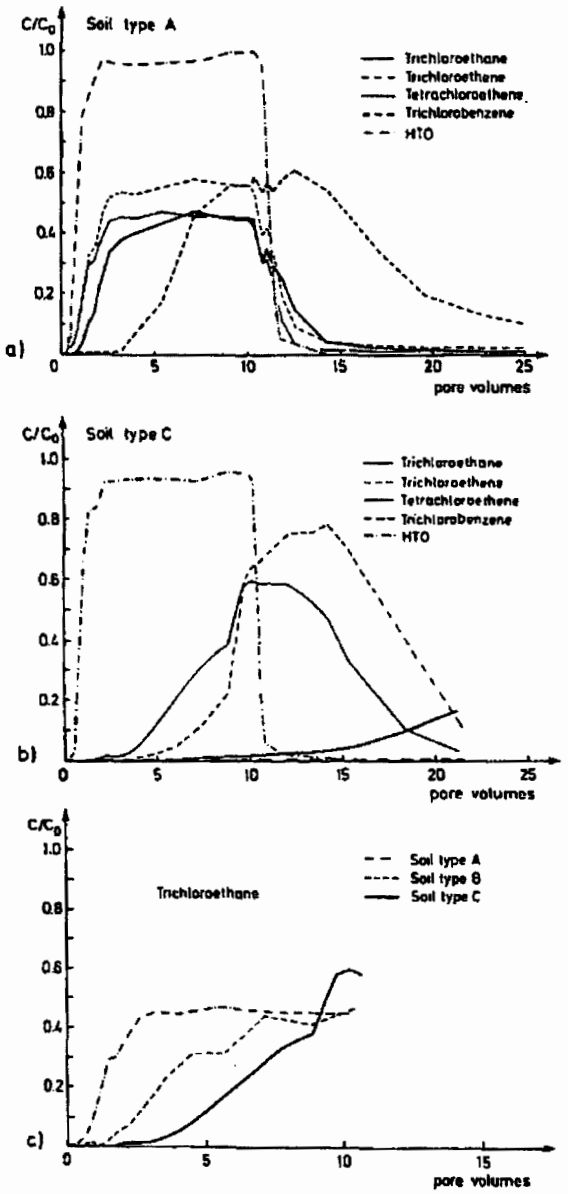

Fig. 3. Concentration profiles for chlorinated compounds after percolation through different soils. C_0 is the concentration in the input solution. (a) Soil type A; (b) soil type C; (c) comparison of the concentration profiles for trichloroethane for the three soil types, A, B, and C.

The aromatic compounds (in group 3) were extracted from the water (100 ml) with n-pentane (5 ml) and analysed by GC equipped with a glass-capillary column (SE 54) and flame-ionization detector. The quantification was based on one set of standard concentrations.

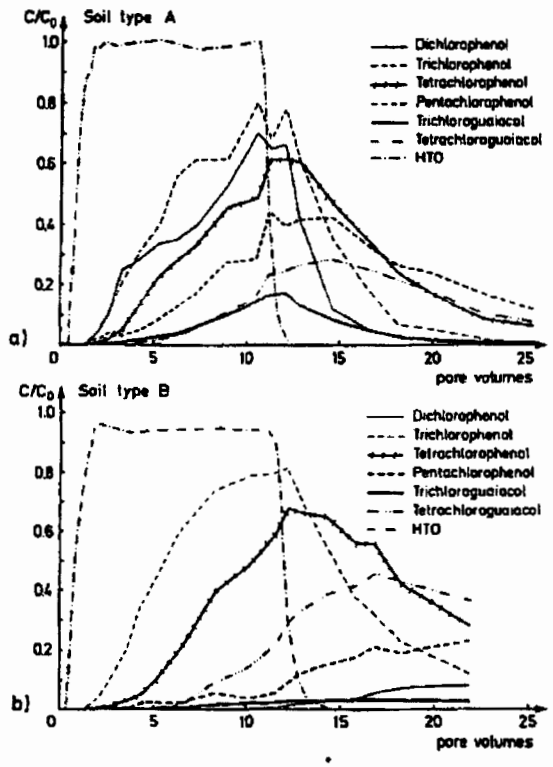

Fig. 4. Concentration profiles for chlorinated phenols after percolation through different soils. C_0 is the concentration in the input solution. (a) Soil type A; (b) soil type B.

Tritiated water, HTO, was determined by liquid scintillation counting of ^3H in the eluate samples.

RESULTS AND DISCUSSION

Chlorinated hydrocarbons

Concentration profiles of these compounds in the eluates are shown in Fig. 3a and b for soil types A and C, respectively. For soil A, with a low organic matter content, trichloroethane, trichloroethene and tetrachloroethene move almost at the same rate as water through the soil, whereas trichlorobenzene is more retarded. For soil type C the concentration of trichlorobenzene was always below the detection limit ($0.5\,\mu g\,l^{-1}$), and the other compounds also, especially tetrachloroethene, show considerable retention. The results for soil type B are intermediate between those for soil types A and C as illustrated in Fig. 3c for trichloroethane.

Chlorophenols

The concentration profiles for soil types A and B are given in Fig. 4a and

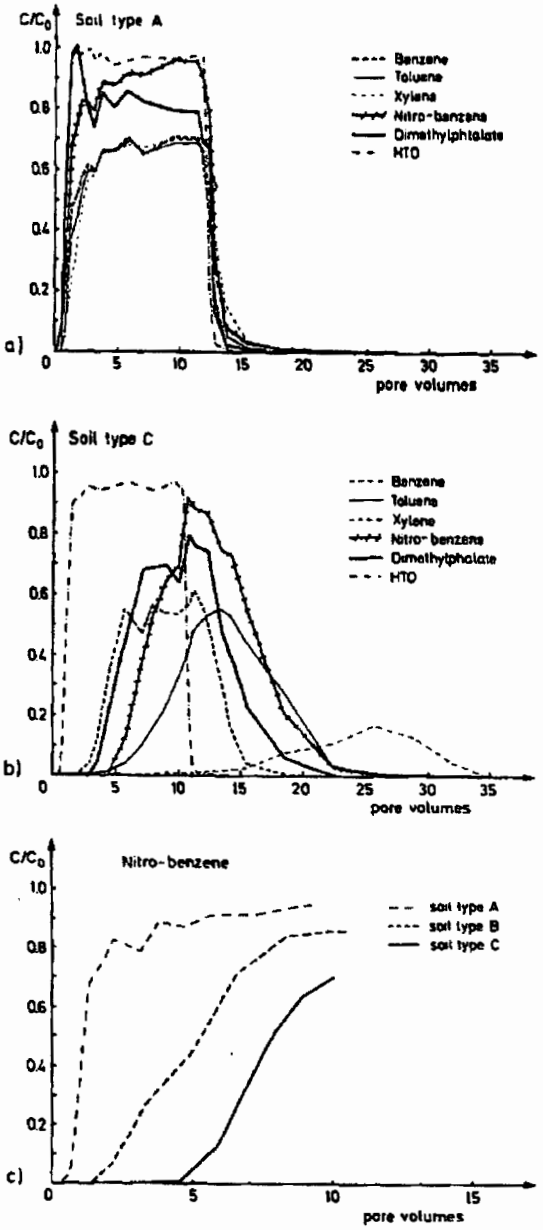

Fig. 5. Concentration profiles for light aromatic compounds after percolation through different soils. C_0 is the concentration in the input solution. (a) Soil type A; (b) soil type C; (c) comparison of the concentration profiles for nitrobenzene for the three soil types, A, B, and C.

b, respectively. The chlorophenols show longer retention than the chlorinated hydrocarbons and, for soil type C, the concentrations in the eluate were always below the detection limit ($0.05\ \mu g\ l^{-1}$).

Light aromatic compounds

The concentration profiles for soil types A and C are given in Fig. 5a and b, respectively. The results are similar to those for the chlorinated hydrocarbons and the results for soil type B were again intermediate, as illustrated in Fig. 5c for nitrobenzene.

Mass balances

The concentrations of the compounds in the "rain" (C_0) did not vary more than 2—3% during the experiment. The concentrations in the eluate (C) usually did not reach C_0. Even for compounds where C has reached a rather stable level and decreased to values close to the detection limit, the total amount in the eluate is less than that in the input solution (Figs 3—5). The soil was analyzed for some of these compounds after terminating the experiment without detecting significant amounts. The loss is often particularly large for the most volatile compounds (e.g. chlorinated hydrocarbons) indicating loss by evaporation even though the equipment was designed to minimize such effects. In addition to evaporation we suspect some reduction in the recovery is due to adsorption on the walls of tubing and the cylinder and, possibly, some degradation during the experiments. The contributions from the various factors mentioned here should be studied more carefully in future work.

Estimation of retention indices and adsorption coefficients

For a convenient comparison of all the results, a characteristic property of the concentration curves (Figs 3—5) is required. The most obvious quantity is the relative retention with respect to the water movement (R_f). For most compounds a fairly stable concentration level (C^s) is reached. The number of pore volumes necessary to reach $C^s/2$ is denoted R_x for compound X and R_w for tritiated water. Then

$$R_f = R_x/R_w \tag{1}$$

values for R_f are given in Table 4. For compounds showing an increasing concentration trend when the experiment was terminated, we used the maximum observed value to compute R_f. These R_f values, which are likely to be too low, are given in parentheses in Table 4. For compounds that give undetectable concentrations in the eluate, we have estimated the lower limit of R_f by using the total number of pore volumes for R_x.

Assuming $n = 1$ in Freundlich's adsorption equation (Bolt and Bruggenwert, 1976; Hasset et al., 1981), we have

$$C_{soil} = K_{ads} \cdot C_w \tag{2}$$

where C_{soil} is the quantity of compound adsorbed per unit weight of soil (mol kg^{-1}); C_w is the equilibrium concentration in soil water (mol l^{-1}); and K_{ads} is the soil adsorption coefficient.
We then have

$$K_{ads} = (R_f - 1)\epsilon_l/d_s \tag{3}$$

TABLE 4

RETENTION COEFFICIENTS (R_f), ADSORPTION COEFFICIENTS (K_{ads}) AND K_{oc} VALUES FOR THE 15 COMPOUNDS STUDIED IN COLUMN EXPERIMENTS

Compound	Soil A			Soil B			Soil C		
	R_f	K_{ads}	K_{oc}	R_f	K_{ads}	K_{oc}	R_f	K_{ads}	K_{oc}
Trichloroethane	1.53	0.12	60.0	4.52	1.40	63.7	8.11	4.00	108
Trichloroethene	1.65	0.14	72.5	6.29	2.11	95.8	10.3	5.24	142
Tetrachloroethene	2.58	0.35	177	12.3	4.51	205	(23.9)	(15.5)	(348)
Trichlorobenzene	7.25	1.40	700	>23.5	>9.0	>406	>24	>13	>355
Dichlorophenol	7.27	1.39	695	(20.6)	(7.8)	(356)	>33	>17	>475
Trichlorophenol	6.09	1.13	564	6.02	2.01	91.2	>33	>17	>475
Tetrachlorophenol	7.77	1.50	750	9.46	3.38	154	>33	>17	>475
Pentachlorophenol	9.32	1.84	922	(17.1)	(6.4)	(293)	>33	>17	>475
Trichloroguaiacol	9.77	1.94	972	>26.6	>10.2	>465	>33	>17	>475
Tetrachloroguaiacol	11.8	2.38	1192	14.1	5.24	238	>33	>17	>475
Benzene	1.34	0.076	38.2	3.40	0.96	43.5	4.48	1.98	53.5
Toluene	1.49	0.11	55.5	6.21	2.08	94.4	9.70	4.95	134
Xylene	2.15	0.25	129	9.71	3.47	158	19.8	10.7	289
Nitrobenzene	1.27	0.061	30.6	5.90	1.95	88.8	7.69	3.81	103
Dimethylphthalate	1.07	0.015	7.6	3.36	0.94	42.8	5.52	2.57	69.6

TABLE 5

VALUES OBTAINED FOR K_{ads} IN TWO EXPERIMENTS WITH LIGHT AROMATIC COMPOUNDS AND SOIL TYPE C

Compound	K_{ads}		K_{ads} (I) / K_{ads} (II)
	I	II	
Benzene	2.24	1.98	1.13
Toluene	4.53	4.95	0.91
Xylene	11.5	10.7	1.08
Nitrobenzene	3.80	3.81	1.00
Dimethylphthalate	2.81	2.57	1.09

TABLE 6

K_{ads} VALUES OBTAINED IN BATCH EXPERIMENTS

Compound	Soil		
	A	B	C
Dichlorophenol	0.49	11.3	28
Trichlorophenol	0.72	2.4	72
Tetrachlorophenol	1.33	4.0	235
Pentachlorophenol	2.1	12.1	187
Trichloroguaiacol	2.5	26	368
Tetrachloroguaiacol	3.1	8.5	311

where d_s is the density of soil in the column (kg l^{-1}) and ϵ_I is the interstitial fraction.

Since the organic matter in the soil plays an important role in determining the adsorption (Bolt and Bruggenwert, 1976; Laskowski et al., 1982), a new factor, sometimes called the soil adsorption constant, is defined by

$$K_{oc} = 100\,K_{ads}/(\%\ \text{organic carbon in soil}) \quad (4)$$

The values obtained for K_{ads} and K_{oc} are also given in Table 4.

Reproducibility

As indicated in Table 3 duplicate runs were performed with light aromatic hydrocarbons and soil type C. The column was re-packed between the runs. The values obtained for K_{ads} given in Table 5 show quite good agreement with deviations between 0 and 13%.

Comparison between column and batch experiments

The values for K_{ads} [eqn (2)] were also determined in batch experiments.

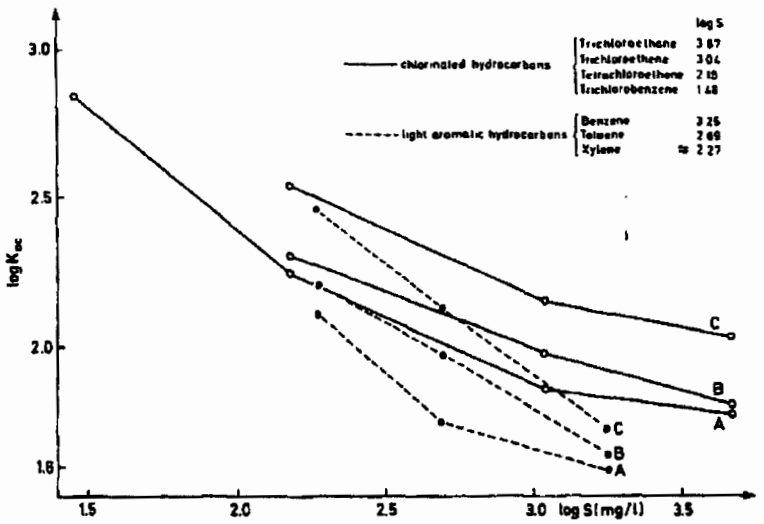

Fig. 6. Relationships between K_{oc} and solubility in water (S) for some similar compounds. A, B, and C stand for soil type.

The initial concentrations were 0.1 mg l^{-1} for dichlorophenol and 0.05 mg l^{-1} for the other compounds, i.e. 4 times higher than in the column experiments (Table 1). The averages obtained for three (soil types A and B) or two (soil type C) experiments are given in Table 6. The standard deviations were 1—10% for soil types A and B and 1—14% for soil type C, where the concentrations in the filtrate were low. In general, the two methods rank the compounds in the same order. Dichlorophenol, however, has the lowest value for K_{ads} on soil type A according to the batch experiments, whereas in Table 4 the value for dichlorophenol is slightly higher than found for trichlorophenol. Inspection of the concentration profiles for these compounds (Fig. 4a) shows that the curve for dichlorophenol falls off more rapidly than the curve for trichlorophenol, in agreement with the results from the batch experiment. The value for K_{ads} obtained from the column results by using the increasing part of the curve only, is therefore not reliable in this case.

Adsorption mechanisms

Several authors have reported a high correlation between K_{oc} and water solubility (see, e.g., Kenaga, 1980; Chiou et al., 1979) or the octanol/water partition coefficient, K_{ow} (see, e.g. Karickhoff et al., 1979), at least when similar compounds are compared. We obtained fairly good correlations between K_{oc} and water solubility for "chlorinated hydrocarbons" and for the three compounds benzene, toluene and xylene (Fig. 6). The K_{oc} values clearly decrease as solubility increases. Nitrobenzene and dimethylphthalate did not fit very well into this picture, showing a larger shift from soil A to soil B than the other compounds (Table 4). The reason for this is probably the possible formation of hydrogen bonds between

oxygen atoms in these molecules and hydrogen atoms in the soil. The higher K_{oc} values obtained for chlorinated hydrocarbons than for aromatic hydrocarbons, with approximately the same solubility (see Fig. 6), may probably also be explained by weak hydrogen bonds between the chlorine atoms in the adsorbed molecules and the hydrogen atoms in the soil. The amount of organic compounds in the soil is then of particular importance. For the chlorophenols there is no clear trend with solubility or K_{ow}; for these compounds the formation of hydrogen bonds is most likely the dominating adsorption mechanism, as discussed below.

The values for R_f and K_{ads} for the compounds studied show a general increasing trend from soil A to B and from B to C (Table 4). The K_{oc} values vary, as expected, much less than K_{ads} between the soil types, especially for compounds with low polarity. With the exception of the phenols, K_{oc} values also show an increasing trend from soil type A to soil type B and from B to C. The change from soil A to soil B may be related to an increase in clay content.

For the phenols we find the lowest K_{oc} values for soil B, which has the highest pH value (Table 2). At this pH (7.4), trichlorophenol ($pK_s = 6.15$), tetrachlorophenol ($pK_s = 5.39$), pentachlorophenol ($pK_s = 4.75$), and tetrachloroguaiacol ($pK_s = 5.97$) are almost completely dissociated. As anions they move fairly easily through the soil. Dichlorophenol ($pK_s = 7.9$) and trichloroguaiacol ($pK_s = 7.4$) are less dissociated, and the values for K_{oc} for soil B do not show such clear differences from the results for soils A and C.

REFERENCES

Bolt, G.H. and M.G.M. Bruggenwert, 1976. Soil Chemistry. Developments in Soil Science, Vol. 5A. Elsevier, Amsterdam.

Boyd, S.A., 1982. Adsorption of substituted phenols. Soil Sci. 134: 337—343.

Burmaster, D.E., 1982. The new pollution: Groundwater contamination. Environment, 24 (2): 6.

Chiou, C.T., L.J. Peters and U.H. Freed, 1979. A physical concept of soil equilibria for nonionic organic compounds. Science, 206: 831—832.

Eklund, G., B. Josefsson and C. Roos, 1978. Determination of volatile halogenated hydrocarbons in tap water, sea water and industrial effluents by glass capillary gas chromatography and electron capture detection. HRC & CC, 1: 34—40.

Gjessing, E., E. Lygren, L. Berglind, T. Gulbrandsen and R. Skaane, 1984. Effect of highway runoff on lake water quality. Sci. Total Environ., 33: 245—257.

Hassett, J.J., W.L. Banwart, S.G. Wood and J.C. Means, 1981. Sorption of α-naphtol: Implications concerning the limits of hydrophobic sorption; Soil Sci. Soc. Am. J., 45: 38—42.

Jackson, D.R., B.C. Garrett and T.A. Bishop, 1984. Comparison of batch and column methods for assessing leachability of hazardous waste. Environ. Sci. Technol., 18: 668—673.

Karickhoff, S.W., D.S. Brown and T.A. Scott, 1979. Sorption of hydrophobic pollutants on natural sediments. Water Res., 13: 241—248.

Kenaga, E.E., 1980. Predicted bioconcentration factors and soil sorption coefficients for pesticides and other chemicals. Ecotoxicol. Environ. Safety, 4: 26—38.

Laskowski, D.A., C.A.I. Goring, P.J. McCall and R.L. Swann, 1982. Terrestrial environment. In: R.A. Conway (Ed.), Environmental Risk Analysis for Chemicals. van Nostrand Reinhold, New York, pp. 198—240.

Means, J.C., S.G. Wood, J.J. Hassett and W.L. Banwart, 1980. Sorption of polynuclear aromatic hydrocarbons by sediments and soils. Environ. Sci. Technol., 14: 1524—1528.

Rao, P.S.C., J.M. Davidson, R.E. Jessup and H.M. Selim, 1979. Evaluation of conceptual models for describing nonequilibrium adsorption—desorption of pesticides during steady flow in soils. Soil Sci. Soc. Am. J., 43:22—28.

Schwarzenbach, R.P. and J. Westall, 1981. Transport of nonpolar organic compounds from surface water to groundwater. Laboratory sorption studies. Environ. Sci. Technol., 15: 1360—1367.

Van Duijvenbooden, W., P.G. Glasbergen and H. van Lelyveld, (Eds), 1981. Quality of Groundwater. Elsevier, Amsterdam.

Voss, R.H., J.T. Wearing and A. Wong, 1981. A novel gas chromatographic method for the analysis of chlorinated phenolics in pulp mill effluents. In: L.H. Keith (Ed.), Advances in the Identification and Analysis of Organic Pollutants in Water. Ann Arbor Science Publishers, Inc. Ann Arbor, MI, pp. 1059—1097.

Wilson, J.T., C.G. Enfield, W.J. Dunlap, R.L. Cosby, D.A. Foster and L.B. Baskin, 1981. Transport and fate of selected organic pollutants in a sandy soil. J. Environ. Qual., 10: 501—506.

Zoeteman, B.C.J., E. de Greef and F.J.J. Brinkmann, 1981. Persistency of organic contaminants in groundwater, lessons from soil pollution incidents in the Netherlands. Sci. Total Environ., 21: 187—202.