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# Department of the Environment

1. THE REMOVAL OF VOLATILE AND NON-VOLATILE ORGANIC COMPOUNDS FROM SMALL WATER SUPPLIES
2. REVIEW OF EUROPEAN EXPERIENCE AND ATTITUDES TO GROUNDWATER CONTAMINATION BY ORGANIC COMPOUNDS

## **FINAL REPORT**

Contract PECD 7/7/204

December 1987



**CONSULTANTS IN ENVIRONMENTAL SCIENCES LTD.**

DEPARTMENT OF THE ENVIRONMENT

1. THE REMOVAL OF VOLATILE AND NON-VOLATILE ORGANIC COMPOUNDS FROM SMALL WATER SUPPLIES.
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CONTRACT PECD 7/7/204

## SUMMARY

The extent of organic contamination of private groundwater-derived water supplies in the UK has been evaluated. Little information was found to exist with regard to specific organic compounds, other than that obtained as a result of investigations relating to complaints or serious contamination incidents caused by spillage or improper disposal of chemicals. Where monitoring of private supplies is carried out by Local Authorities, emphasis is, for reasons of limited resources, placed upon bacteriological quality and basic inorganic chemical parameters. One particular incident of aquifer contamination by chlorinated solvents in the Midlands was discovered, where supply to a factory had to be discontinued.

Treatment processes for the removal of volatile and non-volatile organic compounds have been identified and the performance characteristics have been assessed. Counter-current aeration towers are most efficient for volatile organics removal, whilst granular activated carbon filters are more suitable for reduction of non-volatile organic compounds.

Cost assessments of both aeration and granular activated carbon treatments revealed that for volatile contaminants counter-current aeration would be the preferred treatment method to granular activated carbon on cost grounds and that treatment by both methods was financially advantageous when compared with the alternative of resorting to a municipal water supply.

An assessment of the effects of aeration upon downstream water quality indicated that no significant changes would occur, but it is considered that disinfection should be carried out before aeration in order to preclude the possibility of bacterial growth in the aeration tower packing.

The extent of groundwater contamination by organic compounds in other European countries has been assessed, with particular emphasis on water quality standards and attitudes to public health, in the light of the current UK position.

Volatile chlorinated solvents were found to be the most common and widespread contaminants of aquifers, although there is increasing concern over the occurrence of agriculturally-applied pesticides in groundwater beneath intensive arable farming areas. Water quality standards have been established for chlorinated solvents by the Netherlands and West Germany, although in the latter country there is some dispute both over the relevance of the standard and the apparent politicisation of drinking water quality issues.

Public concern over the contamination of drinking water is well-developed in European countries, and particularly so in the Netherlands and West Germany, and concern is growing in the UK. This concern may not be valid scientifically or medically, given the low levels of contamination found at present. It is concluded that in the UK, with an increasing trend in groundwater contamination, there is a need to assist water undertakers, local authorities and industry in decisions over when to undertake or

require treatment of water through national interim guideline standards for chlorinated solvents in potable water.

Some other European countries appear to be more advanced in groundwater protection and treatment with respect to chlorinated solvents, than the UK. There is scope for economic application of remedial measures for treatment in some situations and to return use of sources which might otherwise be abandoned.

TITLE: STUDY OF THE REMOVAL OF VOLATILE AND NON-VOLATILE ORGANIC COMPOUNDS FROM SMALL WATER SUPPLIES

OBJECTIVES

- (i) To investigate the applicability of counter-current aeration treatment for the removal of volatile organic solvents from small water supplies, where abstraction rates are less than or equal to  $2.0 \text{ Ml d}^{-1}$ .
- (ii) To assess the suitability of aeration treatment to remote, unattended operation for long periods and to evaluate the likely effects upon downstream water quality and possible problems arising from unmanned operation.
- (iii) To evaluate the potential and limitations in performance of combined counter-current aeration units/granular activated carbon (GAC) absorption units for removal of volatile (principally trichloroethene and tetrachloroethene) and involatile (pesticides and others) organic contaminants.
- (iv) To examine the possibility of using combined counter-current aeration/GAC units for the control of tastes and odours in small water supplies.
- (v) Investigate and review situation in other EC Member States with regard to contamination of groundwater by organic compounds, to obtain information on control strategies and national legislation. Relate to situation and strategy in UK determined in Objectives (i to iv). Consider potential markets for treatment plant, and likely UK share.

Note:

The Report is presented in 2 parts:

Part 1 'The Removal of Volatile and Non-Volatile Organics from Small Water Supplies', (reports on objectives (i) to (iv))

Part 2: 'Review of European Experience and Attitudes to Groundwater', (reports on objective (v)).

## PROGRAMME OF WORK

### Phase 1            August - October 1986

Identification of potential numbers of small water supplies which would require aeration and/or GAC treatment.

Evaluation of literature pertaining to removal of organic compounds from water by aeration and GAC units.

Investigation of scaling factors to enable design of low throughout process units.

### Phase 2            October 1986 - January 1987

Collaboration with UK and other European agencies to establish in-service operating times and typical problems experienced.

Examine potential design of units for unattended operation with possible facilities for ICA and remote telemetric monitoring.

Study the effects of aeration/GAC treatment upon downstream water quality and suitability for potable supply.

Provide interim report by end November 1986.

### Phase 3            January - March 1987

Finalise design guidelines for combined aeration/GAC units for organics removal.

Assess the capital, installation and operating costs of typically-sized systems in the range up to 2.0Ml d<sup>-1</sup>.

Phase 4

April - September 1987

Establish contact with relevant persons concerned with water supply and the water industry in EC Member States to obtain information on:-

- Groundwater contamination by organics, present and predicted trends.
- Treatment/control strategies adopted.
- Relevant national legislation on organics in potable water (not specified individually in EC Directive on Quality of Water for Human Consumption).
- Implementation of this EC Directive and any derogations being considered for organic contamination covered by the Directive (including pesticides).
- Attitude to public health effects of organics.

Compare information and trends with UK position.

Prepare final report for DOE, incorporating the interim report and information obtained in all the study; including evaluation of situation and current practices and making recommendations for further action; noting extent of likely markets for suitable treatment.

1. THE REMOVAL OF VOLATILE AND NON-VOLATILE ORGANIC  
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## 1. INTRODUCTION

### 1.1 Background

Increased concern over the quality of water resources, and in particular the health risks associated with chemical contamination of potable water, have resulted in the promulgation of European legislation for the improvement and protection of water supplies. Of central concern are large municipal supplies, operated under the auspices of public water undertakings, where control of resources and quality have been the subject of concerted research and development over recent years. In addition, there exists in the United Kingdom a significant number of private water supplies, which may or may not be licensed by public water undertakings, ranging from fully-treated piped water systems to simple untreated abstractions from wells or river gravels and water drawn by buckets from springs, lakes or streams. It would appear, however, that the greater majority of private supplies are derived from shallow wells and springs and therefore may be considered to be drawn from groundwater sources which are susceptible to contamination by a variety of substances.

Private water supplies in the United Kingdom are responsible for approximately 2% by volume of water provided for human consumption. Such sources may be owned by public organisations, private industrial companies, users co-operatives or private individuals. Approximately 78,000 licensed private supplies are known to exist although it is further estimated that over one million may be in use, either continuously or infrequently. As many as 450,000 people regularly consume water supplied by private sources and it is suspected that up to 2 million people per annum consume water which is privately supplied, including those who drink at work, when on holiday and when visiting friends and relatives.

Comparatively few problems have been apparent in terms of the quality of private supplies with regard to the manifestation of health effects. Investigations conducted by the Private Supplies Sub-Committee of the Standing Technical Advisory Committee on Water Quality, over the years 1981-1983 (1), revealed that during the years 1930 to 1977 there were a total of 18 reported outbreaks of water-borne diseases "associated almost entirely with private sources of supply." With reference to the requirements of the EC Directive on the Quality of Water Intended for Human Consumption (2), it has been determined that only 20% (by volume) of private supplies yield suitable water, assessed mainly on the basis of bacteriological standards. Some sources are apparently satisfactory in microbiological terms but have problems associated with elevated mineral contents such as sulphate, sodium and nitrate. In the majority of cases, there are no widespread problems with continued consumption of such supplies, due possibly to acclimatisation on the part of regular users, but occasional or new users may be at risk. A recent communication with one of the Regional Water Authorities revealed that this was the case in an area where high concentrations of sodium sulphate occur naturally in shallow groundwaters. Minor short-lived stomach complaints are regularly experienced by visitors to the area, while the indigenous population remains largely unaffected.

Information made available to the Sub-Committee indicated that private supplies are declining in bacteriological quality and that quality problems may well arise by contamination from septic tank seepage and by the aggressive action of untreated water in the (albeit short) distribution systems. It was concluded that "whilst at present (1984) some supplies are excellent...the potential hazard to health of private supplies is increasing" and "a very large number of these private supplies are of poor bacteriological quality and will not meet the standards set by and contained in the EC Directive".

To date, therefore, the main areas of concern with regard to the quality of private water supplies have been microbiological and mineral. Little or no attention has been paid to the possible contamination of aquifers providing private supplies to individual dwellings, offices and industrial premises, by potentially toxic man-made chemicals.

## 1.2 Legislation Affecting Private Water Supplies

The legislation is largely complex, ill-defined and contained within a number of Acts, including the Public Health Act 1936, The Water Act 1945, The Water Act 1973 and The Water Resources Act 1963. Powers, duties and responsibilities provided by these Acts are adequately summarized in the Standing Technical Advisory Committee Report (1) and will not be repeated here. The EC Directive (2) also covers private water supplies and it is evident that the current UK legislation is insufficient to enable full compliance with the terms of the Directive and the Standing Technical Advisory Committee Report includes a number of recommendations for provisions to be made prior to improve and tidy the existing powers.

The main thrust of these recommendations includes firstly, clarification of the duties and rights of water authorities to inspect and sample water supplies, and secondly, improved powers to require a source owner to ensure compliance of the supply with the EC Directive. The Government is currently considering the necessary measures which should be taken.

## 2. CURRENT QUALITY OF PRIVATE WATER SUPPLIES

In an attempt to accumulate information on contamination problems with private groundwater supplies, Regional Water Authorities and the Environmental Health Departments of local authorities were contacted regarding any recorded incidents of pollution or complaints. Little information was forthcoming from water authorities as their involvement with private supplies tends to be mainly on a licensing basis, unless analytical or technical support is requested by a local authority when particular problems with a supply exist. However, some incidents of contamination were reported although most information was gleaned from public complaints received by Environmental Health Departments.

### 2.1 Coventry City Area

A particular contamination incident has occurred in the Coventry area of the West Midlands where a number of industrial premises with private groundwater abstractions have experienced high concentrations of trichloroethene in the supply. In one case, where groundwater was used to supply the factory canteen, the abstraction point was closed. Concentrations up to 5200 µg/l trichloroethene have been reported. The overall problem is under active consideration by the Coventry Pollution Prevention Panel (consisting of representatives from industry, the local authority and Regional Water Authority) and to date, efforts have been concentrated upon minimising the improper disposal of waste solvents which, it is suspected, has been practised previously. It is understood that approximately 10 supplies to industrial premises are affected by this type of contamination and, in addition, a Water Authority abstraction in the same area has exhibited contamination over a number of years (up to 150 µg/l trichloroethene) and a counter-current aeration unit has recently been installed to reduce pollutant concentrations to acceptable levels. This occurrence highlights an important aspect of

groundwater contamination in that, although it is known that contaminants tend to move in plumes through the saturated zone of an aquifer in the general direction of groundwater flows, it is possible that pollution detected in one abstraction may also be present, albeit at different concentrations, in another abstraction. Therefore, if it is known that an aquifer is contaminated at a major public abstraction, the possibility exists for contamination of private supplies abstracted from the same overall source aquifer.

## 2.2 Wessex Area

Only one incident in this Water Authority area is known, involving contamination of a relatively shallow (10m) chalk borehole supplying water for agricultural and domestic purposes. In 1984, a maximum concentration of 8.3µg/l carbon tetrachloride was detected during Water Authority analyses, conducted at the request of the local Environmental Health Department. The private supply was subsequently disconnected and the premises were connected to the public mains supply. The contamination was considered to have arisen from the indiscriminate disposal of waste solvent from metal degreasing operations.

A total of 3,000 private abstractions are licensed by Wessex Water Authority, the majority of which are groundwater sources. In addition, the regional civil defence planners, in conjunction with local authority emergency planning officers, are currently compiling a detailed register of all unlicensed abstractions in the area. Inspection of this register, compiled for use in times of national emergencies, revealed that there are numerous unlicensed spring and well supplies, many now disused, neglected or used only infrequently. Much of this information was gleaned from local council and parish records and these indicate that as many as 10,000-13,000 supplies may exist in the Wessex area.

### 2.3 South-West Area

Approximately 7,500 licensed abstractions exist in this area, most of which supply  $\leq 10,000$  l/d for mainly agricultural and domestic purposes. Occasional problems and complaints concerning taste and odour have been experienced but specific causes have not been identified. There also exist up to 400 abstractions used almost exclusively for seasonal domestic supply. No incidents of contaminations by organic substances have been reported to date.

### 2.4 Thames Area

Of the 3640 licensed private water abstractions, approximately 283 private groundwater sources exist for industrial, office and welfare purposes. No particular incidents of contamination by organic compounds are known by the Water Authority. Contact with selected Environmental Health Departments in the Thames area revealed no further information regarding contamination of private supplies, although a response from the City of London Health Department, in whose area a number of private borehole sources exist, revealed that regular monitoring for bacteriological and major chemical parameters is carried out, as required under the terms of the EC Directive (2).

### 2.5 Yorkshire Area

Out of a total of 3,600 licensed abstractions, approximately 170 are private industrial groundwater sources and a similar number of domestic/agricultural supplies exist. In common with other Water Authorities, the quality of private supplies is not monitored; those termed as domestic being the responsibility of the Environmental Health Departments, while industrial sources are the responsibility of the individual users.

No instances of organic contamination of private supplies were known.

## 2.6 Northumbrian Area

A moderate number (2000) of licensed private abstractions exist in this area with some unlicensed groundwater abstraction, mainly for domestic/agricultural use. The major problems experienced to date include bacteriological quality, occasional taste and odour complaints and, in some areas, high concentrations of magnesium and sodium sulphates, due to adverse regional geological features.

In general, from the information accumulated to date, it appears that relatively few instances of contamination by organic substances of private water supplies have been detected although some specific problems do exist in particular areas of the country. A number of local authority Environmental Health Departments are aware of their potential greater involvement in monitoring private supplies under the terms of the EC Drinking Water Directive and are currently formulating plans for checking the quality of abstractions in their areas. Such exercises will obviously place a greater burden on local authority resources and it appears doubtful whether comprehensive analyses can be carried out for all private water supplies in all areas of the country, due to limitations in local authority budgets and manpower.

### 3. TREATMENT TECHNOLOGY

Efficient removal of organic contaminants from potable water supplies is difficult to achieve with conventional water treatment processes unless the individual compounds have very low water solubility and can be removed by coagulation and sedimentation or can be oxidised by disinfection processes.

The choice of treatment options is basically between aeration or adsorption using activated carbon. Because of the volatile nature of many of the trace organic contaminants in ground water aeration is an effective treatment, causing volatilisation of the contaminants. This can be achieved by using a simple diffused air aeration system or using a counter-current packed column.

Activated carbon treatment also gives good removal of volatile organics and may be used in addition to, or as an alternative to aeration.

Resins may also be used for adsorption, but little work has been carried out to assess their suitability for potable water treatment. The indications at present are that their use would be uneconomic in comparison with aeration or activated carbon treatment.

#### 3.1 Activated Carbon

Activated carbon has been successfully used in water treatment for many years, particularly for the removal of humic substances and organics that give rise to taste and odour problems. Two systems are available, these being powdered activated carbon (PAC) and granular activated carbon (GAC). PAC is used at approximately 100 water treatment works in the UK and is useful where the carbon dosing requirement is intermittent. There is a low capital cost but high running cost because PAC cannot be

regenerated and has to be disposed of with the water works sludge. GAC systems are used on only 4 treatment works in the UK. These have high capital but low running costs because the carbon can be regenerated and re-used when exhausted, and because the carbon itself has a higher absorption capacity than PAC.

GAC is effective in removing volatile organic compounds, particularly those with low polarity, low water solubility and high molecular weight. For continuous removal of contaminants PAC would not be suitable and will not be considered further.

### 3.1.1 Adsorption Process

The adsorptive properties of activated carbon are mainly attributable to the highly porous structure and large surface area. A particle of activated carbon has a complex network of interconnecting pores. Water carrying contaminants diffuses into this system and the molecules of the impurities are attracted and held to the carbon surface by weak intermolecular forces. The basic properties of materials that increase their adsorption onto activated carbon are:

- (a) low solubility in water
- (b) low polarity or ionic character
- (c) increased molecular weight
- (e) low pH for organic acids, high pH for organic bases
- (f) low temperature

### 3.1.2 Isotherms

Adsorption from an aqueous solution involves concentration of the solute on the carbon surface. As the process proceeds the equilibrium condition is reached at which point the rate of exchange of material between the carbon and the solution is equal, i.e., no change can be observed in the concentration of the solute on the carbon surface or in the bulk solution.

Isotherms provide a relationship between the amount of solute adsorbed per unit of carbon and the equilibrium concentration. This provides a starting point for design evaluations. The most commonly used isotherms are the Langmuir and Freundlich. These may be described as follows:

Langmuir

$$X/M = \frac{X_m b C_e}{1 + b C_e}$$

X/M = Amount of solute adsorbed per unit weight of carbon

C<sub>e</sub> = Equilibrium concentration of the solute

X<sub>m</sub> = Monolayer capacity

b = Constant

Freundlich

$$X/M = K C_e^{1/N}$$

X/M = Amount of solute adsorbed per unit weight of carbon

C<sub>e</sub> = Equilibrium concentration of the solute

K, 1/N = System constants

The Freundlich isotherm equation is probably the most widely used and is an empirically derived expression. For calculation purposes equilibrium concentration (C<sub>e</sub>) is set to the desired out-flow concentration. The values of K and 1/N can be found in the literature, these being specific to the individual compounds and carbon types. Examples are given in Table 1.

As can be seen there is a wide variation of values for the different compounds, even for the same compound different carbon types give widely varying parameters. The value of 1/N for most compounds is less than 1/A (steep slope i.e. 1/N ≈ 1) indicates high capacity at high equilibrium concentrations

TABLE 1. Examples of Freundlich Isotherm Parameters

Mean Adsorption Capacity, mg/gm @ Equilibrium Concentration = 500 µg/L

	Freundlich Parameters		Freundlich Parameters				
	K	1/n	K	1/n			
Benzene	1.0	1.6*	trans-1,2-dichloroethylene	3.1	0.5*		
	16.6	0.4**		1,1-dichloroethylene	4.9	0.5*	
	49.3	0.5†			16.0	0.5‡‡	
	29.5	0.4††			Methylene chloride	1.3	1.2*
	14.2	0.4§				1.6	0.7***
Carbon Tetrachloride	11.1	0.8*	Tetrachloroethylene			50.8	0.6*
	28.5	0.8†		84.1		0.4§§	
	39.1	0.7**		273.0		0.6***	
	25.8	0.7††		128.0	0.5‡‡		
	14.2	0.7§		1,2,4-trichlorobenzene	157.0	0.3*	
	14.8	0.4§§			1,1,1-trichloroethane	2.5	0.3*
18.7	0.6‡‡	9.4	0.5§§				
Chlorobenzene	91.0	1.0*	13.5			0.5‡‡	
	1,2-dichlorobenzene	129.0	0.4*			Trichloroethylene	28.0
		1,3-dichlorobenzene	118.0	0.4*			26.2
			1,4-dichlorobenzene	121.0	0.5*		28.2
226.0				0.4**	63.1		0.5‡‡
1,2-dichloroethane	3.6			0.8*	cis-1,2-dichloroethylene	8.4	0.5§§
	5.7	0.5§§		8.5		0.7†	
	4.8	0.5†‡	10.2	0.6‡‡			

Freundlich equation:  
 $x/m(\text{mg/gm}) = K C(\text{mg/l})^{1/n}$

\*Filtrisorb® 300(5)      §Hydrodarco® 1030(9)      ††Nuchar® WV-G(9)  
 \*\*Filtrisorb® 400(9)      §§Witcarb® 950(11)      ‡Filtrisorb® 300(11)  
 \*\*\*Filtrisorb® 400(10)      †Norit(9)      ‡‡Filtrisorb® 400

rapidly diminishing at lower equilibrium concentrations. Gentler slopes ( $1/N \approx 0$ ) indicate a capacity relatively unaffected by the equilibrium concentration. An increased value of K (for a given value of  $1/N$ ) increases capacity.

### 3.1.3 Design Considerations

There are three basic types of GAC contactors. These are:

(a) Gravity Contactor - concrete construction.

These are essentially the same as rapid gravity filters (RGF) used for water treatment. An inexpensive contactor can be made by replacing the sand in an RGF with GAC.

(b) Gravity Contactor - steel construction.

These are normally large diameter, field erected structures.

(c) Pressure Contactor.

These are usually shop fabricated, cylindrical pressure vessels. They may be constructed from steel, plastics or reinforced resins.

For the purpose of this study (in view of the flow rates considered), the most likely design would be a pre-fabricated pressure vessel.

The first design stage is to select the flow rate of the water being treated, the type of contaminant, the inflow and required outflow concentrations, the surface loading rate and the empty bed contact time (EBCT). If the raw water source contains several different contaminants the design must be directed towards the compound most difficult to remove (i.e. high  $1/n$  and low K), the compound with the most stringent water quality standard or the compound with the highest inflow concentration.

The EBCT is a critical design character for an adsorption system. This represents the length of time the contaminated water is in contact with the carbon and so determines whether or not the system reaches equilibrium. Ideally a pilot plant should be set up to determine the optimum EBCT but if this option not possible a minimum value of 10 minutes is recommended.

The usual range of surface loading rates is  $1.36 \times 10^{-3}$ – $5.43 \times 10^{-3} \text{ m}^3 \text{ m}^{-2} \text{ S}^{-1}$ . However, this is dependent on the optimisation of capital and operating costs, in terms of size of column and pumping costs.

The design proceeds by calculating the quantity of carbon required to produce the desired outflow water quality for the quoted flow rate and inflow concentration. From this the bed size and run time between regenerations can be calculated. Details of the design procedure are given in Appendix 1.

A short computer programme was written to run through the basic design calculations. The listing, along with examples of print out, are given in Appendices 3 and 4.

On large treatment plants it may be economic to have a GAC regeneration plant on site. However, on treatment plants using less than  $900 \text{ kg d}^{-1}$  this is not worth considering, with off-site regeneration a much more cost-effective option. On plants using less than about  $200 \text{ kg d}^{-1}$  it may be economic to dispose of the spent carbon and purchase new material.

### 3.2 Aeration

The general principles and operation of both diffused air and counter-current aeration units have been described in a previous report to the DoE (11) and therefore consideration here of these processes will be confined to their possible application to the treatment of small private groundwater supplies, which will involve an examination of performance at relatively low water abstraction rates and detailed design and costing factors.

### 3.2.1 Diffused-air System

Also termed plate-aerators, these units consist of a tunnel-shaped horizontally-inclined hemi-spherical vessel, where the abstracted water flows across perforated plates in the base, through which filtered air is force-blown. The maximum practical air to water ratio that can be applied is of the order 20:1 which, as a result, limits the mass transfer of volatile organics from water to the air phase and thus limits the overall removal efficiency of the process. Therefore, these units have only been considered for 'roughing' treatment purposes, such as those which have been used at Hilversum in the Netherlands for pre-treatment of polluted groundwaters abstracted from interceptor wells prior to re-use for cooling purposes. However, it is possible that such units may have some beneficial application to the treatment of small groundwater supplies, due to their uncomplicated construction, small size and relative ease of operation, which may be factors of prime consideration in such circumstances. An additional factor of central interest in the case of small water supplies is that minimal headloss is incurred with the use of plate aerators which obviates the possible requirement for relatively costly re-pumping of flows (owing to the horizontal orientation of the units) and therefore the units could be incorporated into existing treatment/supply systems with little disturbance. Although the higher mass transfer and removal efficiencies will not be achieved (compared to those possible with counter-current aeration). It is possible that diffused-air systems, such as plate aerators, could achieve modest removal efficiencies, which may be sufficient for complying with public health requirements, although the exact nature of current legislation is far from clear with regard to volatile organic contaminants. This will be discussed more fully in a subsequent section.

### 3.2.2 Counter Current Packed Tower Aeration

A more effective method of removing volatile organics is the use of a counter-current packed column. The aeration system consists of a column in which packing materials are used to provide a large surface area and large void volume. The contaminated water flows downward by gravity and air is blown upward. Continuous contacting of gas and liquid is achieved, minimising the thickness of liquid film on the packing and thus promoting efficient mass transfer. Contaminant free water runs off from the bottom of the tower and the exhaust air, contaminated with organics, is blown off to atmosphere.

### 3.2.3 Theory of Aeration

The tendency for a compound to distribute between the gas and liquid phases is described by Henry's Law which states:

$$P_A = H_A X_A^*$$

(Valid at low concentrations)

$P_A$  = partial pressure of component in air

$H_A$  = Henry's Law coefficient

$X_A^*$  = Solution concentration of contaminant at equilibrium

Dalton's Law States that:

$$P_A = Y_A P_T$$

$Y_A$  = mole fraction of contaminated air

$P_T$  = total air pressure

combining these:

$$Y_A = (H_A/P_T) \cdot X_A^*$$

This tells us that for higher  $H_A$  values the contaminant will favour the gas phase. Thus in water treatment for removal of volatile organics, compounds with high  $H_A$  values will be more easily removed.

This relationship only gives the equilibrium situation in the column. The 'driving force' for stripping to occur is the difference between the actual conditions (operating relationship) in the column and the equilibrium conditions, and indicates how far the system is from equilibrium. The operating relationship can be found by performing a mass balance over the column. In order to determine the rate at which the system moves to equilibrium the mass transfer coefficient is required which is primarily dependent on the water flow conditions and the packing characteristics.

#### 3.2.4 Design Considerations

The depth of packing in a counter-current tower is a complex function of the required removal, the volatility of the contaminant, the air/liquid ratio, the liquid loading rate, the packing type and physical conditions such as ambient temperature and pressure.

Assuming steady state operation a mass balance can be performed over the tower to give the following relationships:

$$Z = HTU + NTU$$

Z = packing height

HTU = height of transfer unit

NTU = number of transfer units

#### 3.2.5 Basic Design Example

Assume  $500\text{m}^3\text{d}^{-1}$  abstraction,  $100\mu\text{g}\text{l}^{-1}$  trichloroethene, 95% removal required.

### STEP 1

Select type of packing. The most recent development is Intalox (trademark) 'snowflake'. Packing factor,  $F$ , = 13.

### STEP 2

Determine the mass transfer coefficient  $K_L a$ . Ideally, this should be experimentally derived but there are a number of reported values for trichloroethene in the literature and a good average figure is  $K_L a = 0.013s^{-1}$ .

### STEP 3

Select an air to water ratio (A:W). (From the literature, A:W of 45 maximises the  $K_L a$  value for trichloroethene) and compute the dimensionless stripping factor,  $R$ :-

$$R = (A:W) \cdot \frac{\rho_a}{\rho_w} \cdot \frac{M_w}{M_a} \cdot \frac{H_a}{P}$$

where  $\rho_a$  is density of air ( $Kgm^{-3}$ )

$\rho_w$  is density of water ( $Kgm^{-3}$ )

$M_w$  is molecular weight of water

$M_a$  is molecular weight of air

$H_a$  is Henry's law constant (387.66 atm)

$P$  is operating pressure of aerator (1 atm) at given temperature ( $10^\circ C$ ).

$$R = 45 \cdot \frac{1.247}{999.6996} \cdot \frac{18}{28.8} \cdot \frac{387.66}{1} = 13.6$$

### STEP 4

Select required pressure drop gradient through packing. A value of  $250 Nm^{-2}m^{-1}$  is suitable for this type.

Compute air to water mass flux ratio ( $G_1$ )

$\overline{L_1}$

$$= (A:W) \cdot \frac{p_a}{p_w} = 45 \cdot \frac{1.247}{999.6996} = 0.056$$

use this value to obtain an abscissa value in figure 1.

Then compute:  $L_1 (p_a)^{0.5} = 0.63$

$$\overline{G_1} \cdot \overline{p_w - p_a}$$

Therefore, from figure 1,

$$\frac{G_1^2 \cdot F \cdot v^{0.1}}{p_a (p_w - p_a)} = 0.02 \quad (v = \text{dynamic viscosity of water, } 0.0012 \text{ Kgm}^{-1}\text{S}^{-1})$$

Therefore the water surface loading rate,  $L_1 =$

$$\frac{G_1}{0.056} = 1.06$$

$$\frac{\quad}{0.056} = 18.93 \text{ Kgm}^{-2}\text{S}^{-1}$$

Therefore, the volumetric water surface loading rate,  $L_2$ , is  $68.2 \text{ m}^3\text{m}^{-2}\text{h}^{-1}$ .

#### STEP 5

Compute required diameter of aerator (DM) where  $Q =$  volumetric water flow rate,  $\text{m}^3\text{h}^{-1}$ .

$$D = (4Q)^{0.5} = (4 \times 20.833)^{0.5} = (0.39)^{0.5} = 0.63\text{m}$$

$$\frac{\quad}{\pi L_2} \quad \frac{\quad}{\pi \times 68.2}$$

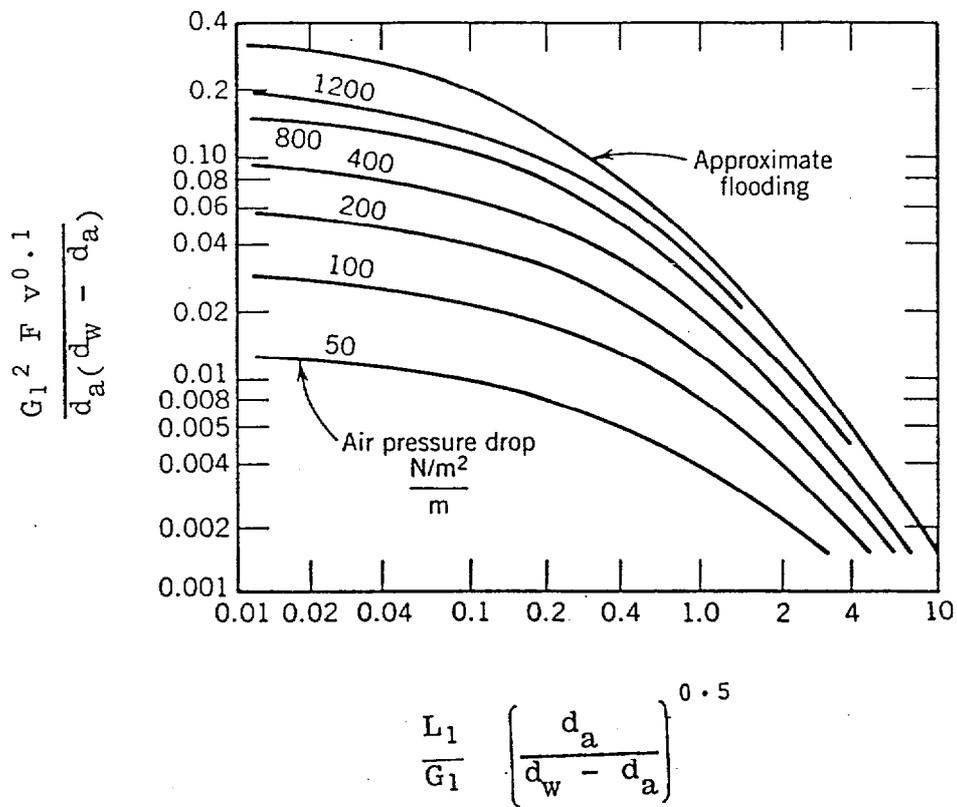


Figure 1. Generalised Pressure Drop Correlation.

STEP 6

Determine height of a transfer unit (HTU)

$$HTU = L_2 = \frac{18.9 \times 10^{-3}}{K_L a} = \frac{18.9 \times 10^{-3}}{0.013} = 1.454$$

STEP 7

Determine the number of transfer units (NTU).

$$C_1 = 100 \text{gl}^{-1}$$

$$C_2 = 5 \text{gl}^{-1}$$

$$NTU = \frac{R}{R-1} \ln \left[ \frac{(C_1 \cdot (R-1)) + 1}{C_2} \right]$$

$$NTU = \frac{13.6}{12.6} \ln \left[ \frac{(20.12.6) + 1}{13.6} \right] = 1.079 \ln 18.6$$

$$NTU = 3.15$$

STEP 8

Determine height of packing required, Dp (m)

$$Dp = HTU \cdot NTU = 1.454 \cdot 3.15 = 4.58 \text{ m}$$

Therefore, this procedure gives an aerator of diameter 0.63m, packing height 4.58m, air flow 937.5 m<sup>3</sup>h<sup>-1</sup>, water flow 20.83 m<sup>3</sup>h<sup>-1</sup> to reduce 100gl<sup>-1</sup> trichloroethene to 5gl<sup>-1</sup>.

#### 4. FINANCIAL CONSIDERATIONS AND COSTING

##### 4.1 General Aspects

Various cost estimates have been produced for granular activated carbon (GAC) and aeration treatment of groundwaters (6,7) in addition, the most comprehensive EPA document available (8) contains a comparison of counter-current and diffused-air aeration systems. Operating costs of counter-current aerators were found to be 30% to 50% of those associated with comparable GAC adsorbers and the total costs of aeration were computed as 55% of the costs of GAC. The aeration costs comparison also revealed that counter-current aerators were more cost-effective than diffused-air systems and were particularly so when water flow rates were high and high removal rates (>95%) of contaminants were required. Typical unit costs of counter-current aeration varied between 13% and 50% of those for diffused-air units.

Such cost comparisons, in the main, are computed solely for additional treatment of water and generally assume capital and running cost expenditure by a public body such as (in the UK context) a Regional Water Authority or water company. In the case of small private water supplies, a more comprehensive cost benefit assessment may have to be made, in order to compare the costs of treatment with the possible alternative strategy of curtailing abstraction from a contaminated supply and connecting to the public supply provided by a statutory water undertaking.

In most cases in the UK, water supplied to domestic premises by a Regional Water Authority or water company costs the consumer between 17p/m<sup>3</sup> and 25p/m<sup>3</sup>, whereas the costs of producing water from a private supply of abstraction size <1 Ml/d can be, typically, of the order 5 - 10 p/m<sup>3</sup> or less, (figure derived

from Warden, 1986 (9)). Therefore, given the unit cost differential, there exists the possibility that treatment of a private supply to the required standard can be achieved such that the eventual unit cost of supplied water could be lower than that of an introduced public supply.

A recent paper (9) details the costs involved in producing potable water from a private abstraction source and these are reproduced below.

**TABLE 2. Estimated Operating Costs of Small Supplies**

Cost Element	Each Supply £ per annum	Number of Supplies	Total for all Supplies £000 per annum
Routine attendance	1500	1200	1800
Maintenance & Repair	300	1200	360
Sampling & Analysis	850	1200	1020
Chemicals	50	1200	60
Electricity - dosing	88	600	53
- pumping	3017	420	1267
Dealing with complaints	1200	1200	1440
<b>TOTAL ANNUAL OPERATING COST</b>			<b>6000</b>

From Warden, 1986 (9).

Although these costs were estimated for abstraction sources of less than 1Ml/d, it is considered that the unit costs derived will also apply to those in the range up to 2Ml/d.

In the case of privately-owned sources of potable water, works to improve either water quality or renew components of the treatment or distribution systems qualify for mortgages and loans to home owners through building societies and banks and therefore, such loans will presumably be subject to income tax relief at the applicable percentage rate. Where improvements to larger private

supplies are concerned, such as an estate-owned and run supply, finance would have to be sought in the form of a normal bank loan (at an interest rate above bank base rates which may be negotiable) or, where a local authority initiates improvement schemes, financial support can be arranged under the provisions of the Public Health Act (1).

Previous cost evaluations of counter-current aeration treatment of contaminated groundwaters, for abstraction rates in the range 2.25 Ml/d to 9 Ml/d revealed that unit costs would vary between 0.6 p/m<sup>3</sup> and 0.9 p/m<sup>3</sup>. At flow rates below 2 Ml/d, economies of scale inherent in the above analysis would not apply to the same extent and therefore unit costs would be proportionately greater.

As far as purely domestic private supplies are concerned, the costs of any remedial measures taken are either borne by the individual or, in the case of a communal supply, can be recovered from the consumers. The situation is less straightforward in the case of industrial premises utilising a private water source for process or production purposes, which requires treatment to remove organic contaminants. The additional financial burden involved in either providing treatment or converting to a public mains water supply may have a significant effect upon profitability, particularly for a marginal industrial operation, in terms of both capital and operating costs.

An additional problem may occur where a number of industries in a particular location or region are affected by contaminated groundwater (e.g. Section 2.1) in that, should on-site treatment prove undesirable, impracticable or financially unacceptable, there may be insufficient supply capacity available in the Water Authority or Water Company Distribution system to satisfy the requirements of the potential consumers. In the extreme case, it is possible that the public water undertaking may be obliged to treat water from the contaminated aquifer to supply the

industrial premises involved, although it is unlikely that this situation would arise in practice. In the majority of cases, it is financially advantageous for a water undertaking to increase the number of customers, particularly industrial consumers of water, in its area but unusual circumstances can exist in particular areas which may encourage private water supply users to develop and improve their own abstraction sources.

#### 4.2 COST ASSESSMENT OF COUNTER-CURRENT AERATION

Although some preliminary indications of the cost of operating and maintaining private water supplies have been given by Warden (9), these are generally assumed to apply to remote communities where no mains water supply is available and where the source of finance for improvements to the supply may be diffuse. In the case of industrial premises utilizing a private borehole source, as a cost-effective alternative to the mains supply, the costs involved in treatment to remove volatile organic contaminants can be more accurately derived and compared to the alternative option of switching to municipal supplies.

For removal of volatile organic contaminants from water counter-current packed column aeration units are acknowledged to be the most effective and economical process. For the subsequent cost assessments, budget prices were obtained from equipment manufacturers and suppliers, based upon the required system capacities of 500 and 1000 m<sup>3</sup>d<sup>-1</sup> abstraction rate. Installations were designed using the procedure outlined in Appendix 2, to achieve 95% removal of trichloroethene at an initial concentration of 100µg l<sup>-1</sup>.

The following assumptions were made:

- \* All costs at 1st quarter 1987 prices
- \* Systems would operate at 100% design capacity with the exception of air blowers which would be 50% over-designed to allow for an increase in air : water ratio in the event of increases in contaminant concentration.

- \* Units installed at industrial premises, therefore lowering operator attendance/routine maintenance times. Remotely-sited units would generate high routine attendance costs (possibly by a factor of 2-3).
- \* Operation 24h/day, 7 days/week, 48 weeks/year, allowing for annual shut-down Christmas and summer.
- \* Lifetime of equipment has been assumed to be 20y non-mechanical, 10y mechanical/electrical.
- \* Capital blower costs allow for 1 duty plus 1 standby unit.
- \* Total head for pump calculations taken as 15m plus 2m losses plus column height (22m).
- \* Efficiency of water pump and air blower taken as 75% and 50% respectively.
- \* Electricity cost 5p KWh<sup>-1</sup>
- \* Mains water cost 20p m<sup>-3</sup>.

As a result of the above assumptions, the financial analyses in Tables 3 and 4 may not be taken as absolute, but rather as indicative of the scale of costs involved.

Table 3 Budget Cost Assessment 500 m<sup>3</sup>d<sup>-1</sup> system for 95% removal of 100 µg l<sup>-1</sup> Trichloroethene

	£	p/m <sup>3</sup>
<hr/>		
CAPITAL COST	COST	UNIT COST*
COLUMN SHELL 5mx 0.5m diameter 304SS	2 710	0.08
COLUMN INTERNALS (distributors, gas injection plate)	1 600	0.05
COLUMN PACKING	375	0.01
PUMP (submersible)	2 800	0.08
BLOWER	1 200	0.04
INSTRUMENTATION	2 000	0.06
INSTALLATION	5 000	0.15
<hr/>		
TOTAL CAPITAL	15 685	0.46
<hr/>		
OPERATING COSTS		
PUMP 20y	9 150	0.27
BLOWER 20y	7 500	0.22
MAINTENANCE - operator	19 500	0.58
- spares	12 937	0.38
<hr/>		
TOTAL OPERATING	49 087	1.46
<hr/>		
TOTAL COST	64 772	1.92

\* Over 20 years

Table 4 Budget Cost Assessment 1000 m<sup>3d-1</sup> system for 95% removal of 100 gl<sup>-1</sup> Trichloroethene

	£	p/m <sup>3</sup>
CAPITAL COST	COST	UNIT COST *
COLUMN SHELL 5mx 1.0m diameter 304SS	3 672	.055
COLUMN INTERNALS (distributors, gas injection plate)	2 070	.03
COLUMN PACKING	1 875	.03
PUMP (submersible)	3 500	.05
BLOWER (centrifugal)	1 600	.02
INSTRUMENTATION	2 500	.04
INSTALLATION	5 000	.07
<b>TOTAL CAPITAL</b>	<b>20 217</b>	<b>0.30</b>
<b>OPERATING COSTS</b>		
PUMP 20y	18 329	0.27
BLOWER 20y	12 000	0.18
MAINTENANCE - operater	27 000	0.40
- spares	16 380	0.24
<b>TOTAL OPERATING</b>	<b>73 709</b>	<b>1.09</b>
<b>TOTAL COST</b>	<b>93 926</b>	<b>1.39</b>

\* Over 20 years

The budget cost assessments compiled herein reveal that treatment of solvent-contaminated water can be achieved at a favourable cost, when compared to the alternative of resorting to a municipal mains water supply. The unit costs in p/m<sup>3</sup> have been computed on the basis of a 20 year operational lifetime, to include maintenance and component replacement as necessary. However, it is possible or even likely that contamination in the groundwater aquifer will not persist for this length of time and, hence, a comparison of the unit costs over varying periods of operational time has been compiled and is included in Table 5.

**TABLE 5.**  
Comparison of Unit Costs incurred over different operating lifetimes.

System Capacity m <sup>3</sup> /day	Lifetime y	Unit Cost p/m <sup>3</sup>
1000	2	3.62
	5	2.14
	10	1.64
	20	1.39
500	2	5.17
	5	3.00
	10	2.28
	20	1.92

When compared with the cost of municipal water supplied to industrial users at approximately 20 p/m<sup>3</sup>, the financial advantages are seen to be substantial. If the treatment system should become redundant after only 2 years, the net asset value inherent in the capital items of the treatment plant will also accrue to the total company assets.

Considered over an operating period of 2 years, the potential cost savings incurred by treating a contaminated supply rather than resorting to mains water are considerable, as indicated in Table 6, amounting to £49,960 and £110,380 for  $500\text{m}^3\text{d}^{-1}$  and  $1000\text{m}^3\text{d}^{-1}$  supplies respectively. The above examples have been derived on the basis of 24h operation for 48 weeks per annum. Should the aeration units only be operated for an 8h working day, then the unit costs would change to those given in Table 7, together with the cost savings incurred over the use of a mains water supply.

Table 6 Potential cost savings incurred over 2 year period by treating a contaminated supply.

VOLUME m <sup>3</sup> d <sup>-1</sup>	SOURCE	UNIT COST pm <sup>-3</sup>	TOTAL COST £ (2 years) 000	COST SAVING £000
500	mains	20	67.38	49.96
	treated	5.17	17.42	
1000	mains	20	134.77	110.38
	treated	3.62	24.39	

Table 7 Unit costs for treated water assuming 8hd<sup>-1</sup> operation over 2 year period and cost savings

VOLUME m <sup>3</sup> d <sup>-1</sup>	SOURCE	UNIT COST pm <sup>-3</sup>	TOTAL COST £000	COST SAVING £000
500	mains	20.0	22.46	5.14
	treated	15.42	17.32	
1000	mains	20.0	44.92	22.26
	treated	10.09	22.66	



The two cost examples for trichloroethene reveal that treatment of contaminated groundwater by GAC adsorption is more expensive than counter-current aeration, where respective unit costs of 5-6  $\text{pm}^{-3}$  compare to 1.3-1.8  $\text{pm}^{-3}$ . Where non-volatile organics are concerned and air-stripping cannot be applied, approximate unit costs for GAC adsorption of gamma-HCH are in the range 2.1-2.8  $\text{pm}^{-3}$ . All of these examples serve to illustrate that treatment of a private supply can be achieved at favourable cost in comparison to utilising municipal mains water, providing a suitable treatment process is selected.

Table 8 500 m<sup>3</sup>/day system for 95% removal of 150 gl<sup>-1</sup> Trichloroethene from water

CAPITAL COSTS	COST £	UNIT COST * p/m <sup>3</sup>
PRESSURE VESSEL Carbon bed depth 2.44m diameter 1.3m	10 900	0.32
ACTIVATED CARBON CHARGE	2 302	0.07
INSTRUMENTATION/CONTROLS	1 700	0.05
PUMP	1 950	0.06
INSTALLATION	5 000	0.15
<b>TOTAL</b>	<b>19 352</b>	<b>0.65</b>
<b>RUNNING COSTS</b>		
ELECTRICITY Pump	11 530	0.34
CARBON REPLACEMENT 2302x60	138 120	4.10
MAINTENANCE Spares Labour	5 840 24 000	0.17 0.71
<b>TOTAL</b>	<b>198 842</b>	<b>5.97</b>

\* Over 20 years

Table 9 1000 m<sup>3</sup>/day system for 95% removal of 150 gl<sup>-1</sup> Trichloroethene from water.

CAPITAL COSTS	COST £	UNIT COST p/m <sup>3</sup>
PRESSURE VESSEL to allow Carbon bed depth 2.44m diameter 1.9m	13 000	0.19
ACTIVATED CARBON CHARGE	4 604	0.07
INSTRUMENTATION/CONTROLS	2 000	0.03
PUMP	2 600	0.04
INSTALLATION	5 000	0.07
<b>TOTAL</b>	<b>24 704</b>	<b>0.40</b>
<b>RUNNING COSTS</b>		
ELECTRICITY Pump	15 724	0.23
CARBON REPLACEMENT 20y 4604x60	138 120	4.10
MAINTENANCE Spares Labour	9 960 24 000	0.15 0.35
<b>TOTAL</b>	<b>350 628</b>	<b>5.23</b>

Table 10 500 m<sup>3</sup>/day system for 95% removal of 150 g/l<sup>-1</sup> gamma-HCH from water.

CAPITAL COSTS	COST £	UNIT COST p/m <sup>3</sup>
PRESSURE VESSEL to allow Carbon bed depth 2.44m diameter 1.3m	10 900	0.32
ACTIVATED CARBON CHARGE	2 302	0.07
INSTRUMENTATION/CONTROLS	1 700	0.05
PUMP	1 950	0.06
INSTALLATION	5 000	0.15
TOTAL	19 352	0.65
RUNNING COSTS		
ELECTRICITY Pump	11 530	0.34
CARBON REPLACEMENT 20y 2302x15	34 530	1.02
MAINTENANCE Spares Labour	5 840 24 000	0.17 0.71
TOTAL	95 252	2.89

Table 11 1000 m<sup>3</sup>/day system for 95% removal of 150 g/l gamma-HCH from water.

CAPITAL COSTS	COST £	UNIT COST p/m <sup>3</sup>
PRESSURE VESSEL to allow Carbon bed depth 2.44m diameter 1.9m	13 000	0.19
ACTIVATED CARBON CHARGE	4 604	0.07
INSTRUMENTATION/CONTROLS	2 000	0.03
PUMP	2 600	0.04
INSTALLATION	5 000	0.07
<b>TOTAL</b>	<b>24 704</b>	<b>0.40</b>
RUNNING COSTS		
ELECTRICITY Pump	15 724	0.23
CARBON REPLACEMENT 20y 4064x15	69 060	1.02
MAINTENANCE Spares Labour	9 960 24 000	0.15 0.35
<b>TOTAL</b>	<b>143 448</b>	<b>2.15</b>

## 5. DOWNSTREAM WATER QUALITY EFFECTS OF AERATION

Few studies have been concerned with the above topic with the exception of some limited work conducted in the USA (10).

### 5.1 Iron and Manganese Precipitation

Aeration is a well known technique for removal of iron and manganese from groundwaters, where concentrations are in excess of  $1\text{mg l}^{-1}$ . In the study referred to above (10), iron concentrations in the raw water entering an aeration tower were of the order  $4\text{--}5\text{ mg l}^{-1}$  and the polypropylene packing material turned a bright orange colour, due to ferric oxide deposition, after only a few hours operation. Effluent colour and turbidity levels were found to be approximately 70 cu and 20 NTU respectively. Where it is intended that ferruginous or manganese-bearing groundwaters are to be treated by aeration, therefore, an additional filtration step would be required to remove precipitated oxidised iron or manganese.

### 5.2 Microbiological Contamination and Disinfection

By treating water with large amounts of ambient air, the possibility of introducing microbiological contamination exists, particularly where prior disinfection (chlorination) of the water is not practised. The packing units in aeration towers can provide an ideal growth support medium for certain organisms, seeded from the process air. Unless groundwater treated by aeration is to be used in non-critical applications, it would appear prudent to chlorinate before aeration to ensure acceptable downstream quality and to prevent growths in the tower packing.

With regard to effects upon chlorine species of aeration, experiments conducted in the USA have indicated that total chlorine residuals in aerated water were at least 90% of those measured in the influent stream, even where air to water volumetric ratios of 100 : 1 were used (10).

### 5.3 Mineral Scaling, pH and Langelier Index

Stripping of dissolved carbon dioxide ( $\text{CO}_2$ ) from water in an aeration unit can have several effects, including disruption of the bicarbonate/carbonate balance, increase in pH and increase in the Langelier index, a measure of the scale-forming or aggressive potential of the water. Experiments conducted at a pilot scale air stripping facility in California (10) reported average increases in pH of 0.4-1.4 units, little change in calcium levels but a significant increase in the Langelier index, indicating an increased tendency for scale formation. However, no scale formation on the column packing was experienced over 3 months of operation. In cases where scale formation has been found to occur, simple acid washing and rinsing of the unit with minimal operational downtime can be conducted.

## 6. CONCLUSIONS

- 6.1 Information on the contamination of private water supplies by organic substances is at best scarce and is largely non-existent. In the majority of cases where information is available, it has been acquired by Regional Water Authorities or Water Companies, in response to requests from Local Authority Environmental Health Departments following complaints by individuals using a private supply. Little information, with the exception of that from the Coventry area, has been acquired by Local Authorities or individual consumers.
- 6.2 From enquiries conducted to date, it appears that most Local Authorities are aware of their responsibilities to monitor the quality of private supplies, in line with the provisions of the EC Drinking Water Directive, but anticipate difficulties with discharging these duties owing to limitations in manpower and resources. Some Environmental Health Departments have already initiated programmes to examine all private water supplies in their areas, but to date no results have been forthcoming.
- 6.3 An evaluation of processes for treatment of groundwaters contaminated with organics, where both aeration and adsorption processes are applicable, has indicated that whilst both techniques are capable of achieving required removal rates, granular activated carbon adsorption would appear to be relatively inefficient, in terms of carbon usage, for particular volatile organic compounds (Appendix 4). The relatively lower operating costs involved in aeration units will be a significant factor affecting the selection of a suitable treatment scheme.
- 6.4 An examination of the pertinent scientific literature with regard to counter-current aeration and GAC adsorption design considerations has enabled the development of computer models for the rapid optimisation of potential designs for these processes to achieve required removals of organic contaminants. A major

outcome of this assessment confirms that counter-current aeration units can operate across a wide band of water flow rates and contaminant concentrations and are thus applicable to small private water abstractions.

- 6.5 An examination of the costs involved in operating counter-current aeration units has revealed that substantial savings can be incurred when compared to purchasing a water supply from a statutory undertaking. Installation and operation of such units can be cost-effective even over as short a time span as 1-2 years, assuming that an industrial siting is involved, where placement, installation of basic services and facilities and manpower for operation and maintenance are available.

Cost savings are also applicable to the use of GAC adsorption systems although the higher operating costs, chiefly involved in carbon bed replacement and monitoring of carbon exhaustion, tend to mitigate against their use for removal of volatile organics. Removal of less volatile organics, such as  $\tau$ -HCH, by GAC may be achieved at similar costs to those of aeration for volatile organics removal and is thus an attractive alternative to a municipal mains supply.

- 6.6 It appears that where groundwater aquifers have become contaminated by organics, this will have occurred as a result of industrial activity or improper waste disposal and the problems will therefore tend to manifest themselves in or around urban areas. The majority of private water supplies in such areas will be utilised by industry as process water or as an ingredient in the final product, although in some cases the supply may be used for on-site welfare or canteen services. Few private domestic supplies will exist in such areas, being normally within the supply curtilage of a Water Authority or Water Company.

In rural areas where private domestic supplies are more common, the major threat to groundwater contamination arises from agricultural activities involving use of fertilizers and pesticides, although small isolated industrial premises may exist in some areas. Problems already exist with elevated nitrate concentrations in private domestic supplies in some parts of the UK and, with the reported occurrence of triazine herbicide residues in some UK groundwaters, it would appear that private supplies are particularly susceptible to this form of contamination, owing to their relatively shallow depth.

7. REFERENCES

1. Department of the Environment/National Water Council (1984) Standing Technical Advisory Committee on Water Quality. 4th Biennial Report. London, HMSO 111pp.
2. Council of the European Communities (1980) Council Directive of 15 July 1980 relating to the quality of water intended for human consumption. Offic. J. Europ. Commun. L229, 11-29.
3. Department of the Environment (1982) EC Directive relating to the quality of water intended for human consumption (80/778/EEC). Joint Circular from DOE, London (20/82) and Welsh Office, Cardiff (33/82).
4. Department of the Environment (1983) Letter giving further guidance and information about operation of the EC Directive, 80/778/EEC.
5. World Health Organisation (1984) Guidelines for Drinking Water Quality. WHO, Geneva, pp 155-176.
6. McKinnon, R.J. & Dyksen, J.E. (1983) Removal of organics from groundwater using aeration plus carbon adsorption. Proc. Annual Conf. AWWA, Las Vegas, June.
7. Love, O.T. & Eilers, R.G. (1982) Treatment of drinking water containing trichloroethylene and related industrial solvents. J. Am. Water Works Assoc. 74, 413-425.
8. Love O.T., Fiege, W.A., Carswell, J.K., Milner, R.J., Clark, R.M. and Fronk, C.A. (1984) Aeration to remove volatile organic compounds from groundwater. Draft Interim Report to the Office of Drinking Water, Cincinnati, Ohio.

9. Warden, J.H. (1986) The problems of small supplies in Britain. Assoc. Water Offic. J. 22, 35-40.
10. Umphres, M., Tate, C.H., Wojslaw, J.A. and Van Wagner, J.H. (1984) Packed Tower aeration-an evaluation of secondary effects. Proc. AWWA Conf., Dallas Texas.
11. Folkard, G.K., Peters, C.J., McIntyre, A.E. and Perry, R. (1984) Investigation into Chlorinated Hydrocarbon Solvents in Groundwaters. Final Report to the Department of the Environment, Contract PECD 7/7/088.

# Appendices

APPENDIX 1.

Design Procedure for GAC System

(1) Select flow rate ( $F - m^3/s$ ), contaminant inflow concentration ( $IC - \mu g/l$ ), carbon type, empty bed contact time (EBCT), surface loading rate ( $SLR - m^3/m^2s$ ).

(2) From isotherm data for carbon type and contaminant calculate X/M from:-

$$X/M = K C_e^{1/N}$$

X = Mass of contaminant adsorbed (kg)

M = Mass of carbon (kg)

K, 1/N = Isotherm parameters

$C_e$  = Contaminated equilibrium concentration

(3) Calculate carbon usage rate:

$$CUR = \frac{X/M \times \sigma_b \times 10^6}{IC - OC} \quad (m^3 \text{ water}/m^3 \text{ carbon})$$

$\sigma_b$  = bulk density of carbon ( $kg/m^3$ )

(4) Calculate effective carbon dose:

$$ECD = \frac{\sigma_b}{CUR} \quad (kg/m^3)$$

(5) Calculate carbon exhaustion rate:

$$CER = ECD \times F \quad (kg/day)$$

(6) Calculate carbon charge:

$$\text{Charge} = F \times EBCT \times \sigma_b \quad (kg)$$

(7) Calculate bed volume:

$$V = F \times EBCT \quad (m^3)$$

Select bed depth h (m)

Calculate column diameter

$$D = \left[ \frac{4 \times V}{L \pi} \right]^{1/2} \quad (m)$$

## APPENDIX 2.

### Design of Stripping Column

- (1) Select the liquid flow rate ( $Q_L$  m<sup>3</sup>/s), liquid temperature ( $T_w$  K), air temperature ( $T_a$  K), percentage removal of contaminant
- (2) The properties of air and water are determined at the operating temperature e.g. density of air ( $\sigma_a$  kg/m<sup>3</sup>), density of water ( $\sigma$  kg/m<sup>3</sup>), viscosity of water ( $\mu$  kg/ms)
- (3) Determine the properties of the compound at the operating conditions, ie. Henry's Law coefficient ( $H$  atm) and diffusivity coefficient ( $D_w$  m<sup>2</sup>/s).  $H$  can be found in the literature, and  $D_w$  can be calculated from the following operation

$$\frac{D_w \mu}{T} = 7.4 \times 10^{-8} (XM)^{0.5} / V_b^{0.6}$$

$D_w$  = Diffusivity of solute (cm<sup>2</sup>/s)

$\mu$  = Viscosity (Cp)

$T$  = Temperature of water (K)

$X$  = Association parameter  
= 2.6 for water

$M$  = Solvent molecular weight

$V_b$  = Molar volume of solute  
(cm<sup>3</sup>/mol)

- (4) Select the packing type and obtain the constants from manufacturers' data ie.  $C_p$  - packing factor,  $a$  and  $n$  - constants

APPENDIX 2. continued

- (5) Select a stripping factor and calculate the ratio of the gas and liquid loading rates, using the equation:

$$R = \frac{G}{L} \frac{\sigma_a M_w H}{\sigma M_a P}$$

- G = Air loading ( $m^3/m^2s$ )  
 L = Liquid loading ( $m^3/m^2s$ )  
 R = Stripping factor  
 P = Operating pressure (atm)  
 Ma = Molecular weight of air  
 Mw = Molecular weight of water

- (6) Select a pressure drop per unit height of packing ( $\delta P/z$ ) and using the graph (Fig.2) calculate the air mass loading  $G'$  ( $kg/m^2s$ ) and liquid mass loading  $L'$  ( $kg/m^2s$ )

- (7) Calculate the mass transfer coefficient  $K_L a$

$$K_L a = a \left[ \frac{L'}{\mu} \right]^{1-n} \left[ \frac{\mu}{\sigma_w D_w} \right]^{0.5} D_w$$

Sherwood-Holloway relationship

- (8) Calculate NTU and HTU

$$NTU = \frac{R}{R-1} \ln \left[ \frac{(C_{in}/C_{out}) (R-1) + 1}{R} \right]$$

$$HTU = \frac{L}{K_L a}$$

- (9) Calculate height and dimensions of column

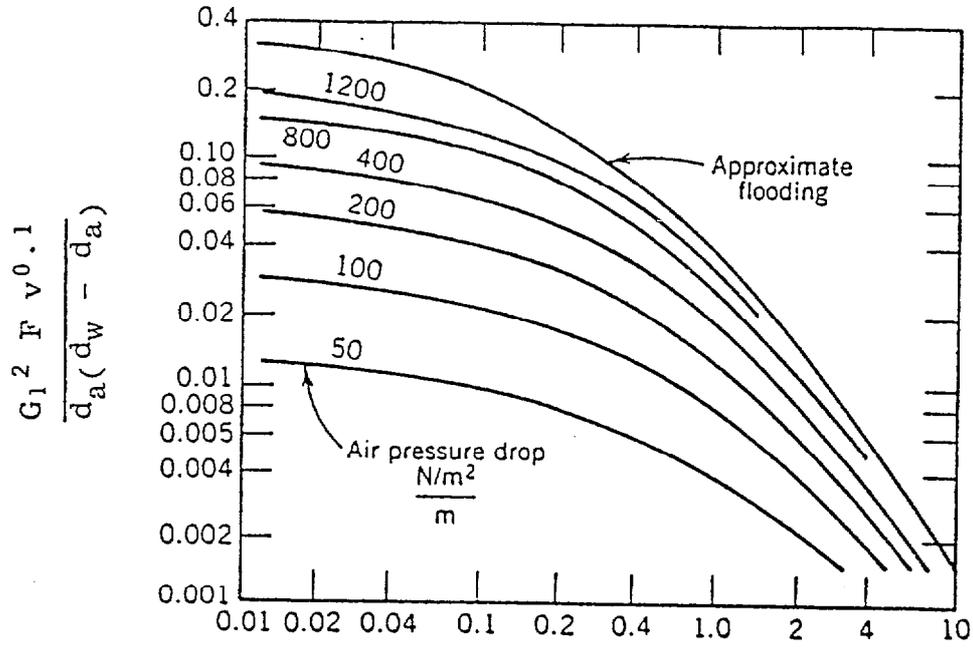
$$Z = (NTU) (HTU) \quad Z = \text{Column height (m)}$$

$$\text{Area} = \frac{L}{L'}$$

$$\text{Diameter} = \left[ \frac{\text{area} \times 4}{\pi} \right]^{0.5}$$

(10) Increment stripping factor and repeat calculations from step 5.

Fig.2.



$$\frac{L_1}{G_1} \left( \frac{d_a}{d_w - d_a} \right)^{0.5}$$



SIZES OF CARBON ADSORBERS FOR THE REMOVAL OF VARIOUS  
ORGANIC CONTAMINANTS

CARBON TETRACHLORIDE - FILTRASORB 300 - (EBCT= 10 mins)

K	L/N	CONCN IN (ug/l)	CONCN OUT (ug/l)	FLOW (l/d)	CARBON USAGE	EXHAUST RATE (Kg/d)	MASS PER BED (Kg/d)	RUN TIME (days)	BED DEPTH (m)	COLUMN DIAM (m)
11	0.80	200	20	2000000	1052	741.58	5417	7	2.44	2.7
11	0.80	200	10	2000000	572	1362.89	5417	4	2.44	2.7
11	0.80	100	10	2000000	1208	645.58	5417	8	2.44	2.7
11	0.80	100	5	2000000	657	1186.46	5417	5	2.44	2.7
11	0.80	200	20	1000000	1052	370.79	2708	7	2.44	1.9
11	0.80	200	10	1000000	572	681.44	2708	4	2.44	1.9
11	0.80	100	10	1000000	1208	322.79	2708	8	2.44	1.9
11	0.80	100	5	1000000	657	593.23	2708	5	2.44	1.9
11	0.80	200	20	500000	1052	185.39	1354	7	2.44	1.3
11	0.80	200	10	500000	572	340.72	1354	4	2.44	1.3
11	0.80	100	10	500000	1208	161.39	1354	8	2.44	1.3
11	0.80	100	5	500000	657	296.62	1354	5	2.44	1.3
11	0.80	200	20	100000	1052	37.08	271	7	2.44	0.6
11	0.80	200	10	100000	572	68.14	271	4	2.44	0.6
11	0.80	100	10	100000	1208	32.28	271	8	2.44	0.6
11	0.80	100	5	100000	657	59.32	271	5	2.44	0.6

CARBON TETRACHLORIDE - NORIT - (EBCT= 10 mins)

K	L/N	CONCN IN (ug/l)	CONCN OUT (ug/l)	FLOW (l/d)	CARBON USAGE	EXHAUST RATE (Kg/d)	MASS PER BED (Kg/d)	RUN TIME (days)	BED DEPTH (m)	COLUMN DIAM (m)
29	0.80	200	20	2000000	2701	288.82	5417	19	2.44	2.7
29	0.80	200	10	2000000	1469	530.81	5417	10	2.44	2.7
29	0.80	100	10	2000000	3102	251.44	5417	22	2.44	2.7
29	0.80	100	5	2000000	1688	462.10	5417	12	2.44	2.7
29	0.80	200	20	1000000	2701	144.41	2708	19	2.44	1.9
29	0.80	200	10	1000000	1469	265.40	2708	10	2.44	1.9
29	0.80	100	10	1000000	3102	125.72	2708	22	2.44	1.9
29	0.80	100	5	1000000	1688	231.05	2708	12	2.44	1.9
29	0.80	200	20	500000	2701	72.21	1354	19	2.44	1.3
29	0.80	200	10	500000	1469	132.70	1354	10	2.44	1.3
29	0.80	100	10	500000	3102	62.86	1354	22	2.44	1.3
29	0.80	100	5	500000	1688	115.52	1354	12	2.44	1.3
29	0.80	200	20	100000	2701	14.44	271	19	2.44	0.6
29	0.80	200	10	100000	1469	26.54	271	10	2.44	0.6
29	0.80	100	10	100000	3102	12.57	271	22	2.44	0.6
29	0.80	100	5	100000	1688	23.10	271	12	2.44	0.6

## CARBON TETRACHLORIDE

## - NORIT

K	I/N	CONCN IN (ug/l)	CONCN OUT (ug/l)	FLOW (l/d)	CARBON USAGE	EXHAUST RATE (Kg/d)	MASS PER BED (Kg/d)	RUN TIME (days)	BED DEPTH (a)	COLUMN DIAM (a)	EBCT (an)
29	0.80	200	20	1000000	2701	144.41	1354	9	1.22	1.9	5
29	0.80	200	20	1000000	2701	144.41	1625	11	1.47	1.9	6
29	0.80	200	20	1000000	2701	144.41	1896	13	1.71	1.9	7
29	0.80	200	20	1000000	2701	144.41	2167	15	1.95	1.9	8
29	0.80	200	20	1000000	2701	144.41	2438	17	2.20	1.9	9
29	0.80	200	20	1000000	2701	144.41	2708	19	2.44	1.9	10
29	0.80	200	20	1000000	2701	144.41	2979	21	2.69	1.9	11
29	0.80	200	20	1000000	2701	144.41	3250	23	2.93	1.9	12
29	0.80	200	20	1000000	2701	144.41	3521	24	3.17	1.9	13
29	0.80	200	20	1000000	2701	144.41	3792	26	3.42	1.9	14
29	0.80	200	20	1000000	2701	144.41	4062	28	3.66	1.9	15
29	0.80	200	20	1000000	2701	144.41	4333	30	3.91	1.9	16
29	0.80	200	20	1000000	2701	144.41	4604	32	4.15	1.9	17
29	0.80	200	20	1000000	2701	144.41	4875	34	4.40	1.9	18
29	0.80	200	20	1000000	2701	144.41	5146	36	4.64	1.9	19
29	0.80	200	20	1000000	2701	144.41	5417	38	4.88	1.9	20
29	0.80	200	20	1000000	2701	144.41	5688	39	5.13	1.9	21
29	0.80	200	20	1000000	2701	144.41	5958	41	5.37	1.9	22
29	0.80	200	20	1000000	2701	144.41	6229	43	5.62	1.9	23
29	0.80	200	20	1000000	2701	144.41	6500	45	5.86	1.9	24
29	0.80	200	20	1000000	2701	144.41	6771	47	6.10	1.9	25

TRICHLOROETHYLENE - FILTRASORB 300 - (EBCT= 16.6667 mins)

K	1/N	CONCN IN (ug/l)	CONCN OUT (ug/l)	FLOW (l/d)	CARBON USAGE	EXHAUST RATE (Kg/d)	MASS PER BED (Kg/d)	RUN TIME (days)	BED DEPTH (m)	COLUMN DIAM (m)
28	0.60	200	20	2000000	5802	134.44	9028	67	4.07	2.7
28	0.60	200	10	2000000	3626	215.09	9028	42	4.07	2.7
28	0.60	100	10	2000000	7656	101.89	9028	89	4.07	2.7
28	0.60	100	5	2000000	4785	163.01	9028	55	4.07	2.7
28	0.60	200	20	1000000	5802	67.22	4514	67	4.07	1.9
28	0.60	200	10	1000000	3626	107.55	4514	42	4.07	1.9
28	0.60	100	10	1000000	7656	50.94	4514	89	4.07	1.9
28	0.60	100	5	1000000	4785	81.50	4514	55	4.07	1.9
28	0.60	200	20	500000	5802	33.61	2257	67	4.07	1.3
28	0.60	200	10	500000	3626	53.77	2257	42	4.07	1.3
28	0.60	100	10	500000	7656	25.47	2257	89	4.07	1.3
28	0.60	100	5	500000	4785	40.75	2257	55	4.07	1.3
28	0.60	200	20	100000	5802	6.72	451	67	4.07	0.6
28	0.60	200	10	100000	3626	10.75	451	42	4.07	0.6
28	0.60	100	10	100000	7656	5.09	451	89	4.07	0.6
28	0.60	100	5	100000	4785	8.15	451	55	4.07	0.6

TRICHLOROETHYLENE - FILTRASORB 400 - (EBCT= 16.6667 mins)

K	1/N	CONCN IN (ug/l)	CONCN OUT (ug/l)	FLOW (l/d)	CARBON USAGE	EXHAUST RATE (Kg/d)	MASS PER BED (Kg/d)	RUN TIME (days)	BED DEPTH (m)	COLUMN DIAM (m)
63	0.50	200	20	2000000	19335	40.34	9028	224	4.07	2.7
63	0.50	200	10	2000000	12952	60.22	9028	150	4.07	2.7
63	0.50	100	10	2000000	27343	28.53	9028	316	4.07	2.7
63	0.50	100	5	2000000	18317	42.58	9028	212	4.07	2.7
63	0.50	200	20	1000000	19335	20.17	4514	224	4.07	1.9
63	0.50	200	10	1000000	12952	30.11	4514	150	4.07	1.9
63	0.50	100	10	1000000	27343	14.26	4514	316	4.07	1.9
63	0.50	100	5	1000000	18317	21.29	4514	212	4.07	1.9
63	0.50	200	20	500000	19335	10.09	2257	224	4.07	1.3
63	0.50	200	10	500000	12952	15.06	2257	150	4.07	1.3
63	0.50	100	10	500000	27343	7.13	2257	316	4.07	1.3
63	0.50	100	5	500000	18317	10.65	2257	212	4.07	1.3
63	0.50	200	20	100000	19335	2.02	451	224	4.07	0.6
63	0.50	200	10	100000	12952	3.01	451	150	4.07	0.6
63	0.50	100	10	100000	27343	1.43	451	316	4.07	0.6
63	0.50	100	5	100000	18317	2.13	451	212	4.07	0.6



## APPENDIX 6

## COLUMN SIZES FOR THE REMOVAL OF CHLOROFORM

STRIPPING FACTOR (Dimensionless)	KLA (1/s)	X-COORD	Y-COORD	PRESSURE DROP (KN/m)	HEIGHT (m)	DIAMETER (m)	C. IN (ug/l)	C. OUT (ug/l)
2	0.01226	1.1104	0.0030	50	4.50	1.12	100.0	5.0
3	0.00969	0.7402	0.0040	50	3.66	1.28	100.0	5.0
4	0.00827	0.5552	0.0050	50	3.33	1.39	100.0	5.0
5	0.00676	0.4441	0.0050	50	3.12	1.56	100.0	5.0
6	0.00623	0.3701	0.0060	50	3.01	1.63	100.0	5.0
7	0.00581	0.3172	0.0070	50	2.93	1.70	100.0	5.0
8	0.00516	0.2776	0.0070	50	2.85	1.81	100.0	5.0
9	0.00464	0.2467	0.0070	50	2.79	1.92	100.0	5.0
10	0.00448	0.2221	0.0080	50	2.76	1.96	100.0	5.0

STRIPPING FACTOR (Dimensionless)	KLA (1/s)	X-COORD	Y-COORD	PRESSURE DROP (KN/m)	HEIGHT (m)	DIAMETER (m)	C. IN (ug/l)	C. OUT (ug/l)
2	0.01795	1.1104	0.0070	100	4.70	0.91	100.0	5.0
3	0.01324	0.7402	0.0080	100	3.79	1.07	100.0	5.0
4	0.01130	0.5552	0.0100	100	3.45	1.17	100.0	5.0
5	0.01003	0.4441	0.0120	100	3.26	1.25	100.0	5.0
6	0.00912	0.3701	0.0140	100	3.14	1.32	100.0	5.0
7	0.00819	0.3172	0.0150	100	3.04	1.40	100.0	5.0
8	0.00748	0.2776	0.0160	100	2.97	1.47	100.0	5.0
9	0.00691	0.2467	0.0170	100	2.92	1.54	100.0	5.0
10	0.00629	0.2221	0.0170	100	2.86	1.62	100.0	5.0

STRIPPING FACTOR (Dimensionless)	KLA (1/s)	X-COORD	Y-COORD	PRESSURE DROP (KN/m)	HEIGHT (m)	DIAMETER (m)	C. IN (ug/l)	C. OUT (ug/l)
2	0.02200	1.1104	0.0110	200	4.81	0.81	100.0	5.0
3	0.01703	0.7402	0.0140	200	3.90	0.93	100.0	5.0
4	0.01396	0.5552	0.0160	200	3.53	1.04	100.0	5.0
5	0.01262	0.4441	0.0200	200	3.34	1.10	100.0	5.0
6	0.01141	0.3701	0.0230	200	3.22	1.17	100.0	5.0
7	0.01012	0.3172	0.0240	200	3.12	1.25	100.0	5.0
8	0.00977	0.2776	0.0290	200	3.06	1.27	100.0	5.0
9	0.00893	0.2467	0.0300	200	3.00	1.34	100.0	5.0
10	0.00824	0.2221	0.0310	200	2.95	1.40	100.0	5.0

STRIPPING FACTOR (Dimensionless)	KLA (1/s)	X-COORD	Y-COORD	PRESSURE DROP (KN/m)	HEIGHT (m)	DIAMETER (m)	C.IN (ug/l)	C.OUT (ug/l)
2	0.03507	1.1104	0.0310	400	5.06	0.62	100.0	5.0
3	0.01953	0.7402	0.0190	400	3.96	0.86	100.0	5.0
4	0.01675	0.5552	0.0240	400	3.60	0.94	100.0	5.0
5	0.01515	0.4441	0.0300	400	3.41	1.00	100.0	5.0
6	0.01413	0.3701	0.0370	400	3.30	1.04	100.0	5.0
7	0.01274	0.3172	0.0400	400	3.20	1.10	100.0	5.0
8	0.01167	0.2776	0.0430	400	3.12	1.15	100.0	5.0
9	0.01103	0.2467	0.0480	400	3.07	1.19	100.0	5.0
10	0.01022	0.2221	0.0500	400	3.02	1.24	100.0	5.0

STRIPPING FACTOR (Dimensionless)	KLA (1/s)	X-COORD	Y-COORD	PRESSURE DROP (KN/m)	HEIGHT (m)	DIAMETER (m)	C.IN (ug/l)	C.OUT (ug/l)
2	0.02943	1.1104	0.0210	800	4.96	0.69	100.0	5.0
3	0.02288	0.7402	0.0270	800	4.03	0.79	100.0	5.0
4	0.01985	0.5552	0.0350	800	3.67	0.86	100.0	5.0
5	0.01800	0.4441	0.0440	800	3.48	0.90	100.0	5.0
6	0.01756	0.3701	0.0600	800	3.38	0.92	100.0	5.0
7	0.01552	0.3172	0.0620	800	3.27	0.98	100.0	5.0
8	0.01453	0.2776	0.0700	800	3.20	1.02	100.0	5.0
9	0.01372	0.2467	0.0780	800	3.15	1.05	100.0	5.0
10	0.01262	0.2221	0.0800	800	3.09	1.10	100.0	5.0

## 2. REVIEW OF EUROPEAN EXPERIENCE AND ATTITUDES TO GROUNDWATER CONTAMINATION BY ORGANIC COMPOUNDS

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## 1. INTRODUCTION

Groundwater resources in the European Community contribute a significant proportion of water supplies, comprising an appropriate average of 65% of potable supplies. A breakdown of the relative importance of groundwater for some of the member countries is given in Table 1.

Groundwater has long been considered to be a relatively pure source of water for potable supply being largely isolated from potential pollution sources. In recent years however, an increasing number of contamination incidents have been detected in the European Community (EC) and these have highlighted the susceptibility of this resource to contamination by a variety of substances, including many organic compounds.

The sources of such contamination can include any or a combination of the following:

- \* Percolation/leachate from municipal and industrial waste disposal sites
- \* Leakage from underground chemical storage tanks
- \* Improper waste disposal practices
- \* Rainfall washout of atmospheric contaminants
- \* Leaching of agrochemicals (pesticides)
- \* Accidental chemical spillage

Of most concern are persistent organic compounds, those which are resistant to chemical or biological degradation, which include volatile chlorinated solvents. The solvents which have been detected most frequently in groundwater during analytical surveys conducted in the USA, Netherlands, UK and West Germany are:

Table 1 Proportion of potable water supplied from groundwater sources in EEC member countries.

Country	Proportion derived from Groundwater %
Belgium	70
Denmark	98
France	50
FRG	71
Italy	92
Netherlands	65
Norway	5
UK	34

trichloroethene, tetrachloroethene, trichloroethane, dichloroethenes, dichloroethanes, carbon tetrachloride and dichloromethane. Concentrations of these compounds found in surface waters are rarely above  $0.1-1.0 \mu\text{g l}^{-1}$  since they are easily volatilised to the atmosphere. In groundwater, however, this route for dispersion is unavailable and, being immiscible with and denser than water, they tend to migrate to the lower levels of aquifers. Concentrations of one of the most frequently-detected compounds, tetrachloroethene, up to  $80,000 \mu\text{g l}^{-1}$  have been recorded in one particularly serious contamination incident (1).

Estimates of the scale of production and use of chlorinated solvents in the EC are difficult to obtain, owing to reasons of commercial secrecy and the diffuse nature of solvent usage. In 1973, the following figures were given (2) for world production of four solvents.

trichloroethene	$1.01 \times 10^6 \text{ t a}^{-1}$
tetrachloroethene	$1.05 \times 10^6 \text{ t a}^{-1}$
trichloroethane	$0.48 \times 10^6 \text{ t a}^{-1}$
dichloromethane	$0.40 \times 10^6 \text{ t a}^{-1}$

Actual usage in the UK also proved difficult to quantify although in 1976 (3,4) approximately 1000-2500 tonnes of waste solvent arose from the dry cleaning industry and a further 3000-7000 tonnes from metal degreasing operations.

Because of the volatile nature a large quantity of solvents used will be lost to the atmosphere by evaporation and a proportion of these will be returned to the ground by atmospheric washout and may enter groundwater by subsequent percolation through the soil profile.

A recent study by a joint German/French/Dutch research team (5) has estimated that a total of  $9 \times 10^6$  tonnes per annum of volatile organic compounds are emitted to the atmosphere by the 12 EC member countries. Of this total, it is further estimated that

approximately  $3.8 \times 10^6$  tonnes are emitted annually by industrial and non-industrial solvent usage. Assuming, conservatively, that 50% of this figure consists of chlorinated solvents and that, again, 50% is lost to atmosphere, it may be estimated that of the order  $3-4 \times 10^6$  tonnes of chlorinated solvents are used annually in the EC, of which  $1.5-2.0 \times 10^6$  tonnes are incorporated into products or arise for disposal.

The preferred disposal route for non-recyclable chlorinated solvent wastes is destruction by high-temperature incineration, although much is disposed of in landfill waste disposal sites in drums. Such landfill sites accepting hazardous liquid wastes have to be licensed as being 'secure' with no potential for contamination of groundwaters. Past waste disposal practises were not so stringently regulated, however, and it is possible that wastes were disposed to non-secure sites. This aspect, together with risks from spillage or leakage from chemical storage facilities and improper or illegal waste disposal, constitutes the greatest possibility of groundwater contamination.

In addition to volatile chlorinated solvents, there also exists concern over the contamination of groundwaters by pesticides, particularly those used in agriculture. The most frequently detected components are the triazine herbicides and these have been found to occur in aquifers located beneath intensive arable farmland in the UK, in some cases above the MAC level specified in the EC drinking water directive. In addition, a recent government-initiated study in the Netherlands, involving analysis of groundwater samples for commonly-used pesticides, revealed the presence of trace levels of triazine herbicides (6).

Legislation pertaining to trace organic contaminants in drinking water is largely incomplete owing to the lack of an unequivocal data base on the potential toxicological and mutagenic effects upon the human population and the technical difficulties involved in obtaining and, indeed, interpreting such information. Relevant parameters included in the EC drinking water directive are given

in Table 2. It can be seen that for organochlorine compounds a guide level is quoted, but there is no value for a MAC. This reflects the lack of knowledge enabling a sensible MAC to be devised. The guide level represents a desirable target, but is likely to be achieved only for the highest quality water sources remote from anthropological activity. In Table 3 guidelines for Drinking Water Quality issued by World Health Organisation some ten years ago after the values in the EC Directive were being decided, demonstrate that the knowledge of occurrence and significance of chlorinated compounds is developing. So far individual or blanket MAC values for such compounds have not been included in parameter 32 in the requirements of the EC Directive by Member States, as they could do, except for chlorine containing trihalomethanes. Although the WHO Guidelines have no legal significance, it would be prudent for authorities concerned with chlorinated organic compounds in water to work to them until such time as clarification or extension of the EC parameter is made.

**Table 2 EC drinking water directive parameters for organic contaminants.**

Parameter	Units	GL <sup>1</sup>	MAC <sup>2</sup>	Comments
(28) Dissolved or emulsified hydrocarbons	$\mu\text{g l}^{-1}$	-	10	
(29) Phenols	$\mu\text{g l}^{-1}$	-	0.5	Excluding natural phenols
(32) Organochlorine compounds not covered by (55)	$\mu\text{g l}^{-1}$	1	-	Haloform concentrations must be as low as possible
(55) Pesticides and related products	$\mu\text{g l}^{-1}$			
- separately		-	0.1	
- total		-	0.5	
(56) PAH	$\mu\text{g l}^{-1}$	-	0.2	Total of six representative compounds

1. GL - guide level
2. MAC - maximum admissable concentration

Table 3 WHO Guidelines for drinking water quality

Parameter	Unit of Concentration	Guideline Value (GV)	Remarks
Aldrin and dieldrin	$\mu\text{g l}^{-1}$	0.03	
Benzene	$\mu\text{g l}^{-1}$	10	a
Benzo (a) pyrene	$\mu\text{g l}^{-1}$	0.01	a
Carbon tetrachloride	$\mu\text{g l}^{-1}$	3	a,b
Chlordane	$\mu\text{g l}^{-1}$	0.3	
Chloroform	$\mu\text{g l}^{-1}$	30	a
2,4-D	$\mu\text{g l}^{-1}$	100	c
DDT	$\mu\text{g l}^{-1}$	1	
1,2-dichloroethane	$\mu\text{g l}^{-1}$	10	a
1,1-dichloroethene	$\mu\text{g l}^{-1}$	0.3	a
Heptachlor/heptachlor epoxide	$\mu\text{g l}^{-1}$	0.1	
Hexachlorobenzene	$\mu\text{g l}^{-1}$	0.01	a
Lindane (BHC)	$\mu\text{g l}^{-1}$	3	
Methoxychlor	$\mu\text{g l}^{-1}$	30	
Pentachlorophenol	$\mu\text{g l}^{-1}$	10	
Tetrachloroethene	$\mu\text{g l}^{-1}$	10	a,b
Trichloroethene	$\mu\text{g l}^{-1}$	30	a,b
2,4,6-trichlorophenol	$\mu\text{g l}^{-1}$	10	a,c

Notes: a Derived using multistage model. Value could be from 1/10  
10 x value for 1 in  $10^5$  lifetime risk of cancer

b Tentative value - uncertainty greater

c May be detectable by taste at lower concentrations than GV

## 2. GROUNDWATER CONTAMINATION IN EUROPEAN COUNTRIES

### 2.1 West Germany

To date, no nation-wide survey of groundwaters for organic compounds has been conducted in the FRG, although many incidents of aquifer and potable water contamination have been reported and a number of air-stripping and activated carbon treatment plants have been installed.

At present the national standard for volatile chlorinated solvents in drinking water is set at  $25\mu\text{g l}^{-1}$  for the total of trichloroethene, tetrachloroethene, 1,1,1-trichloroethane and dichloromethane, which is an annual average guideline concentration that should not be exceeded. Some concern has been expressed (7) over the apparent stringency of this standard, particularly with regard to the inconsistency with the WHO-recommended limits for trichloroethene ( $30\mu\text{g l}^{-1}$ ) and tetrachloroethene ( $10\mu\text{g l}^{-1}$ ) and the absence from the WHO list of dichloromethane and 1,1,1-trichloroethane.

A study around the city of Bonn in the Rhine-Sieg area of the FRG (8) involving analysis of 88 ground-water abstractions supplying water to 24 groundwater treatment plants in 1983/84 revealed that whilst 75 samples yielded total halocarbon concentrations below  $25\mu\text{g l}^{-1}$  a total of 13 were found to be above this standard level, set by the Federal Bureau of Public Health in 1982. Elevated concentrations of trichloroethene ( $262\mu\text{g l}^{-1}$ ), tetrachloroethene ( $59\mu\text{g l}^{-1}$ ) and trichloroethane ( $16\mu\text{g l}^{-1}$ ) were detected in one borehole, adjacent to a derelict industrial estate and a completed landfill site.

In the Frankfurt area in 1981, analysis of a groundwater-derived potable supply revealed the presence of trichloroethene and tetrachloroethene at concentrations up to  $10.7\mu\text{g l}^{-1}$  and  $109\mu\text{g l}^{-1}$  respectively (9).

A joint study programme on 'halo-organics in water' has been carried out over the last twelve months by research workers from the University of Karlsruhe and the Wahnachtalsperrenverband (10). Although the report has not yet been published, some preliminary conclusions have been forthcoming, in relation to treatment technologies, potential health effects and the derivation of drinking water quality standards. It is considered that parameter 32 contained in the EC drinking water directive was ill-conceived and that the current national standard of  $25\mu\text{g l}^{-1}$  for the sum of four volatile chlorinated solvents, although not derived strictly upon the basis of sound toxicological data, represents an acceptable compromise between the former standard (EC) and unqualified implementation of the WHO guideline values. However, some criticism is made of the fact that the  $25\mu\text{g l}^{-1}$  standard for chlorinated solvents, and also the  $250\mu\text{g l}^{-1}$  standard for total trihalomethanes in drinking water are stipulated as annual average concentrations. It is considered that a re-evaluation of toxicological and carcinogenic data is required in order to arrive at a preferred maximum concentration standard, which would facilitate decisions concerning control and treatment strategies.

Groundwater-derived potable supplies in the FRG undergo varying degrees of treatment prior to distribution and it is recommended that alternative processes should be considered for the reduction of chlorinated organics, involving ozonation, aeration and GAC adsorption. Although it appears that trihalomethane formation during water disinfection is well under control, the detection of an additional chlorination by-product, trichloronitromethane, (8) arising from the reaction between chlorine, natural matter and nitrate in groundwaters, has caused some concern.

It is the opinion of at least one of the report's authors that the present concentration of concern on the possible health effects of organics in drinking water is scientifically fallacious, since the potential human intake of toxic substances from drinking water is small when compared to the exposure presented from other sources (food and air) during the lifetime of an individual.

## 2.2 The Netherlands

In 1976-1978 all groundwater pumping stations in Holland were sampled and analysed for halogenated hydrocarbons, some 232 samples. Results of this survey are given in Table 4.

Table 4 Netherlands Groundwater survey for halogenated hydrocarbons

Compound	Numbers of samples in concentration ranges					
	$\mu\text{g l}^{-1}$					
	<1.0	1-5	5-10	10-50	50-100	>100
Trichloroethene	217	6	5	2	0	1
Tetrachloroethene	228	1	1	2	0	0

The majority of samples were below the  $1\mu\text{g l}^{-1}$  level for both trichloroethene and tetrachloroethene, but some results gave rise to concern, since the Netherlands National Institute of Public Health and Environmental Hygiene had indicated to the water supply undertakings that the guide level of  $1\mu\text{g l}^{-1}$  for organochlorine compounds, as specified in the EC drinking water Directive, should be applied to volatile chlorinated solvents in groundwater. Although WHO tentative guideline levels for trichloroethene and tetrachloroethene are set at  $30\mu\text{g l}^{-1}$  and  $10\mu\text{g l}^{-1}$  respectively, the traditional high quality of Dutch groundwaters (many of which do not require disinfection) encouraged adoption of the EC guide level. Those water supplies which exhibited concentrations in excess of the guide level were either removed from public supply or were subjected to treatment or blending to comply with the standard.

A major research programme has been established by the National Institute of Public Health and Environmental Hygiene, involving the Netherlands Waterworks' Testing and Research Institute and several University research groups, with the aim of investigating

optimum treatment methods for volatile chlorinated organics in drinking water. In addition, measures are also being implemented on a national level to prevent contamination of aquifers by such chemicals. This is of particular importance to the Netherlands, since the geomorphology and resultant overlying soil types are such as to facilitate movement of chemicals through the ground into unconfined aquifers.

A number of major contamination incidents have been reported in recent years, the most serious of which resulted in disconnection of supplies to part of the city of Hilversum. The groundwater was found to be contaminated by trichloroethene at concentrations up to a maximum of  $1500\mu\text{g l}^{-1}$ . In order to deal with the problem, a series of interceptor boreholes were sunk into the aquifer across the path of the pollutant plume (previously delineated by hydrogeological surveys) and it was planned that contaminated water should be pumped to waste into a nearby lake. However, the lake water was utilised for cooling purposes by the adjacent broadcasting studios and concern was expressed over the possible volatilization of trichloroethene in the cooling system. The contaminated water was therefore treated by use of perforated-plate aeration troughs prior to discharge to the lake. Public supply could then be resumed from the aquifer, by sinking new abstraction wells at some distance downstream from the interceptor boreholes. The potable water as supplied is the most expensive in the Netherlands, but no alternative supply exists. The source of the contamination was traced to an abandoned metal-working factory which had used large volumes of degreasing solvents in the past. Current sources in the Netherlands has been centered upon measures for aquifer protection, involving the establishment of 'water capture zones' around major groundwater sources, where certain industrial activities are banned or stringent conditions are applied to preclude accidental or unlicensed discharge of wastes which might subsequently contaminate groundwater. Similar controls are applied to landfill waste disposal operations, where all possible controls are exercised to prevent percolation of leachate to groundwater.

It appears that there is mounting concern in particular over the possible presence of potentially carcinogenic chemicals in groundwater, as opposed to potable supplies. The traditional good quality of the groundwater resources, where only minimal treatment is required in a few cases, and the high susceptibility of aquifers to contamination because of the predominantly sandy soils, has resulted in a virtually 'zero carcinogens' approach to potable water quality. Reliance upon treatment procedures to produce a potable water of acceptable quality is viewed only as a secondary approach to the primary objective of preventing contamination of groundwater occurring.

As far as volatile chlorinated solvents are concerned, the zero concentration approach for groundwater may perhaps be regarded as somewhat unrealistic, since it is generally acknowledged that concentrations of, for example, tetrachloroethene in groundwater of between 0.01 to  $1.0\mu\text{g l}^{-1}$  may well arise from atmospheric washout of airborne emissions from industrial processes and subsequent deposition on and leaching through the soil horizons. Therefore, ultimate protection of groundwater may only be achieved in the long term and is perhaps of questionable necessity at the outset.

A further example which illustrates the prevailing attitude to groundwater contamination involves the withdrawal of registration approval for a particular herbicide formulation. Toxicological studies had indicated the presence of a carcinogenic reaction in certain test species to a particular metabolite/breakdown product of the active ingredient and it was hypothesised that this metabolite could be produced by soil micro-organisms and had potential to leach into groundwater.

Although much circumstantial evidence exists to demonstrate the unliklihood of such an occurrence, the apparent attitude of the Dutch authorities is to withhold approval for use until the herbicide is proved to be environmentally safe. The implications.

of such an approach to prevention of groundwater contamination is considered further in a later section of this report.

In general, it appears that groundwater contamination in the Netherlands is receiving much attention from the relevant authorities. Although much work has been carried out into selected water treatment processes for organics removal and a number of full-scale plants have been installed, there is currently a concerted trend towards prevention of contamination by means of stringent controls upon waste-producing activities.

There is also great concern over the maintenance and continued improvement in drinking water quality, in some cases to a higher quality than that required by accepted standards. This is exemplified by a recent announcement (June 1987) by the Minister of Health of the intention to reduce the EEC MAC of  $50\text{mg l}^{-1}$  for nitrate in drinking water to a uniform level of  $25\text{mg l}^{-1}$ .

### 2.3 France

National surveys of groundwater abstractions in France during the years 1979 to 1981 revealed the presence of trichloroethene, trichloroethane, dichloroethene and dichloroethane at concentrations up to  $20\mu\text{g l}^{-1}$  for individual compounds. In a few cases, treatment systems utilising GAC have been installed to reduce concentrations below  $10\mu\text{g l}^{-1}$ . Few particularly serious contamination incidents have been detected to date although the competent authorities are continuing to monitor the situation with periodic analysis of groundwater abstractions for contaminants.

A major research programme is currently being carried out by the CGE research centre at Maisons Lafite, involving an evaluation of aeration and GAC technology for the treatment of contaminated groundwaters using pilot-scale plant. However, the main thrust of research work, carried out jointly by Universities, treatment plant manufacturers and water companies, has been concerned with the study of alternative disinfection agents and mechanical treatment plant for the reduction of mutagenic activity in potable water, including those supplies derived from underground sources. The general attitude and approach to organic contamination of potable water appear to involve optimisation of current treatment procedures in the short term, together with concerted research into the production of new treatment technologies for efficient and cost-effective removal of organics. To this end, the organizational basis of the water industry, together with the cooperative programmes of research undertaken by private sector companies, water company research institutes and universities appears to provide an effective approach to the problem.

## 2.4 Italy

Approximately 93% of the water supply is derived from aquifers and underground springs which have traditionally been of good quality in both chemical and bacteriological terms. In the Lombardy region of northern Italy and in particular in the province of Milan, where there is a concentration of industry, virtually all the water is derived from a network of interconnecting aquifers ranging in depth from 40-110m. In 1984 there were 36 principal distribution plants drawing groundwater from a total of 510 boreholes. Little or no treatment has been required in the past owing to the high quality of the water, disinfection by chlorination only being required infrequently for short periods to prevent contamination in the distribution system.

In the mid - 1970's, random chemical analyses of some groundwater abstractions revealed contamination by a range of organic compounds at high  $\mu\text{g l}^{-1}$  levels, including phenols, aliphatic and aromatic hydrocarbons and amines, derived from the unregulated disposal of industrial wastes into insecure landfill sites and holding lagoons. The predominant geomorphology and resultant soil types in this area facilitate the percolation of contaminants to groundwater levels. Further subsequent analyses also revealed the presence of volatile chlorinated hydrocarbons (trichloroethene, tetrachloroethene, chloroform and trichloroethane) at concentrations varying between 100 and  $200\mu\text{g l}^{-1}$ .

In response to this discovery, and subsequent medical cases amongst the population of acute exposure to chlorinated solvents in potable water, a working group was established in 1975 to consider the sources of the contamination, conduct a survey of groundwater abstractions in the region and to recommend remedial measures. This took the form of:

- (i) hydrogeochemical surveys to pinpoint worst-affected areas
- (ii) Census of industrial activities in the area, including assessment of waste arising/disposal and underground storage tanks.
- (iii) Identification of pollution sources
- (iv) Reclamation and rehabilitation of aquifers.

Systematic monitoring of all groundwater abstraction points commenced in 1977 and continued up to 1984. In the urbanised and industrialised area of Milan a total of 17 points in the water distribution system were sampled and the results are shown in Table 5.

Table 5 Total+ chlorinated solvent concentrations in Milan city public water supply

YEAR	CONCENTRATION RANGE* µg l <sup>-1</sup>
1977	30-230
1978	66-245
1979	70-193
1980	86-207
1981	87-237
1982	60-167
1983	63-189
1984	73-185

- + total of trichloroethene, tetrachloroethene, chloroform, trichloroethane
- \* Range of seventeen samples.

In addition, a further 17 sampling points in the suburban areas were monitored over the same period and these results are included in Table 6.

Table 6 Total chlorinated solvent concentrations in Milan suburban water supply

YEAR	CONCENTRATION RANGE * µg l <sup>-1</sup>
1977	ND <sup>1</sup> -105
1978	ND-240
1979	ND-363
1980	ND-286
1981	ND-420
1982	ND-223
1983	11-172
1984	16-154

1. Not detected

\* range of seventeen samples

Contamination at the higher levels was widespread in the inner city areas whereas in the suburban areas, concentrations of chlorinated solvents were generally lower, with the exception of one point in the system which exhibited levels from 136-420µg l<sup>-1</sup> over the 8 year period. Peak concentrations tended to decrease in the inner city area over the 8 years whilst there was a corresponding general increase over the period in the suburban areas, probably due to gradual dispersion/advection of pollutant plumes in the aquifers.

Trichloroethene and tetrachloroethene were found to be the predominant contaminants in groundwater during the early years of the survey but these have been replaced, in frequency of occurrence and concentration terms in more recent years, with the gradual introduction of trichloroethane. The occurrence of chloroform was linked to the production cycles of a particular industry (pharmaceuticals) and was found to be concentrated in certain

areas. Overall, the aquifers under an area of approximately 3000 km<sup>2</sup> are seriously contaminated with trichloroethene and tetrachloroethene, with local 'hot -spots' of chloroform and trichloroethane.

Remedial measures implemented to date have involved large-scale removal and proper disposal of contaminated soil, construction of drains and barrier walls, installation of interceptor wells and purging of aquifers and disconnecting individual boreholes from the supply network. It would appear that few treatment plants have been installed to remedy the problem, although blending of water from different sources has been carried out in some cases.

Although no water quality standards have been established for volatile chlorinated solvents in potable water, concentrations in excess of 50µg l<sup>-1</sup> are generally considered to be of concern but it is uncertain what proportion of the 4 x 10<sup>6</sup> population of the area is directly affected. The local authorities have to date concentrated upon the development of administrative procedures for the future prevention of pollution, whilst the population remains largely exposed to organics in drinking water. The most recent surveys (1984) have indicated that, of the 510 active boreholes in the Milan Lombardy region, approximately 62% were affected by volatile chlorinated solvent concentrations in excess of 50µg l<sup>-1</sup>.

### 3 EVALUATION OF UNITED KINGDOM POSITION

In the light of information received from other EC member countries, it is pertinent to consider the attitude and approach adopted in the UK to organics in groundwater and potable supplies.

There have been a limited number of major groundwater contamination incidents involving chlorinated solvents in the UK, where concentrations in excess of  $100\mu\text{g l}^{-1}$  have been detected. The most recent of these arose from a tetrachloroethene leak into a chalk aquifer where concentrations close to the source of  $80,000\mu\text{g l}^{-1}$  were recorded, decreasing to  $200\mu\text{g l}^{-1}$  at a distance of 2km away. The contaminated borehole has been removed from public supply and it is understood that the Water Authority concerned is considering treatment options. No concerted nationwide survey for chlorinated solvents in groundwater has been carried out to date although a limited study carried out in 1983/84 revealed the presence of these compounds in some potable supply abstractions at concentrations above the WHO tentative guideline values (10). In addition to an examination of analytical data for groundwaters, communication with regional water authorities and water supply companies indicated that only 3 organizations had completed analysis of all groundwater sources for volatile chlorinated solvents and a further water authority was in the process of conducting a major screening exercise. 5 undertakings had analysed some groundwater sources, while 19 had no plans to conduct organic analyses of their groundwater abstractions.

During the early 1980's a national survey was conducted for trihalomethanes in potable waters and, although the accuracy of some of the results was suspect owing to the number of different analytical techniques used, a guideline value of  $100\mu\text{g l}^{-1}$  total trihalomethanes was issued in 1983. Compliance with this guideline, in cases where infringements had occurred, was largely achieved by means of modifying the disinfection procedures during water treatment. The guideline had been issued by the Department of the Environment as a means of clarifying the EC drinking water

directive parameter 32, whilst retaining the condition that 'haloform concentrations must be as low as possible'.

Since a previous report to DOE in 1984 on volatile chlorinated solvents (21), a number of contamination incidents have been reported and, in the main, the problems arising have been addressed by removing the contaminated sources from public supply or blending with an uncontaminated source to produce acceptable concentrations, usually with reference to the WHO tentative guidelines. In only 2 instances have treatment plants been installed to maintain the potable supply. A further measure which has been adopted in a number of cases is intensive pumping from abstraction boreholes to purge contamination from the aquifer concerned or to enhance dispersion and advection of the pollutant plume within the groundwater mass.

Such a technique was used by a water authority during 1986 when contamination of a public supply abstraction with trichloroethane was detected, as a result of a single complaint of adverse taste. Concentrations up to  $207\mu\text{g l}^{-1}$  were recorded in one borehole and it was decided to pump water from this source to waste (local watercourse) in an attempt to purge the aquifer. It was known that a spillage of this material had occurred in the area some 6 months previously, but no action had been taken until receipt of the complaint. It was calculated that at the purge pumping rate adopted, the contaminant would be expelled at a rate of  $0.5\text{ld}^{-1}$ , and that purging to an acceptable level would take over a year. Recent reports indicate that the level of contamination has decreased slightly but has persisted for longer than had been anticipated, albeit below the USEPA drinking water standard of  $200\mu\text{g l}^{-1}$ . Counter-current aeration plant has now been installed and consideration is being given to the addition of GAC adsorption vessels for final polishing. It appears that the installation of treatment plant has been implemented largely in response to the vocal concern of local residents over a potential health scare and the activities of local political pressure groups.

An incident such as this highlights the problems involved in groundwater contamination and raises several pertinent issues which are worthy of consideration at this stage.

The area in which the boreholes are located is essentially urban, with a number of light industrial and commercial premises and it was acknowledged by the water authority that a potential hazard existed. The fact that a spillage occurred and infiltrated the underlying aquifer underlines some of the problems inherent in aquifer protection. Although it is possible that industrial occupation of the area existed prior to exploitation of the groundwater resource, clearly there is a requirement for coherent legislation or at least a clear policy to regulate and control industrial activities, insofar as these may affect the quality of groundwater, in terms of storage and handling of hazardous chemicals. Under section 72 of the Water Resources Act 1963, it is an offence to make an unauthorized discharge of polluting matter into any underground strata, but it is unclear whether the water authority has a statutory duty to inform industrial premises of the requirement to ensure protection of groundwater, but this may be interpreted as falling within the scope of section 10 of the Water Act 1973. However, under the terms of the 1980 EC Directive (11), any activity likely to lead to indirect discharges of List I substances to groundwater is to be controlled (List I substances are detailed in an annexe and this is similar in content, although not identical, to List I as specified in the 1976 Dangerous Substances Directive).

Regional water authorities have developed groundwater protection policies which are applicable and suitable in their areas, taking account of hydrogeological and other factors (12). In addition, in some areas of the country, regional 'pollution prevention panels' have been established which involve representatives of industry, water authorities and waste disposal authorities in formulating guidance and codes of practice for avoidance of all forms of pollution. Accidental discharges are still possible, even with a

stringent system of controls, but contamination arising from normal practice should be minimised.

The absence of any firm standards or guidelines for particular organic substances in ground - or potable water detracts from the ability of a competent authority to take decisive action in response to contamination, although in this case a taste problem arose which necessitated remedial measures. In the absence of this single complaint, it appears unlikely that the incident would have been detected even though it was known that a spillage had occurred previously. Under the EC drinking water directive provisions, as clarified by a DOE circular (13), only 1 statutory sample per annum is required to be analysed, based upon the population supplied (35,000 in this case). It should also be considered that the only standards for trichloroethane are those of the USEPA ( $200\mu\text{g l}^{-1}$ ) and the FRG,  $25\mu\text{g l}^{-1}$  total for 4 chlorinated solvents, including trichloroethane.

In evaluating the potential public health risks of organics in drinking water, reference is most frequently made to the WHO guidelines although these, being derived for long-term exposure purposes (typically  $2\text{ l d}^{-1}$  consumption of water by a 70kg person over a lifetime), can be argued to be inapplicable for relatively short-term exposures, such as may be experienced during a groundwater contamination incident. Therefore, this further complicates the decision-making process over what constitutes a 'safe' level and whether any form of treatment or other remedial action is required.

An additional aspect highlighted by this case study is the strength and influence of local public concern over potential health effects. In the absence of a quality standard with which to evaluate the requirement for treatment, the water undertaking can be subject to local public pressure, such that a final decision may be governed by political aspects rather than from a scientific/technical standpoint, in order to satisfy public opinion. The growth of public awareness over drinking water

quality and environmental issues in general has been notable over the last 5 years and has been reflected in an increasing number of media features. This has led to a polarisation of opinion over drinking water issues and an increasing degree of political pressure. Of particular relevance is the current concern over elevated nitrate concentrations in groundwater and some potable waters.

It is important, therefore, that the significance in public health terms of organic contaminants in drinking water should be considered in proper perspective. In establishing guidelines for drinking water quality, the WHO expert panel took account of, as far as was practicable, the other sources of exposure to hazards including food and air.

For toxic organic compounds, and particularly pesticides, it was established that, given the major source was ingested food, not more than 1% of the Acceptable Daily Intake (ADI) would be derived from drinking water. Based upon this information and application to a 70 kg person consuming 2 litres a day of drinking water over a lifetime, guideline values for concentrations of a range of pesticides in potable water have been promulgated. For carcinogenic substances, a different approach to the setting of guidelines is adopted. In this case, where it can be assumed that the threshold for adverse effects is zero or non-detectable, a linear multi-stage model is utilised to estimate the highest possible upper limit of incremental (excess over normal background) risk from a lifetime of exposure to a particular daily intake of a substance. Again, the standard case of a 70 kg person consuming 2 litres of drinking water daily was adopted. An acceptable criterion of 1 in 100,000 lifetime risk of cancer was selected. For a typical group of carcinogenic compounds, polyaromatic hydrocarbons (PAH), it was estimated that drinking water would contribute only 0.1% to 0.3% of the total exposure to these compounds, over 98% being ingested from food. Although the contribution from volatile chlorinated solvents in drinking water may be somewhat greater owing to their potential occurrence

at  $\mu\text{g l}^{-1}$  levels (as opposed to  $\text{ng l}^{-1}$  levels for PAH), the proportion derived from foodstuffs will be of overwhelming importance. Levels of chlorinated hydrocarbons in a range of foodstuffs are shown in Table 7 (14). Drinking water is, therefore, generally a source of minor toxicological and carcinogenic hazard and proving the postulated causal relationship is difficult.

Epidemiological studies have been carried out in the USA, UK and the Netherlands in attempts to establish links between cancer and consumption of drinking water containing low concentrations of organic compounds. None of these studies has established firm causal links, mainly due to the presence of confounding variables, i.e. the multitude of other possible carcinogenic agents in food and air, general life-style factors and genetic predisposition, and it was evident that the risks presented by drinking water were very low and indistinguishable from the prevailing environmental background.

Although no firm causal links have been established, when viewed collectively the epidemiological studies completed thus far only provide evidence for maintaining a hypothesis that there may be a health risk and that any positive correlation may be due to an association between some constituents of drinking water and cancer-related mortality.

The situation with regard to the occurrence of pesticides in groundwater is also giving rise to some concern in the UK at present. A recent study by the British Geological Survey (15), assessing the threat of pollution of groundwaters from agricultural pesticides and industrial solvents, highlighted the lack of information on the possible contamination of UK aquifer resources and cited reports on the occurrence of phenoxyalkanoic and triazine herbicides in groundwater, at levels above the EC directive limits for drinking water. Their report recommended that a substantial research effort should be concentrated on a survey of UK groundwater resources and a detailed examination of

the behaviour and fate of agricultural pesticides in sub-surface environments. Great concern was also expressed about groundwater contamination by industrial solvents, which was regarded as a potential "environmental disaster". Further weight to this opinion was added by the chairman of the House of Commons' Agriculture Committee (16), who recently urged the Government to initiate a comprehensive assessment of pesticides in major groundwater sources.

The increased concern over pesticides in groundwater is based upon more limited information of their occurrence than for chlorinated solvents. However, since by definition a pesticide must possess biocidal properties, the toxicity of such compounds is reasonably well documented, when compared to chlorinated solvents. In addition, reported concentrations of pesticides are typically one or two orders of magnitude below those of, for example, trichloroethene. Therefore the perceived hazard and risk are considered to be greater while the actual situation may be converse.

Clearly there is a requirement for the aquisition of further information on the contamination of UK aquifers by organic compounds and it is important that the requirements to satisfy public concern are correctly balanced with the necessity for a rational scientific approach.

When compared to the approaches and measures adopted in other European countries, the approach currently assumed in the UK can perhaps be subject to some criticism, in terms of the apparent lack of positive action, although it should be noted that a number of studies are curenly under consideration to provide a sound basis for future programmes, which is necessary if an acceptable outcome to concerted action plans is to be achieved. (It is further understood that in recent weeks, a national study by consultants of the current state of UK groundwaters has been commissioned).

Serious contamination incidents have not, to date, manifested themselves in the UK to the same extent as in other European countries, but it is considered that much can be gained from an exchange of information on this subject. A common criticism levelled concerns the absence of potable water quality standards and it would appear that consideration of information gained from other countries, including the USA, would be of value in facilitating at least a set of long-term guideline concentrations for chlorinated solvents. (A long term guideline value of  $30\mu\text{g l}^{-1}$  for triazine herbicides has recently been recommended by DOE).

However, the problem of groundwater contamination cannot be solved by the water industry alone and consideration should be given to the establishment and effective operation of administrative procedures to integrate the functions of other organizations into a groundwater protection policy.

Table 7 Chlorinated hydrocarbon content \* of foodstuffs (14)

Foodstuff	Chloroform	Carbon tetrachloride	Trichloroethane	Trichloroethene	Tetrachloroethene
<b>Dairy produce</b>					
Fresh milk	5	0.2		0.3	0.3
Cheshire cheese	33	5		3	2
English butter	22	14		10	13
Hens eggs	1-4	0.5		0.6	ND
<b>Meat</b>					
English beef (steak)	4		3	16	0.9
English beef (fat)	3		6	12	1.0
Pig's liver	1		4	22	5
<b>Oils and fats</b>					
Margarine	3			6	7
Olive oil (Spanish)	10		10	9	7
Cod liver oil	6		5	19	2
Vegetable cooking oil	2	0.7		7	0.01
Castor oil	NA		6	ND	3
<b>Beverages</b>					
Canned fruit drink	2	0.5		5	2
Light Ale	0.4	0.2		0.7	ND
Canned orange juice	9	6		ND	ND
Instant coffee	2	5		4	3
Tea (packed)	18		7	60	3
Wine (Yugoslav)	NA	0.3		0.2	ND
<b>Fruit and vegetables</b>					
Potatoes (S. Wales)	18		4	ND	ND
Potatoes (N.W.England)	4		1	3	0.7
Apples	5		3	5	2
Pears	2		2	4	2
Tomatoes	2	4.5		1.7	1.2
Black grapes (imported)	ND				
Fresh bread	2	19.7	2	2.9	ND
				7	1

\* all concentrations in  $\mu\text{kg}\cdot\text{l}^{-1}$

NA = No Analysis; ND = Not Detected

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#### 4. CURRENT AND FUTURE TRENDS

The occurrence of organic compounds in groundwater sources has been reported with increasing frequency in recent years and it would appear that, in the absence of more stringent controls, this trend will continue in the future, both as a result of greater frequency of detection and also as a result of increased industrial activity in the chemicals and service sectors where significant quantities of chlorinated solvents are used. As far as pesticides applied in agriculture are concerned, the situation is less clear since the present state of agricultural over-production in the EC member countries is a matter of concern, to the extent that the present UK government has an intended commitment to releasing farmland to other uses. This will possibly bring about a gradual decrease in the quantities of pesticides applied to the ground in the future but it may be a number of decades before any decrease in the quantities leached to groundwater and here a parallel may exist with the present nitrate problem. It is estimated that, in parts of the UK, the nitrate currently entering groundwater is derived from fertilizer applications made in the 1940-1945 war years. Therefore, even if application were to be ceased immediately, it would take many years before concentrations in groundwater would decrease appreciably. A similar situation may exist with agriculturally-applied herbicides and also with other organic chemicals, in that the quantities already contained within soil horizons and unsaturated zones of aquifers will continue to leach into groundwater. There is a fundamental difference between, for example, pesticides and chlorinated solvents, in that the former constitute a large diffuse source of contaminants which are dispersed initially and can enter groundwater across a broad front, whilst chlorinated solvents tend to arise from point sources such as landfill sites or spillages and dispersion occurs in the unsaturated and saturated aquifer zones. In this latter case, post-contamination control is possible since the pollutant plume may remain reasonably concentrated for a considerable time and thus selective purging of the aquifer can remove or

ameliorate contamination. This has formed the basis of control strategies in a number of cases.

Protection of groundwaters is a complex issue and particularly so with regard to agricultural pesticides. Although major advances have been made recently with the development of biodegradable compounds and biological pesticides are currently being actively researched, it appears that compounds such as triazines and phenoxyalkanoic herbicides will continue to be used for a number of years. Therefore a major alteration in agricultural practice (including fertilizer application) will be required in order to ensure protection of groundwater, which would have serious implications for the agricultural industry, for the EC Common Agricultural Policy and the present farm subsidy system.

A greater degree of control over chlorinated solvents may, however, be possible but would require co-operative action on the part of the solvent producers, users, waste disposal contractors, waste disposal authorities and water authorities in order to minimise losses during production and use and to ensure proper handling and disposal of wastes. In addition, a comprehensive groundwater protection policy, such as that adopted by at least one regional water authority (12), in terms of control over industrial development and activity in aquifer-sensitive areas would also aid in preventing contamination of groundwater. Even a small volume of solvent can cause a serious contamination incident. One such occurrence where trichloroethene concentrations of  $200\mu\text{g l}^{-1}$  were recorded (17) was thought to have been caused by haphazard disposal of as little as 20l of the solvent. Spillage of a single 45 gallon drum of trichloroethene into subsurface strata would release sufficient solvent to contaminate  $10^6 \text{ m}^3$  of groundwater to a level 10 times the WHO guideline concentration of  $30\mu\text{g l}^{-1}$ .

The disposal of waste solvents has received much attention from the Hazardous Waste Inspectorate (HWI) over the last 3 years (18,19) and there is now an active policy to prevent or at least discourage

the disposal of drummed liquids in landfill sites. In addition, HWI are encouraging the recycling of waste solvents, which at the present time accounts for approximately 200,000 tonnes of material per annum. However, increased recovery of solvents will not, in itself, necessarily reduce the risk of spillage or unlicensed discharge into the ground, since the greater number of handling operations may actually increase the risk of contamination, unless strict management and working practices are either adopted or imposed.

A promising approach to the problem has been initiated by Coventry City Council (reported in Volume 1 of this document), in whose area serious contamination of private industrial groundwater sources has occurred. A pollution prevention panel has been set up, consisting of industrial, local council, water authority and waste disposal authority delegates, with the aim of providing information of the previous contamination incident. The group is operated upon a voluntary basis and therefore relies upon the good intentions of the participants.

In terms of control over the siting of industrial premises, this may be achievable with new developments where intervention by a water authority or waste disposal authority can occur during the planning approval processes. With established industry the situation is less straightforward and relies upon the good working practices carried out by that industry and the vigilance of water authorities. Under Section 91 of the Control of Pollution Act 1974, water authorities may enter and inspect any premises for the purposes of carrying out their duties under the Act.

The strength and influence of public opinion over water quality issues is also likely to increase in the future in the UK, both with reference to the national increase in recent years and by comparison with other countries, particularly the Netherlands, where drinking water quality issues have become highly politicised, and the FRG, where recent serious pollution incidents have resulted in media headlines and widespread concern over the contamination of

drinking water. The response by competent authorities to past contamination incidents has in some cases, not completely satisfied public opinion and it is considered that a greater degree of public consultation and accountability will be required in the future. The possible privatisation of water authority services in the UK has also aroused some concern with respect to the long term maintenance and monitoring of drinking water quality.

As described in Volume 1 of this report, treatment technology for the removal of organic contaminants from water is available in the UK and can be deployed at reasonable cost, when compared to the average cost of producing potable water. However, since groundwater has traditionally required only minimal or no treatment prior to distribution and has therefore been considered to be a relatively 'cheap' source of high quality product the installation of additional treatment plant could be regarded as detrimental in economic terms when alternatives exist. Simple disuse of a contaminated borehole does not constitute a solution to the problem in the long term, as chlorinated solvents will persist in aquifers for many years, their concentrations being reduced only gradually by dispersion and dilution.

The market size for treatment plant to remove organics from groundwater (aeration units or GAC contactors) in the UK is small at present, with only two or three aeration plants having been installed in the past 5 years specifically for treatment of contaminated groundwater prior to potable supply. Less than 10 water treatment works currently use GAC contactors for organics removal, many of these for taste and odour abatement. GAC treatment has been regarded with some operational caution since there is a requirement for high-temperature regeneration of exhausted carbon which, unless the scale of usage merits an on-site facility, makes application relatively expensive. However, given the proportion of public water supplies derived from groundwater sources in the UK (34%) (and also the number of private supplies in existence) and considering the current and potential future extent of contamination by organic micropollutants, a modest number of

aeration plants may be required in the next 5 years (possibly 10) for removal of volatile organics. Financial analyses computed for the first volume of this report indicate that treatment of a contaminated stream by aeration can be effected at little additional cost, whilst GAC contactors are to be preferred for less-volatile organics, albeit at some slight increase in cost over and above aeration.

Although the volume market is likely to remain, for the present time, in the public sector with the regional water authorities, the water companies, with their efforts concentrated purely upon water supply, and having a long tradition of commercial operation, may possibly be the most fertile sector for a marketing exercise. In both these cases, the requirement may be solely for equipment supply and erection, the design specification being produced by in-house personnel. In the private water supply sector, however, and particularly in the case of industrial abstraction, there will be requirements for a comprehensive design, supply and operational package. It is considered that the potential UK market will continue to grow, at least in the short-term up to the end of the century. Even though groundwater protection measures will take increasing effect, the quantities of chemicals already contained in the soils above and in the unsaturated zones of aquifers will continue to enter groundwater over an indeterminate period of time. In addition, the future growth in public concern over organics in drinking water coupled with the likely expansion in relevant EC legislation will tend to increase the pressure upon water undertakings to improve the quality of the final product.

A recent programme for the demonstration of new soil and groundwater clean-up technologies, initiated by NATO, may also bring about increased market opportunities, although the UK is apparently not participating officially in the demonstration project (20). It has been estimated that £1.4 x 10<sup>9</sup> requires to be spent per annum community-wide to clean up the existing stock of contaminated land. Demonstration projects involving the clean-up and reinjection of contaminated groundwater are currently underway

in Denmark, Canada, West Germany and France and these include the use of aeration and GAC units on a large scale. The apparent lack of UK resources for expenditure in this field has precluded action at this stage, but it would appear that non-participation in the short-term may damage the prospects for future participation in any potential markets arising from the successful outcome and application of the NATO projects.

## 5. CONCLUSIONS

- 5.1 Contamination of groundwater resources by organic micropollutants in some EC member countries has been known for a number of years and has given rise to particular problems in the Netherlands and Italy, where serious contamination incidents have resulted in the removal of abstraction points from supply networks and, in some cases, the installation of treatment plant. Of most concern are volatile chlorinated solvents whilst there is mounting concern also over agriculturally-applied pesticides, particularly in the Netherlands. In the absence of well defined EC legislation for chlorinated solvents, the approach to setting national standards for drinking water has varied widely between countries. For example, in the Netherlands a stringent stance has been adopted, involving reference to a generalised parameter of  $1\mu\text{g l}^{-1}$  in the EC drinking water directive whilst in the FRG, a limit of  $25\mu\text{g l}^{-1}$  has been adopted. Much effort is currently being directed towards the improved protection of aquifer resources by means of more stringent controls over the production, usage and disposal of chemicals.
- 5.2 In the UK, a small number of serious contamination incidents involving chlorinated solvents have occurred to date and a maximum of three aeration plants have been installed by regional water authorities in order to treat contaminated supply boreholes. Consideration is also being given to the use of GAC units at one of these locations. There exist no guidelines for acceptable concentrations of chlorinated solvents in drinking water and reference is most often made to the WHO guidelines although these do not constitute action levels for decisions concerning treatment.
- 5.3 Because of the lack of conclusive toxicological data, establishing standards for organic compounds in drinking water is difficult and particularly so where the tendency is to err on the side of caution but where to do so would incur increased costs for producing drinking water. Opinion varies throughout the member countries as to the derivation of acceptable potable water

concentrations for organics. Given that the intake of potentially toxic or carcinogenic substances from water will be very small, when compared to the exposure from food and air, the setting of stringent standards could be termed as unreasonable and pointless since the costs of bringing about a marginal and possibly undetectable reduction in drinking water related morbidity (or mortality) could be deemed uneconomic.

However, the strength of public concern in some European countries (particularly the Netherlands and West Germany and, increasingly, the UK) over the presence of potentially toxic and carcinogenic components in drinking water places increasing pressure upon governments and water undertakings to take action and install treatment plants. It is recommended that the establishment of standards for volatile chlorinated solvents (and possibly other organics) in drinking water should be considered on a national 'guideline' basis.

- 5.4 In terms of the potential UK market for relevant water treatment plant arising from the requirement for removal of organics from groundwater-derived potable supplies, several UK-based companies offer counter-current aeration equipment and it is possible that there will be a modest demand for such plant from the water industry in the years up to the end of this century, if, as is considered likely, the trend in solvent contamination of aquifers should continue. For private groundwater-derived supplies, particularly those serving industrial concerns, the market is difficult to estimate but it would appear that a marketing and information initiative would be of value to publicise the availability, merits and economic aspects of aeration treatment.

The potential market for GAC treatment of groundwaters contaminated with non-volatile organics is less certain. It is likely to remain small, but may well expand in the future for surface water supplies, which tend to be more susceptible to higher levels of contamination.

5.5 With regard to the potential wider European market for treatment plant, it appears unlikely that significant market penetration would be achieved in the Netherlands, FRG or France.

It is considered that more positive market opportunities may exist in Italy, where intensive industrialization has caused groundwater contamination in the Northern provinces, and the more recent members of the European Community, including Greece, Spain and Portugal.

## REFERENCES

- 1 Environmental Data Services (1987) Geological survey warns of agrochemical, solvent Pollution threat to aquifers. Ends Bulletin no. 150, p.6.
- 2 C. R. Pearson and G. McConnell (1975) Chlorinated C<sub>1</sub> and C<sub>2</sub> hydrocarbons in the marine environment. Proc. Soc. Lond. 189 305-332.
- 3 Department of the Environment (1976) Halogenated hydrocarbon solvent wastes from cleaning processes. Waste management paper 9 HMSO, London.
- 4 Department of the Environment (1981) Special wastes - a technical memorandum providing guidance on their definition. Waste management paper 23. HMSO, London.
- 5 EUR 10646 (1987) Hydrocarbons: identification of air quality problems in member states of the EEC. HMSO, London.
- 6 Monsanto PLC (1987) Personal Communication.
- 7 G. Baldauf and W. Kühn (1985) Halogenische verbindungen im Grundwasser: Verkommen, Verbreitung und Aufbereitung. DELIWA - Zeitschrift 4, 8pp.
- 8 H. F. Schoeler, B Voss and O. Hoyer. (1984) Chlorinated hydrocarbons in groundwater of the Rhine-Sieg area (West Germany) Proc. Int. conf. on Environ. Contam. London, UK. pp 465-467. CEP consultants, Edinburgh UK.
- 9 M. Sonneborn, S. Gerdes and R. Schwabz (1981) volatile halogenated hydrocarbons in river water, groundwater and swimming pool water in the FRG. Proc. 2nd Symposium on Analysis of organic micropollutants in water. Killarney, Eire.
- 10 W. Kühn (1987) Personal Communication, University of Karlsruhe, FRG.
- 11 Council of the European Communities (1980) Directive on the protection of groundwater against pollution cused by certain dangerous substances. Off. J. Europ. Commun. L.20. 105-109.

- 12 K. H. Selby and A. C. Skinner (1979) Aquifer protection in the Severn-Trent region: Policy and Practice. J. Inst. Water Pollut. Control 78 (22) 254-269.
- 13 Department of the Environment (1983) Letter ref. WS/767/17 giving further guidance and information about operations of the EC directive 80/778/EEC.
- 14 G. McConnell, D. M. Ferguson and G. R. (1975) Chlorinated hydrocarbons and the environment. Endeavour 34 13-18.
- 15 British Geological Survey (1987). The pollution threat from agricultural pesticides and industrial solvents. Hydrogeological Report 87/2. BGS, Keyworth Nottingham UK.
- 16 House of Commons' Agriculture Committee (1987). The effects of pesticides on human health vol.1. 2nd Special Report, Session 1986-7. HMSO, London.
- 17 W. K. Lewis, W. M. Thomas and R. J. C. Barron (1987) Contamination of groundwater resources and impact on potable supplies. Handbook of Inst. Water Environ. Man. 39-47.
- 18 Hazardous Waste Inspectorate (1985) Hazardous Waste Management - An Overview. 1st Report, HMSO, London 59pp.
- 19 Hazardous Waste Inspectorate (1986) Hazardous Waste Management: "....Ramshackle and antediluvian?" 2nd report, HMSO, London 119pp.
- 20 Environmental Data Services (1987) High-tech approaches gaining favour for contaminated land clean-up. Ends bulletin 150 9-11.
- 21 G. K. Folkard, C. J. Peters, A. E. McIntyre and R. Perry (1984) Investigation into Chlorinated Hydrocarbon Solvents in Groundwaters. Final Report to the Department of the Environment, Contract PECD 7/7/088.