

Groundwater Contamination by Trichloroethene (TCE) in a Residential Area of Perth: Distribution, Mobility, and Implications for Management

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- # Geological Survey of Western Australia

Summary:

Substantial TCE and ammonia contamination was detected in groundwater beneath a residential area in Perth. Investigation has successfully determined broad aspects of the extent of the TCE plume and its impact. The plume extends approximately 900 m in groundwater downgradient of an industrial area. The contamination is about 300 m wide and 6 - 8 m thick. A peak concentration of 2000 μgL^{-1} TCE was measured. The mobility of the plume and the residence time for the contamination in the sand aquifer are estimated based on the groundwater velocities and retardation factors. Biological or chemical transformation of TCE cannot be excluded, although no transformation products have been found in a small portion of the plume. Currently no remediation of the contaminated site is planned. An approach for managing the contamination is presented and important issues for future remediation options for TCE contaminated sites in Perth are discussed.

1 INTRODUCTION

Chlorinated aliphatic hydrocarbons such as trichloroethene (trichloroethylene or TCE) and tetrachloroethene (perchloroethylene or PCE) are some of the most commonly detected organic contaminants in groundwater. Many of these compounds are suspected of being carcinogenic. Their presence in groundwater in North America and Europe has lead to a large number of water supply bores being shut down, and necessitated expensive remediation programs. These chemicals are widely used as industrial degreasing agents, and in some urban areas, almost all water supply or monitoring bores are contaminated to some extent with chlorinated solvents (1).

Until recently, there have been no known major occurrences of groundwater contamination by chlorinated aliphatic hydrocarbons in Perth, although there is a large number of industrial areas throughout the Perth metropolitan area which are potential sources of contamination (Fig. 1). In 1989, Atwood and Barber (2) indicated that groundwater contamination by chlorinated solvents was likely to occur in Perth. By late 1992, widespread TCE contamination was detected in a residential area adjacent to an industrial estate. Further investigation of industrial areas of the Swan Coastal Plain is likely to detect increased instances of TCE contamination in groundwater. Characterising the distribution and transport behaviour of TCE in aquifers of the Swan Coastal Plain is, therefore, of increasing importance to aid management of groundwater as a potential water resource.

This paper discusses how TCE contamination was detected beneath a residential area of Perth and the measures that have been undertaken to manage the potential public health and environmental impacts of the groundwater contamination. The distribution of contamination is shown and preliminary results of investigations regarding the mobility of the plume are presented. Uncertainties with respect to TCE mobility are discussed and planned investigations to overcome these

uncertainties are described, as are the implications for management.

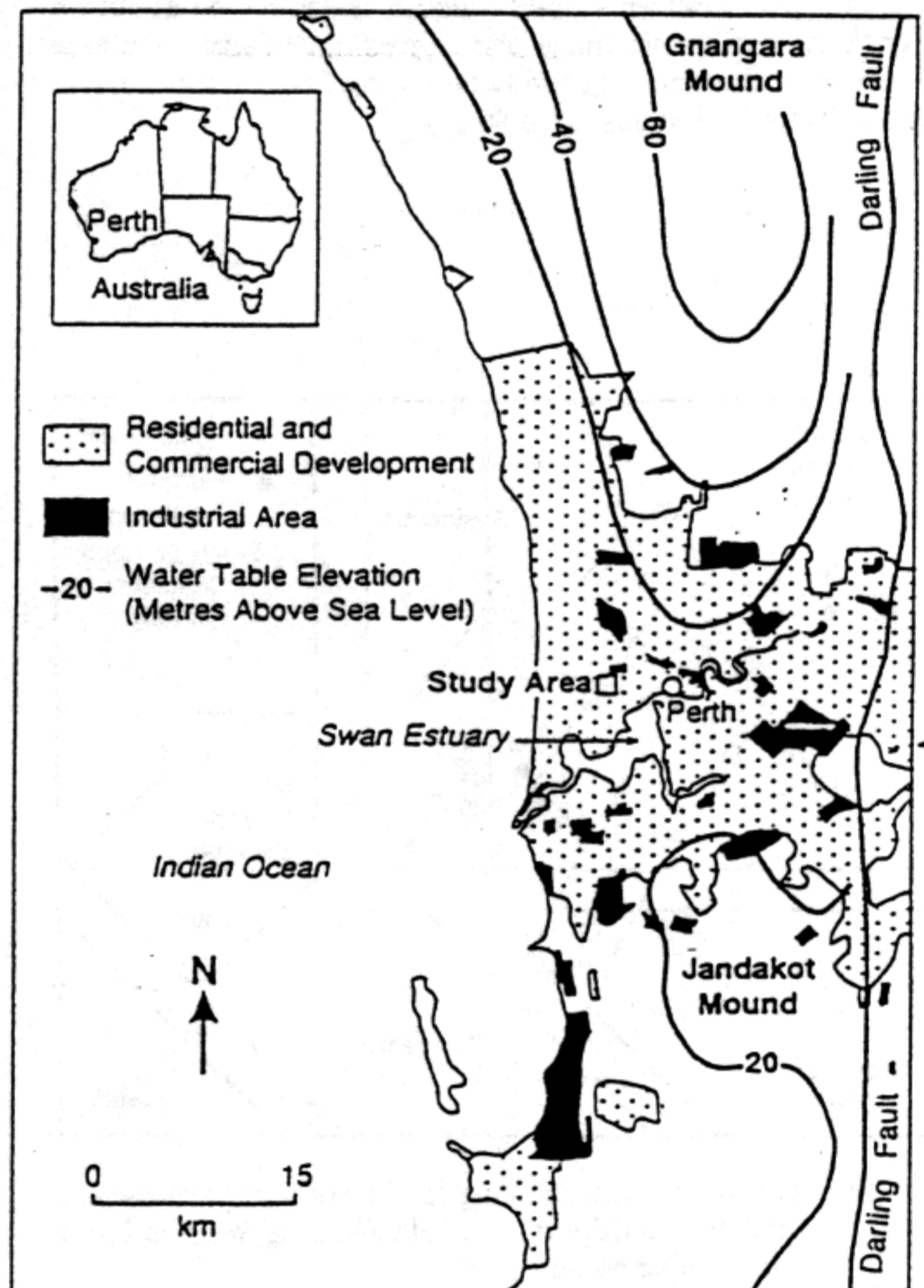


Figure 1: Regional setting showing the location of industrial areas on the coastal plain around Perth.

2 HYDROGEOLOGICAL SETTING

The Perth metropolitan area is located to the west of the Darling Fault, and is predominantly underlain by unconsolidated sands of Quaternary age which form a superficial cover to the Perth Basin sequence of sediments. The superficial sediments form an extensive unconfined aquifer. Two major groundwater flow systems underlie the Perth metropolitan area: the Gnangara Mound flow system to the north of the Swan Estuary; and the Jandakot Mound flow system to the south of the Swan Estuary (Fig. 1).

The study area is located near the southern end of the Gnangara Mound flow system. The superficial sediments have a maximum thickness of about 55 m in this area, consisting mainly of unconsolidated sand. Interbedded clay is also present in the soil profile which, although a minor feature, may have an effect on the contaminant distribution. Siltstone and shale of Tertiary age forms an impermeable base to the unconfined aquifer.

Local to the plume site (see Fig. 2), soil samples are characterised as medium grained, well sorted sand, with a D_{50} range of 0.30 - 0.42 mm, with a uniformity coefficient range of 2.25 - 2.94. Groundwater levels at the site are 6 to 10 m below ground surface, with annual fluctuations of 0.6 to 1.0 m. The groundwater flow direction and gradient are approximately 240 degrees (south westerly), and 0.0018, respectively. Hydraulic conductivities of the surficial sands estimated according to the Hazen method (3) from the grain size analysis (D_{10} range: 0.14 - 0.20 mm) are $2.83 \times 10^{-4} \text{ ms}^{-1}$ (24.5 md^{-1}). Assuming an effective aquifer porosity of 0.3 the groundwater velocity would therefore be about 54 myr^{-1} . A small-scale tracer test carried out within the plume confirmed the local groundwater direction, but estimated groundwater velocities up to 80 myr^{-1} .

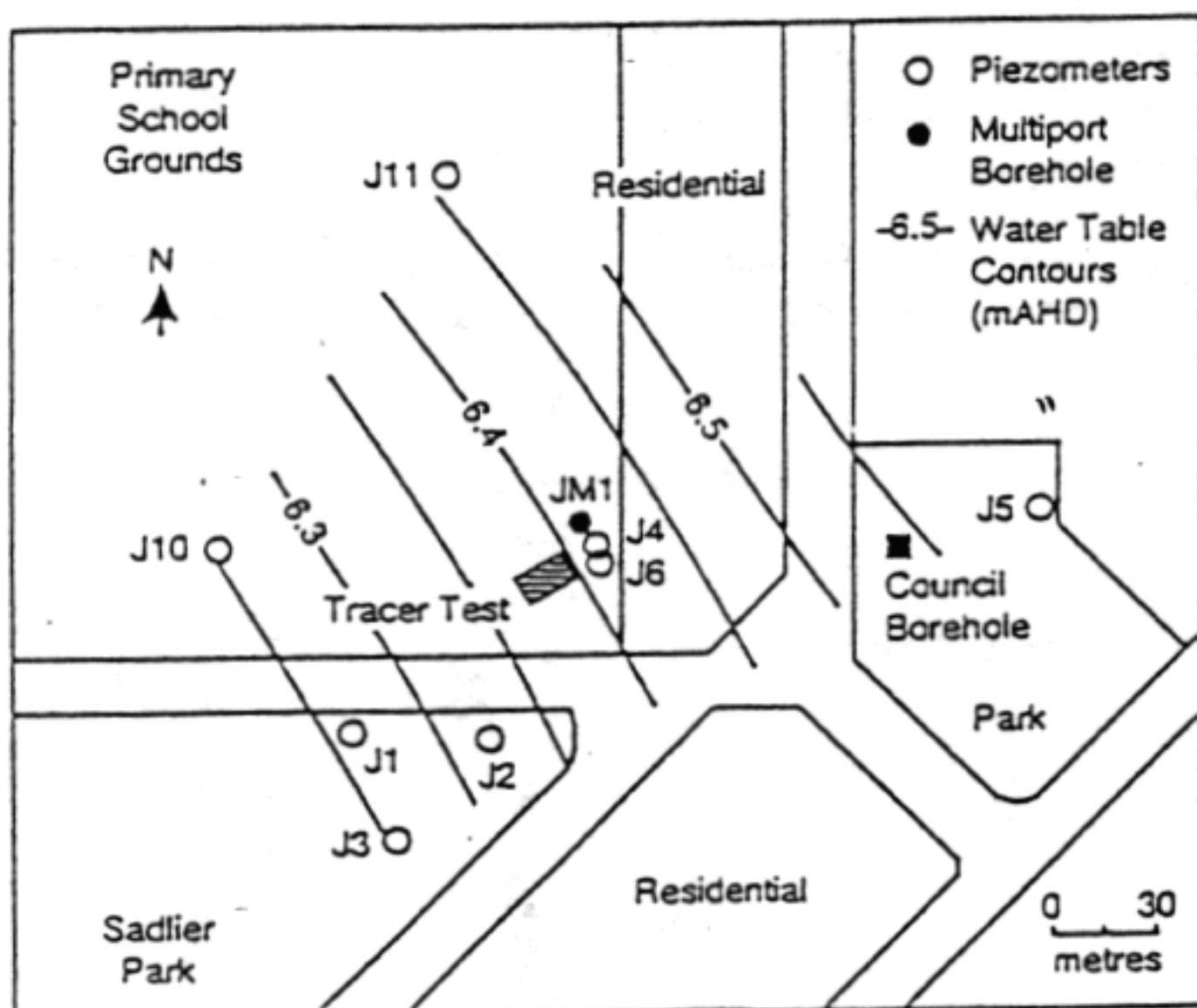


Figure 2: Local test site showing the location of piezometers and the multiport borehole JM1, as well as local water table contours.

3 DETECTION OF CONTAMINATION AND INITIAL RESPONSE

In October 1992, complaints were received from residents adjacent to an industrial area about odorous smells emanating from a residential bore. The odour was determined to be hydrogen sulphide. Field testing indicated that groundwater from the bore also contained high concentrations of ammonia. As the bore was located downgradient of an industrial area, a range of inorganic analyses, and a GC-MS scan for organic constituents was carried out. As a result, TCE was detected. Subsequent resampling and quantitative analysis indicated TCE concentrations in groundwater up to $2000 \mu\text{gL}^{-1}$.

In December State Government agencies coordinated the sampling of an additional 16 private bores, finding that the contamination was severe and extensive enough to warrant further investigations. Subsequently, additional bores were sampled, and soil gas investigations were carried out. These investigations indicated the lateral extent of contamination, but the vertical distribution of contamination was poorly understood due to limited information about the screened depth of many bores.

The major routes of exposure of the public to the TCE contamination are likely to be through drinking contaminated groundwater, and possibly through consumption of produce irrigated from household bores. To prevent exposure to volatile and gaseous emissions, preliminary information about the groundwater contamination problem was communicated to local residents via the media. Information leaflets warning residents that local groundwater was not potable and that local produce should not be consumed were distributed. Residents were also kept informed about subsequent investigations. Air sampling was carried out, indicating that hydrogen sulphide and TCE concentrations were well below levels of health concern near the pumping bore. A range of local produce was also sampled. It contained less than $20 \mu\text{gkg}^{-1}$ of TCE, which was considered safe for consumption.

4 DISTRIBUTION OF CONTAMINATION

In total, 20 bores from private households, a school and the shire were sampled in the initial survey. The results of the analyses indicate that the plume extends for about 900 m to the south-west from the Jolimont industrial area beneath residential areas (Fig. 3). The width of the plume is about 300 m. As mentioned, because of insufficient bore information, the vertical distribution of the TCE plume could not be inferred. The maximum TCE concentration of $2000 \mu\text{gL}^{-1}$ exceeds considerably the current Australian drinking water guideline for TCE of $30 \mu\text{gL}^{-1}$ (4).

To study the mobility of TCE and to determine its vertical distribution a small site within the plume and approximately 500 m downgradient of the industrial area (see Fig. 2 and 3) was selected for more detailed investigation. At the site a number of shallow short-screened piezometers and a multiport bore (JM1) consisting of a bundle of 12 small-diameter piezometers, each spaced 2 m apart vertically, were installed in August 1993 (see Fig. 2 for location). The multiport bore enabled water samples to be taken from the water table down

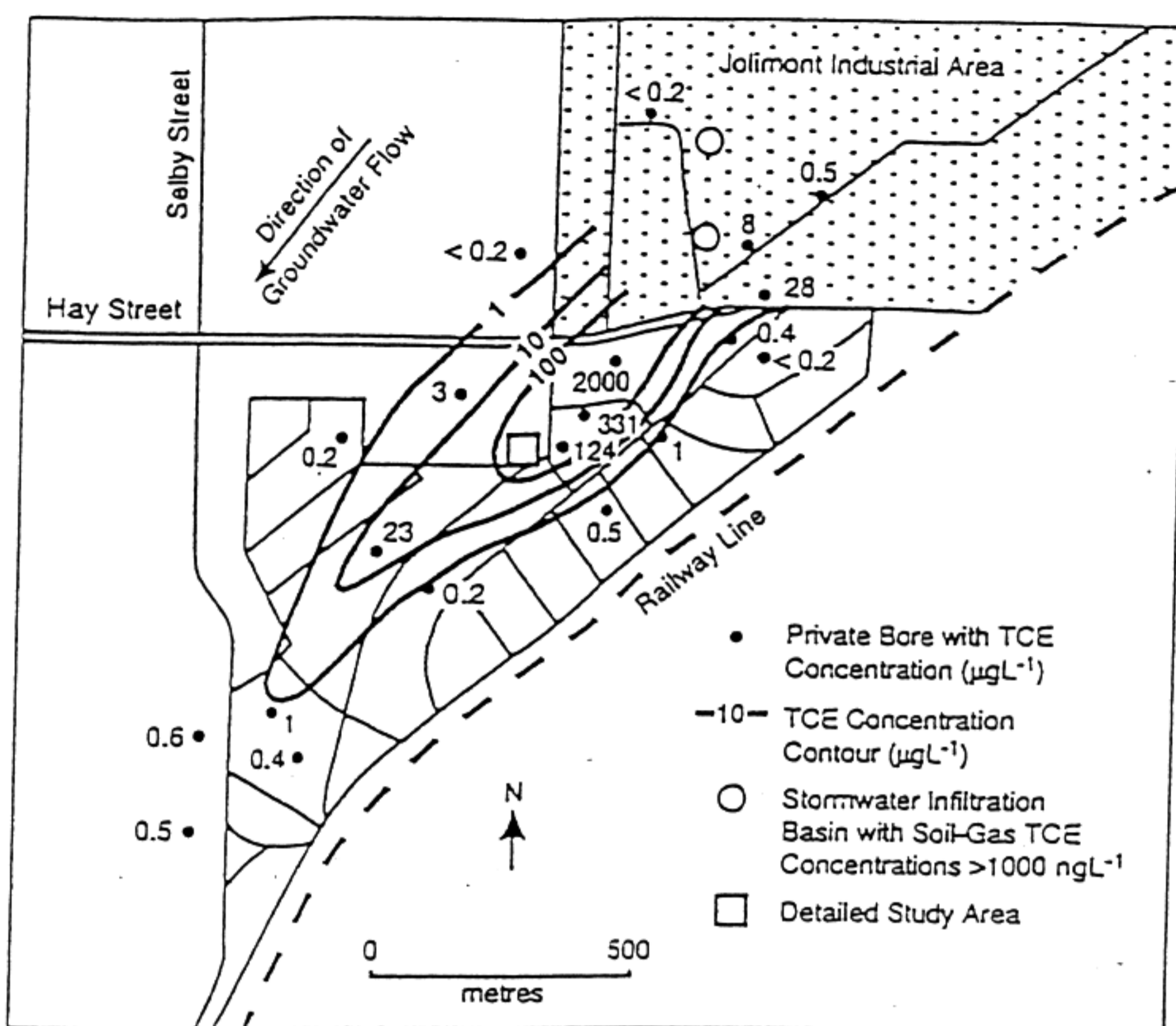


Figure 3: TCE plume extension based on sampling of private bores in December 1992

to 20 m below the water table. Groundwater samples were collected using 50 mL syringes. The syringes were immediately transferred to the laboratory and TCE was extracted, using ether, for subsequent analyses by gas chromatography.

Figure 4 illustrates TCE concentration profiles for samples recovered from JM1 on 18 October, 8 November, and 23

December 1993. The maximum peak concentration of about $75 \mu\text{gL}^{-1}$ TCE was found on 18 October. The peak concentration dropped to about 30 to $40 \mu\text{gL}^{-1}$ in later samplings. The vertical extent of the plume (6 to 8 m) remained fairly constant with TCE contamination present in three ports between 14.5 and 18.5 m. The maximum concentration was found at 16.5 m below ground (about 10 m below the water table) in each of the three sampling sessions.

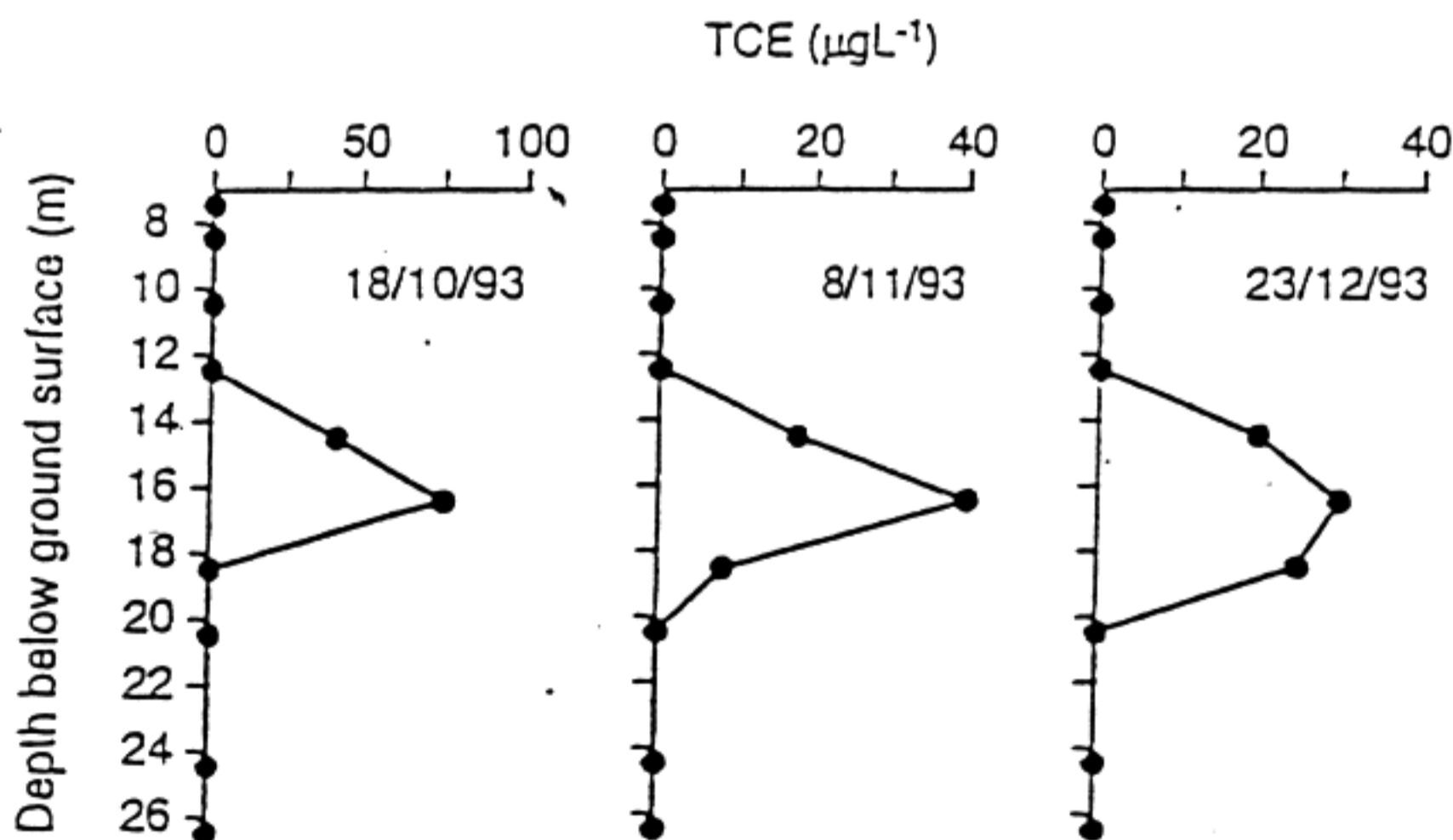


Figure 4: TCE concentration depth profiles sampled from JM1 in October, November and December 1993.

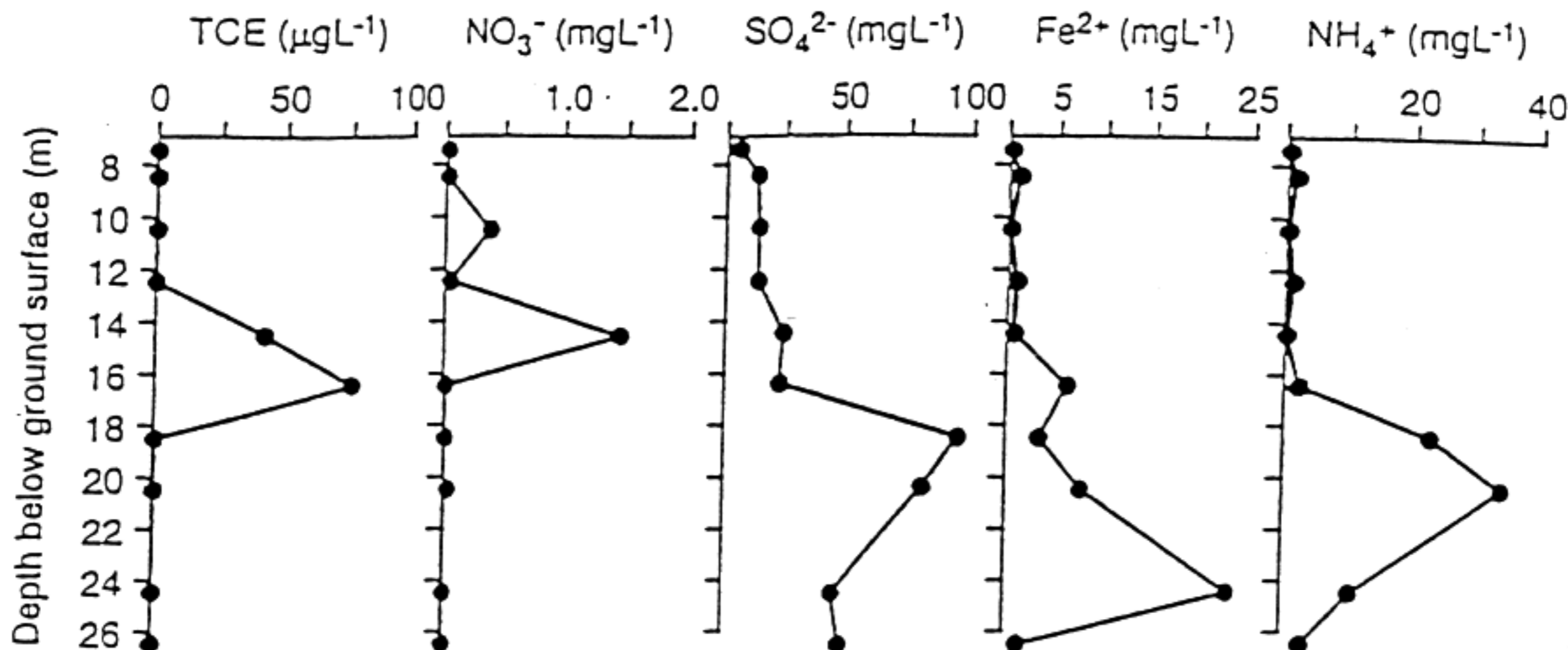


Figure 5: Vertical profiles of TCE and selected inorganic species concentrations in groundwater, sampled from JM1 on 18 October 1993.

Figure 5 shows the distribution of some major ions in groundwater sampled from JM1. Unusually high ammonia concentrations indicate perhaps a second contaminant plume, possibly arising from co-disposal of effluent waters into waste lagoons in the industrial area upgradient. Also, the ammonia plume has peak concentrations at depths below those of the TCE plume, indicating different transport and retention characteristics, if co-disposal did occur.

There is little evidence for the degradation of TCE *in situ*, as no degradation products, such as dichloroethylene (DCE) or vinyl chloride (VC), were detected, despite the abundance of nutrients (e.g., ammonia) and electron acceptors (e.g., nitrate and sulphate) within the zone of TCE contamination. TCE is known to be degradable under both aerobic and anaerobic (methanogenic) redox conditions (5,6). Unfortunately, the reductive dechlorination of TCE, if it were to occur, may result in an accumulation of more hazardous compounds (e.g., VC) than the parent compound.

5 MOBILITY

Due to variable climatic and hydrogeologic factors, there exists no single "standard" approach for assessing the mobility of TCE and other contaminants in groundwater that would be applicable in all cases. Often a simple approach is applied, relying for instance on literature values regarding the partitioning of chemicals and the local equilibrium assumption (LEA), and assuming a simplified one or two dimensional transport description. There is, however, increasing evidence that an idealised modelling approach often fails to describe adequately the mobility of contaminants. Mass transfer resistance is often suggested to delay the establishment of equilibrium within time periods typically considered (7). A more sophisticated approach may require site specific investigation of the partitioning and would incorporate recent research findings.

The complexity of the approach adopted for assessment and modelling depends mainly on the aim of the investigation and the degree of uncertainty that is considered to be acceptable. The more sophisticated approach reduces the degree of uncertainty and serves to test existing research results. Also if clean-up, recovery or management of TCE-contaminated groundwater is required, site specific investigation provides a cost-effective means of evaluating remediation strategies and for planning.

Quantifying the factors affecting the transport behaviour is essential for assessing contaminated sites and remediation methods. Advection is the main transport mechanism in the saturated zone. Assuming that TCE at the site is not degrading or adsorbing (i.e., it is moving at the advective velocity of groundwater; about 55 - 80 m yr^{-1}) then the extent of the plume implies a travel time of about 7.5 to 11 years for the advective front to travel the 600 m to its approximate present location. Sorption/desorption mechanisms, and chemical and/or biological transformation, however, cause the contaminants to be retarded with respect to the apparent average groundwater velocity. Sorption is expected to be the main mechanism responsible for the retardation of chlorinated aliphatics at the Jolimont site since no transformation products were found.

A relatively simple approach in assessing the sorption of TCE is based on the octanol-water partition coefficient (K_{ow}) of the sorbate and the organic carbon content of the sorbent, which have evolved as the two parameters commonly used for estimating sorption of neutral organic compounds (8). The literature contains a number of regression models describing the relationship between sorption coefficients and K_{ow} values (9,10,11). The retardation R of a solute, which is the ratio between the average linear groundwater velocity (v_s) and the average velocity of the retarded compound (v_r), is given by

$$R = 1 + \frac{\rho}{n} K_p = \frac{v_s}{v_r}, \quad (1)$$

where ρ [gcm^{-3}] is the bulk density of the porous medium, n is the effective porosity and K_p [cm^3g^{-1}] is the partition coefficient. Note that K_p is a valid representation of the partitioning between liquid and solids only if the reactions that cause the partitioning are fast and reversible and only if the isotherm is linear over the range of concentrations present. The partition coefficient is related to the organic carbon content fraction by

$$K_p = K_{oc} \times f_{oc}, \quad (2)$$

where K_{oc} [Lkg^{-1}] is the adsorption constant based on organic carbon content, and f_{oc} is the fraction of total organic carbon in the soil.

Comparison of various correlation equations for TCE shows that a rule of thumb can be established, where the numerical value for K_p [Lkg^{-1}] is about the same (in consistent units) as the value for the organic carbon content. Since the average organic carbon content at the site is 0.14%, the K_p value is estimated to be 0.14 Lkg^{-1} . Assuming an average bulk density of 1.7 gcm^{-3} and an effective porosity of 0.3, a retardation factor of 1.8 can be calculated. This indicates that the velocity of TCE may be assumed to be about one-half of the average groundwater velocity, and indicates that the residence time for TCE in the aquifer to travel 600 m may be closer to 14 to 20 years.

Note that a retardation factor based on the K_{oc} - f_{oc} concept is prone to uncertainty. An increasing number of research studies shows this simplified concept to fail (e.g., 12,13,14). These research results indicate that there are limits where physical partitioning between the aqueous solution and the organic matter seems to be no longer dominant. The average organic carbon content at the Jolimont site of 0.14% is near the lower limit commonly cited in the literature (e.g., 15).

A site-specific investigation of the partitioning, therefore, is necessary to allow reliable assessment of the transport behaviour of TCE at the Jolimont site. Batch sorption studies as well as flow-through experiments are planned to address these issues. Miscible displacement experiments will elucidate the effect of flow velocity on the sorption/desorption behaviour. Nonequilibrium sorption/desorption will also be evaluated, since this could significantly effect all remediation strategies currently considered in the cleanup of sites contaminated with chlorinated hydrocarbons. A natural gradient tracer test using labelled TCE will be carried out to evaluate *in situ* sorption/desorption and perhaps the degradation behaviour of TCE. Assessing the field scale behaviour of the TCE will allow evaluation of the usefulness of small-scale laboratory batch and column data for application to plume scale.

6 IMPLICATIONS FOR MANAGEMENT

There is currently no specific legislation in Western Australia for dealing with contaminated sites and associated groundwater contamination, although such legislation is being drafted at present. This factor, combined with the large size of the TCE plume, the fact that there could be multiple sources of

contamination and non-aqueous phase liquids (NAPLs) entrained in the aquifer, and the fact that groundwater is not used for potable supply in the area, make it unlikely that a large scale groundwater remediation program will be attempted in Jolimont in the foreseeable future.

Currently, the only practical way of managing groundwater contamination in this area is by informing nearby residents about the contamination problem through information leaflets or public meetings, and by maintaining strict controls on groundwater use by appropriate licensing. The limited data from this study suggest that TCE has a long residence time in the aquifer, and so controls on groundwater use may have to be maintained for long periods. It is important that the sources of contamination are identified and to determine whether NAPLs are present to ensure that there is not a continuing contamination problem. Long term monitoring will be required to observe any changes in TCE concentration.

The investigation and regulation of groundwater contamination in Western Australia is currently carried out by a number of State Government Agencies. There is often poor coordination between agencies, and investigations of occurrences of groundwater contamination are often poorly funded, and carried out in a reactive way. However, proposed contaminated sites legislation will coordinate State Government activities through an inter-departmental management committee, and there will be increased resources for investigation programs.

As part of this process, it is important that proactive investigations are also undertaken. The TCE plume in Jolimont was only detected because groundwater also contained high levels of hydrogen sulphide. There are many industrial areas in Perth where chlorinated solvents may have been used (Fig. 1), and it is likely that there are other contamination plumes containing solvents extending beneath adjacent residential areas. It is important that these plumes are identified by specific investigation programs to ensure that there are no adverse public health effects on nearby residents. It is also important to research the physical and chemical behaviour of chlorinated solvents in the unconfined aquifers underlying Perth, as this information will be essential for management of contamination instances and for remediation design, if carried out in the future.

7 CONCLUSIONS AND RECOMMENDATIONS

Substantial TCE and ammonia contamination of shallow groundwater, emanating from a light industrial area, was, accidentally discovered underlying a residential area of Perth. The maximum TCE concentration, measured close to the suspected source area, exceeded the current Australian guideline for drinking water by nearly two orders of magnitude.

The TCE plume is longitudinally extensive - extending approximately 900 m in groundwater downgradient of the industrial area, is approximately 300 m wide and 6 - 8 m thick. At the local test site, about 500 m along the plume, the peak concentrations are approximately 10 m below the water table.

The TCE plume is moving about 30 to 45 m yr⁻¹ based on preliminary estimates of TCE retardation on aquifer sediments. The average residence time for the TCE in the aquifer is, therefore, approximately 16 years. Although, subsurface geochemistry suggests that biodegradation may be possible, no transformation products have been found. This issue, however, needs further investigation, since reductive dechlorination of TCE may result in an accumulation of more hazardous compounds than the parent compound.

The groundwater at the site is not used for potable supply. It is, therefore, unlikely that a remediation program will be initiated. The current approach for managing the TCE contamination in groundwater is based on informing nearby residents and applying strict controls on groundwater use. Routine monitoring of further development of the plume, of produce grown in the area, or vapour emissions from reticulation boreholes, although desirable, is not planned.

More groundwater contamination by chlorinated aliphatics is likely beneath other industrial areas in Perth. Specific investigation programs would be needed to identify these sites. If remediation is an option in the future, the sorption/desorption of TCE is likely to play a significant role and needs to be investigated. For relatively slow desorption, the quantities of TCE sorbed onto the aquifer sands may not be inconsequential. For example, if all the dissolved phase TCE was successfully removed from the aquifer via groundwater abstraction, then consequent desorption of TCE from the sediments may lead to groundwater concentrations still well above drinking water standards.

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9 REFERENCES

1. BURSTON, M.W., NAZARI, M.M., BISHOP, P.K., AND LERNER, D.N., "Pollution of Groundwater in the Coventry Region (UK) by Chlorinated Hydrocarbon Solvents", J. Hydrol., 149, 137 - 161, 1993.

2. ATWOOD, D. F. AND BARBER, C., "The effect of Perth's urbanisation on groundwater quality - a comparison with case histories in the U.S.A.", in Proceedings of the Swan Coastal Plain Groundwater Management Conference, Perth, pp. 177 - 190, 1989.

3. HAZEN, A., "Discussion: dams on sand formations, Transactions American Society of Civil Engineers, 73, 1911.

4. NHRMC, National Health and Medical Research Council, "Guidelines for Drinking Water Quality in Australia" (AGPS: Canberra), 1987.

5. WILSON, J.T. AND WILSON, B.H., "Biotransformation of trichloroethylene in soil", Appl. Environ. Microbiol., 49, (1), 242, 1985.

6. BARRIO - LAGE, G., PARSONS, F.Z., NASSAR, R.S., AND LORENZO, P.A., "Sequential dehalogenation of chlorinated ethenes", Environ. Sci. Technol., (20), 1, 96, 1986.

7. BRUSSEAU, M.L AND RAO, P.S.C., "Sorption nonideality during organic contaminant transport in porous media", CRC, Critical Reviews in Environmental Control, 19, (1), 33, 1989.

8. PIWONI, M.D. AND BANERJEE, P., "Sorption of volatile organic solvents from aqueous solution onto subsurface solids", J. Contam. Hydrol., 4, 163, 1989.

9. KARICKHOFF, S.W., BROWN, D.S., AND SCOTT, T.A., "Sorption of hydrophobic pollutants in sediment suspensions", Water Res., 13, 241, 1979.

10. SCHWARZENBACH, R.P. AND WESTALL, J., "Transport of nonpolar organic compounds from surface water to groundwater - Laboratory sorption studies", Environ. Sci. Technol., 15, 1360, 1981.

11. CHIOU, C.T., PORTER, P.E., AND SCHMEDDING, D.W., "Partitioning equilibria of nonionic organic compounds between soil organic matter and water", Environ. Sci. Technol., 17, 227, 1983.

12. PTACEK, C.J. AND GILLHAM, R.W., "Laboratory and field measurements of nonequilibrium transport in the Borden aquifer", J. Contam. Hydrol., 10, 119, 1992.

13. LARSEN, T.P., KJELDSSEN, P., CHRISTENSEN, T.H., SKOV, B., AND REFSTRUP, M., "Sorption of specific organics in low concentrations on aquifer materials of low organic carbon content - laboratory experiments", in Contaminant Transport in Groundwater, edited by H.E. Kobus and W. Kinzelbach, pp 133 - 140, A.A. Balkema, Rotterdam, Netherlands, 1989.

14. STEPHANOTOS, B.N., "Case studies signifying the importance of using site specific assumptions in developing cleanup levels at hazardous waste sites", in Proceedings of the NWWA National Outdoor Action Conference, Las Vegas, Nevada, 1991.

15. MOUVET, C., BARBERIS, D., AND BOURG, A.C.M., "Adsorption isotherms of tri- and tetrachloroethylene by various natural soils", J. Hydrol., 149, 163, 1993.