TECHNOLOGY DEMONSTRATION PROJECT REPORT: TDP9

DESIGN, INSTALLATION AND PERFORMANCE ASSESSMENT OF AN AIR SPARGE CURTAIN SYSTEM

CONTAMINATED LAND: APPLICATIONS IN REAL ENVIRONMENTS

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CL:AIRE was established as a public/private partnership in March 1999, to facilitate the field demonstration of remediation research and technology, including innovative methods for site characterisation and monitoring, on contaminated sites throughout the UK. The results of project demonstrations are published as research or technology demonstration reports and disseminated throughout the contaminated land community.

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Contaminated Land: Applications in Real Environments (CL:AIRE)

September 2004

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This is a CL:AIRE Technology Demonstration Report. Publication of this report fulfils CL:AIRE's objective of disseminating and reporting on remediation technology demonstrations. This report is a detailed case study of the application of air sparging on site specific conditions, prepared from a variety of sources. It is not a definitive guide to the application of air sparging technology. CL:AIRE strongly recommends that individuals/organisations interested in using this technology retain the services of experienced environmental professionals.

EXECUTIVE SUMMARY

The study site is a 0.7 hectare former coal-gas manufacturing works (1850 - 1964) located in the northwest of England. The site has been extensively characterised, with principal contaminants identified as coal tars and other hydrocarbons present in both soil and groundwater. SecondSite Property Holdings (SPH) undertook a voluntary remediation programme to address historic contamination at the site.

Site geology typically comprises up to 2 m of made ground overlying 2 m - 10 m of silty sand above stiff red brown clay and silts. Groundwater flows in an easterly direction, with divergent flows on the eastern side of the site, the flow being to the northeast in the north of the site and to the southeast in the south of the site. Two water features to the east of the site, a brook and an area of low-lying marshy ground, were identified as potential receptors at risk from contaminants on site.

To address the risk to the receptors, a risk-based remediation strategy was adopted, comprising an initial source removal phase, followed by the installation of an air sparging curtain at the eastern site boundary. The sparge curtain acted as the treatment zone, removing contaminants from groundwater before it moved off site.

Air sparging is an *in situ* technique for remediating volatile and/or biodegradable contaminants within the saturated zone. Air sparging is a widely accepted groundwater remediation technology, because it can offer enhanced clean-up rates relative to groundwater pump and treat methodologies, and can be cost-effective by comparison.

The air sparging curtain, consisting of 22 vertical air injection points, creating a linear treatment zone inside the eastern and northeastern site boundaries, was combined with a soil vapour extraction (SVE) system to capture and treat off-gas. The integrated system was installed at the site in August 1999 and operated for over 3 years and was finally decommissioned in January 2003. The installation works were carried out under a Mobile Plant Licence granted by the Environment Agency (EA).

At the conclusion of sparging, performance criteria had been met at 13 of the 14 key monitoring locations. The system successfully removed, and appropriately treated, contaminated soil vapours from the subsurface, with the peak rates of contaminant removal occurring in the first week of system operation, and then rapidly declining thereafter. After 9 weeks of operation, all monitoring points had soil vapour contaminant concentrations below detection limits, and this was maintained for the remainder of the project. Over 80 % of the hydrocarbon mass removed by SVE was benzene.

The groundwater remediation criteria were achieved at most of the key locations in the zone of air movement within one month of system startup and contaminant concentrations remained below the target criteria for the duration of the project at most locations. Overall, target criteria were met on 155 out of a possible 168 occasions since June 2000.

Results of the post-shutdown groundwater monitoring, carried out 4 months after conclusion of air sparging, showed that in the former northern plume area, key contaminant concentrations were below their respective remediation criteria. In the southern plume, exceedences of the remediation criteria were recorded at three locations. However, the groundwater modelling exercise used to develop the 1998 criteria has re-evaluated to incorporate anaerobic biodegradation processes, from which it was shown that, given current groundwater contaminant concentrations on site, concentrations of key contaminants at the southern receptor (the river) would be between 2 and 5 orders of magnitude below the UK Environmental Quality Standards (EQS) respectively.

Costs for the remediation project as a whole compare favourably with the other technically feasible remediation options considered. Estimated costs for remediation by excavation alone were approximately £1.1 M, whereas the air sparging project was completed at a cost of approximately £0.7 M, hence achieving a cost saving of approximately £400,000.

At this site, air sparging was a success from both a technical and financial perspective. As the Mobile Plant Licence regime was new, care was taken by both the operator and the EA to ensure that it was implemented correctly, although it is possible that legislation covering this type of system will be covered by the proposed Single Regeneration Licence (Remediation Permit Working Group, 2002).

ACKNOWLEDGEMENTS

CL:AIRE would like to acknowledge the support of SecondSite Property Holdings Ltd which allowed access and use of site information and provided technical review, and the contribution of Adrian Shields of Komex, for preparing the information and designs upon which this report is based.

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ABBREVIATIONS

ASTM	American Society for Testing and Materials
aOD	above Ordnance Datum
bgl	below ground level
BOD	Biological Oxygen Demand
BTEX	Benzene, Toluene, Ethylbenzene, Xylenes
CDM	Construction Design and Management
CLEA	Contaminated Land Exposure Assessment
COD	Chemical Oxygen Demand
DEFRA	Department for Environment, Food and Rural Affairs
DO	Dissolved Oxygen
DRO	Diesel Range Organics
EA	Environment Agency
EDTA	Ethylenediaminetetra-acetic acid
Eh	redox potential
EPA	Environmental Protection Agency
EPSRC	Engineering and Physical Sciences Research Council
EQS	Environmental Quality Standards
FMP	Field Monitoring Parameter
GCMS	Gas Chromatograph – Mass Spectroscopy
GQA	general quality assessment
GPR	Ground Penetrating Radar
GRO	Gasoline Range Organics
Ha	hectare
HDPE	High Density Polyethylene
ICP	Inductively Coupled Plasma
ID	Internal Diameter
kPa	kilopascals
kVA	kilovolt amps
L	litre
LEL	Lower Explosive Limit
LNAPL	Light Non-Aqueous Phase Liquid
LPH	Lattice Property Holdings
Ls^{-1}	litres per second
m	metre
mbgl	metres below ground level
$mgkg^{-1}$	milligrammes per kilogramme
mgL^{-1}	milligrammes per litre
mL	millilitres
MPL	Mobile Plant Licence
ms	matrix spike
msd	matrix spike duplicate
MTBE	Methyl Tert Butyl Ether
mV	millivolts

NAPL	Non-Aqueous Phase Liquid
OEL	Occupational Exposure Limit
ORC^{TM}	Oxygen Release Compound^{TM}
PAH	Polynuclear Aromatic Hydrocarbon
PID	Photoionisation Detector
psi	pounds per square inch
PTFE	Polytetrafluoroethene
PVC	Polyvinyl chloride
QA/QC	Quality Assurance / Quality Control
RM	Reference Material
scfm	standard cubic feet per minute
SPH	SecondSite Property Holdings Ltd
SVE	Soil Vapour Extraction
SVOC	Semi-Volatile Organic Compound
TPH	Total Petroleum Hydrocarbons
UKAS	United Kingdom Accreditation Service
USEPA	United States Environmental Protection Agency
VOC	Volatile Organic Compound
μScm^{-1}	micro siemens per centimetre

1. INTRODUCTION

1.1 BACKGROUND

The study site is a 0.7 hectare former coal-gas manufacturing works located in the northwest of England. During the period 1986 to 1997, SecondSite Property Holdings Ltd (formerly British Gas Properties, Lattice Property Holdings Ltd) commissioned a number of environmental investigations at the site, as part of their ongoing national programme of voluntary investigation and remediation of former gasworks. The investigations identified soil and groundwater contamination, generally focused on old gasworks facilities (tar tanks, gasholder bases). The groundwater contamination was assessed to have the potential to migrate off-site. Principal contaminants in both soil and groundwater were benzene, toluene, ethylbenzene, xylene (BTEX) compounds, phenols and polynuclear aromatic hydrocarbons (PAHs) such as naphthalene.

Remediation works were undertaken specifically to remove the potential for groundwater contaminants to migrate off-site. A three-phase remediation programme was discussed and agreed with the Environment Agency (EA):

1. Source removal - Excavation and off-site disposal of soil contamination sources and associated historical foundations
2. Air sparging - Installation and operation of an air sparging treatment curtain to remediate groundwater contaminants migrating off-site
3. Polishing - Remediation of residual soil / groundwater contaminants, if required

This report focuses on Phase 2 of the overall remediation programme.

1.2 PURPOSE AND OBJECTIVES

This report is an overview of air sparging technology, aimed at those who have an interest in the use of cost-effective technologies to remediate contaminated soil and groundwater. It describes the environmental conditions and remediation strategy that led to the installation of an air sparging system and provides an objective assessment of the performance of the technology. Specific objectives include the discussion of:

1. Background to air sparging technology;
2. Site characteristics including the nature and distribution of contaminants;
3. Overall remedial approach, design philosophy and development of endpoint criteria;
4. Installation of the air sparging system;
5. Performance of the air sparging system; and,
6. Costs and cost comparisons with alternative remediation approaches.

1.3 REPORT ORGANISATION

The report is divided into the following sections:

1. Introduction;
2. Background to the Use of Air Sparging;
3. Study Site;
4. Technology Demonstration Support Issues;
5. Remediation Design;
6. Phase I Remediation Works;
7. Design, Installation and Operation of Air sparging System;
8. Performance Monitoring;
9. Performance Evaluation;
10. Regulator Liaison and Project Closure;
11. Summary;
12. Economic Considerations, and;
13. Lessons Learned.

2. BACKGROUND TO THE USE OF AIR SPARGING

2.1 INTRODUCTION

This chapter provides an introduction to the use of air sparging technology. Additional information can be found in Suthersan (1999).

2.2 WHAT IS AIR SPARGING?

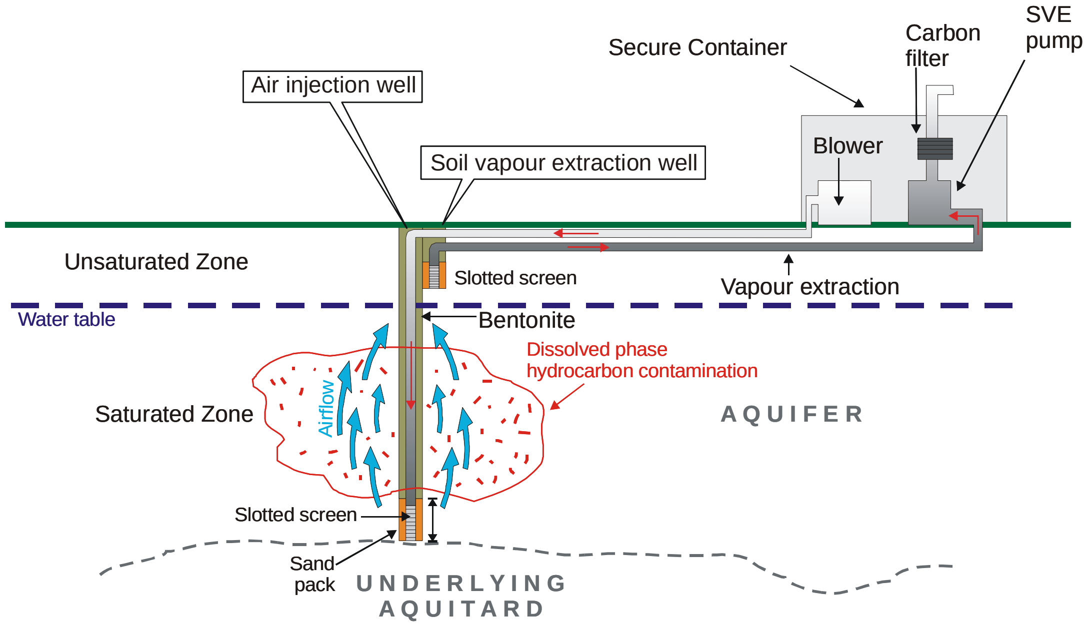
Air sparging is an *in situ* technique for remediating volatile and/or biodegradable contaminants within the saturated zone. Air sparging is becoming a widely-accepted groundwater remediation technology, because it can offer enhanced clean-up rates relative to groundwater pump and treat techniques, and can be highly cost-effective. Air is injected into the saturated zone at a point below the target contamination. The air moves upwards through the contaminated material, causing contaminant removal by two mechanisms:

1. Volatile contaminants partition into the air as it moves upwards through the water. The resulting vapour is collected and treated at surface if necessary.

2. Aerobic bacteria, stimulated by the supply of oxygen, consume contaminants as a food source (biodegradation).

Because air sparging transfers contaminants from the saturated to the unsaturated zone, it is commonly used in conjunction with vapour collection techniques, most commonly vacuum extraction or soil vapour extraction (SVE). Vapour phase treatment (e.g. activated carbon; thermal or catalytic oxidation) is then applied to remove or destroy the contaminant and prevent uncontrolled transfer of the contaminant to the atmosphere.

The second contaminant removal mechanism, biodegradation, occurs when air introduced into the aquifer increases dissolved oxygen concentrations. This leads to increased rates of aerobic biodegradation. A conceptual air sparging system with SVE and vapour treatment is shown in Figure 2.1.



Source: Komex (1998d)

Figure 2.1: Schematic cross section of air sparging / soil vapour extraction system

2.3 OVERVIEW OF THEORY AND APPLICATION

Air sparging involves the mass transfer of contaminants from the dissolved phase to the vapour phase, and the biological degradation of contaminants. The application of air sparging requires a good understanding of site hydrogeology, the nature and extent of contamination and the physical/chemical properties of the contaminants themselves.

2.3.1 PHYSICAL/CHEMICAL PROPERTIES OF CONTAMINANTS

Air sparging promotes removal from groundwater of volatile and biodegradable contaminants. The two key properties which dictate a contaminant's readiness to be removed by air sparging are volatility and biodegradability.

2.3.1.1 Volatilisation

Henry's Constant is a numerical measure of the tendency for a substance in the dissolved phase to partition to the vapour phase. At equilibrium, a substance's Henry's Constant can be determined from its partial pressure and its concentration in solution by Equation 2.1.

$$H = \frac{P}{X} \qquad \text{Equation 2.1}$$

where: H = Henry's Constant $\mathrm{atmm^{3}mol^{-1}}$
P = partial vapour pressure of solute above solution atm
X = concentration of solute in solution $\mathrm{molm^{-3}}$

Contaminants with large Henry's Constants will partition more easily into the vapour phase, and can therefore be removed from the saturated zone by air sparging. Contaminants with low Henry's Constants may not be readily volatilised and removed by air sparging, although they may be biodegraded (see Section 2.3.1.2). Table 2.1 provides a list of common contaminants and their physical properties.

Table 2.1: Common contaminants and their physical properties

Contaminant	Aqueous Solubility (mgL^{-1})	Vapour Pressure (atm)	Henry's Constant ($atm\ m^3\ mol^{-1}$)	Biodegradability
Benzene	1750	0.13	5.6×10^{-3}	High
Toluene	535	0.04	6.7×10^{-3}	High
Ethylbenzene	152	0.01	6.4×10^{-3}	High
Xylenes (mixed)	198	0.01	7.0×10^{-3}	High
Trichloroethene	1100	0.08	9.1×10^{-3}	High
Vinyl chloride	2670	3.50	8.2×10^{-2}	Medium
MTBE (methyl-tert butyl ether)	54300	0.26	1.8×10^{-2}	Medium
Naphthalene	32	3×10^{-4}	1.15×10^{-3}	Medium
Benzo(a)pyrene	0.001	7×10^{-12}	1.55×10^{-6}	Low

Source: Montgomery (1997)

Notes

(1) Vapour pressure is a measure of the pressure that a substance exerts when it is in equilibrium with its solid or liquid phase or, in other words, its tendency to evaporate. A substance with a high vapour pressure will volatilise more readily than one with a low vapour pressure.

(2) Aqueous solubility measures the degree to which a substance will dissolve into a liquid. Higher solubilities indicate those substances which have a preference for partitioning to the liquid phase.

(3) The Henry's Constants in the above table are values at 25 ºC. Average groundwater temperatures in the UK are commonly 10 ºC – 15 ºC, hence the use of the Henry's Constant at 25 ºC would overestimate the volatility of the contaminant in groundwater. Consideration should be given to converting the 25 ºC constants into their equivalents at field temperature.

(4) Henry's Constant is also often stated in the form of a dimensionless air/water partition coefficient, K_{AW}, where:

$$K_{AW} = C_a/C_w \qquad \text{Equation 2.2}$$

and K_{AW} = air/water partition coefficient (dimensionless)
C_a = concentration of chemical in air (eg mgL^{-1})
C_w = concentration of chemical in water (eg mgL^{-1})

2.3.1.2 Biodegradation

During air sparging, the injection of air into the subsurface causes dissolved oxygen concentrations in the groundwater to rise. This can lead to increased aerobic respiration. Respiration is the process in which aerobic microorganisms consume hydrocarbon (HC) as a food source, generating carbon dioxide and water. The process can be generally represented by Equation 2.3.

$$HC + O_2 \rightarrow \text{New Biomass (+ intermediates)} + CO_2 + H_2O \text{ (+ energy)} \qquad \text{Equation 2.3}$$

The hydrocarbon contaminant acts as the substrate (food), and so provides an energy source for the microbial population to generate new biomass. In the process, the contaminant is broken down (degraded), ideally to carbon dioxide and water, a process which is referred to as mineralisation. The supply of oxygen is often the rate-limiting process during *in situ* aerobic biodegradation.

Some hydrocarbons are more easily biodegradable than others, and hence are more amenable to air sparging. As an approximation, smaller molecules are more easily biodegradable than larger ones, and aliphatic hydrocarbons (such as butane, hexane, ethane) are more easily biodegradable than aromatic hydrocarbons (eg benzene, toluene, naphthalene). Some hydrocarbons are more readily degraded under anaerobic conditions (tetracholoroethene, trichloroethene), hence care must be taken to ensure that the remediation technique is appropriate to the contaminant.

2.3.2 PHYSICAL PROPERTIES OF THE SUBSURFACE

2.3.2.1 Hydraulic Conductivity

The physical properties of the subsurface also influence the effectiveness of air sparging. For optimum results, the air-water contact area needs to be maximised, as this will lead to both greater volatilisation and biodegradation potential. Consequently, injected air needs to be distributed evenly over as wide an area of the saturated zone as possible. Saturated zone permeability to water is therefore an important parameter.

Hydraulic conductivity is the measure of the ease with which a fluid passes through a medium. It is a function of the physical properties of both the fluid (such as water or air) and the properties and degree of interconnection of pore space of the medium; for example coarser-grained materials, such as clean gravels and sands, have higher hydraulic conductivities than finer grained silts and clays, and so are more amenable to air sparging. Environmental site investigations often measure hydraulic conductivity (using single well recovery tests or pumping tests) as part of the site characterisation process.

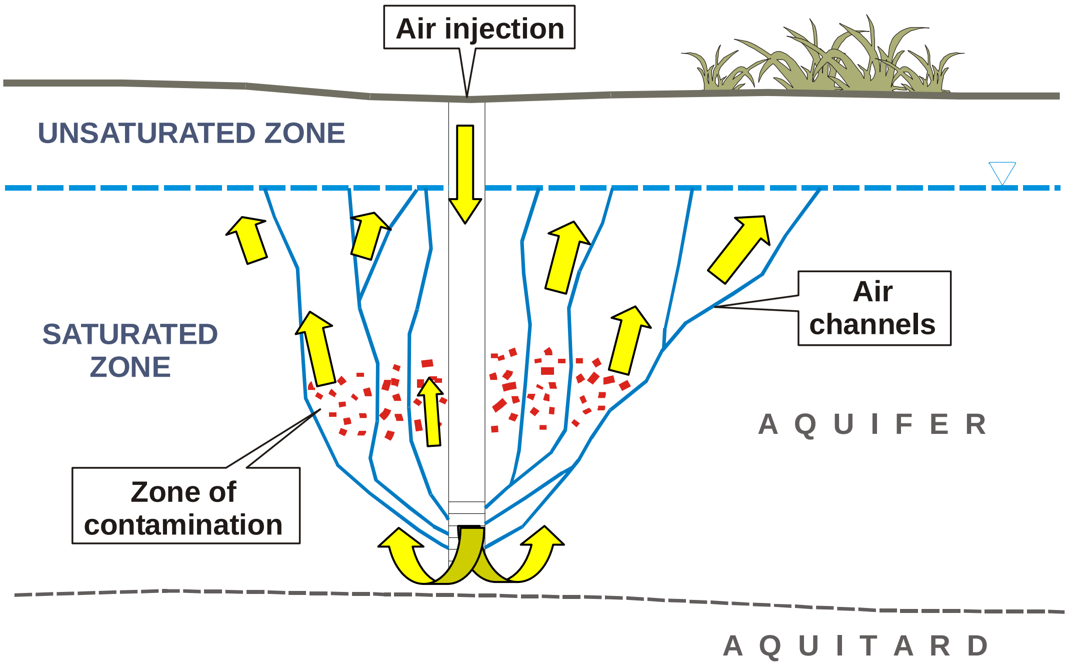
2.3.2.2 Effect of Rock Structure on Permeability

Different rock types lead to different air flow patterns, depending on their structure. Some rock types, such as chalk, tend to be dominated by air flow along fracture planes and such fractured rocks are less amenable to air sparging because the injected air tends to be concentrated along a limited number of highly permeable fractures, leaving large volumes of the subsurface untreated. Granular strata, such as sands and gravels, allow intergranular air flow. Air sparging is more suited to granular strata because they tend to allow a more even distribution of the air.

2.4 APPLICATION OF AIR SPARGING SYSTEMS

Based on the discussion in Section 2.3, integrated air sparging and SVE systems will work most effectively on contaminants that have high Henry's Constants or vapour pressures, that are amenable to biodegradation, and which are distributed within relatively homogeneous granular saturated materials.

In theory, air is injected below the base of the zone of contamination, at a pressure just sufficient to overcome the hydrostatic pressure exerted by the column of water in the formation and the threshold capillary pressure or the air entry pressure (this is inversely proportional to the average grain diameter of the porous medium and its porosity (Suthersan, 1999)). Common air injection well arrangements include vertically orientated pipes or horizontally laid pipes. The injected air enters the formation and displaces some of the water, then migrates upward and laterally, generating a zone of influence around and above the injection point. In granular materials, the air tends to move preferentially along a network of dendritic flowpaths, as shown in Figure 2.2.



After Johnson *et al*., (1993)

Figure 2.2: Schematic drawing showing air channels formed during air sparging

Volatilisation of contaminants is maximised by increasing the air-water contact area, so a high density of narrow air channels is preferable to a limited number of wider channels. Oxygen mass transfer, and hence biodegradation potential, is via diffusion (a much less effective mechanism for mass transfer than volatilisation) between the channels. Consequently, biodegradation processes are also optimised by a high density of air channels.

Air sparging should be applied to only unconfined aquifers, where injected air can freely reach the unsaturated zone and be subsequently collected (such as by SVE). Air sparging should not be applied where significant thicknesses of free phase hydrocarbons are present, since the injection of air inevitably leads to physical disturbance of the free phase hydrocarbons with the result that they could be mobilised by the sparging.

Extreme care should be taken in the vicinity of buildings to prevent contaminant vapour from migrating into building structures, drains and underground utilities.

The introduction of air into the subsurface may also promote inorganic chemical changes. In particular, the additional oxygen in the sparge air may convert iron from its soluble, reduced, state (Fe^{2+}) to insoluble forms (Fe^{3+}), resulting in precipitation of insoluble iron hydroxides which reduce aquifer permeability and therefore inhibit the sparging process. Care should therefore be taken to review the inorganic groundwater chemistry prior to implementing air sparging.

Air sparging is most successfully applied in homogeneous media. Heterogeneity, such as clay lenses, or compositional variation, can lead to uneven air channel distribution, which limits the effectiveness of the mass removal processes.

2.5 AIR SPARGING SYSTEM DESIGN

Field trials are necessary to optimise the design of a full scale system. A field trial commonly consists of a single sparge well with a short screen installed to a position below the zone of contamination, with one or more groundwater and vapour monitoring wells adjacent to the injection point. Ideally, a series of monitoring wells screened within the unsaturated and saturated zones should be installed at varying distances and directions from the air injection point.

The SVE system should initially be assessed as a separate system. A controlled and monitored vacuum is applied to the air extraction point. Satellite wells screened in the unsaturated zone are used to monitor changes in subsurface pressures, so allowing assessment of the zone of influence of the vacuum. Other wells, screened across the water table, are used to monitor water levels to assess water table mounding induced by the vacuum. The extracted vapour is monitored for contaminant concentrations, allowing an appropriate vapour treatment technology to be identified.

In addition to the above, the air sparging system is operated at a variety of injection pressures and the pressures and flow rates are monitored. This provides data on both air and contaminant vapour phase pressures in the unsaturated zone. Saturated zone air monitoring includes groundwater elevations, contaminant and dissolved oxygen concentrations and respiration testing, which helps to assess the biodegradative potential of the subsurface.

Testing also includes running both the SVE and the air sparging systems concurrently, as a full scale, integrated, system would require. Field trials may be required at several locations at the site to ensure that all conditions are evaluated.

The data from the tests provide an understanding of the radius of influence of the system which is a key parameter required in full scale system design. It also helps identify likely optimum operating pressures, vacuums and flow rates, and provide the basis for estimating mass removal rates.

2.6 PERFORMANCE OF AIR SPARGING SYSTEMS

Performance of all soil and groundwater treatment technologies can broadly be assessed in two ways:

1. Measurement of contaminant mass removed.
2. Measurement of remaining soil/groundwater/vapour contaminant concentrations, and comparison of these concentrations with the project objectives.

2.6.1 MASS REMOVAL MEASUREMENT

Measurement of contaminant mass removal resulting from air sparging must incorporate measurement of both biodegradative and vapour extraction mass removal mechanisms. Calculation of volatile hydrocarbon mass removed in soil vapour is relatively straightforward and simply involves measurement of soil vapour concentrations and flow rate. Measurement of hydrocarbon mass biodegraded is less straightforward and not commonly evaluated, because the calculation depends on multiple variables, many of which are difficult to measure and include an element of uncertainty. For example, the air-water contact area of the channel network in the saturated zone is a difficult parameter to measure.

2.6.2 MEASUREMENT OF REMAINING CONTAMINANT CONCENTRATIONS

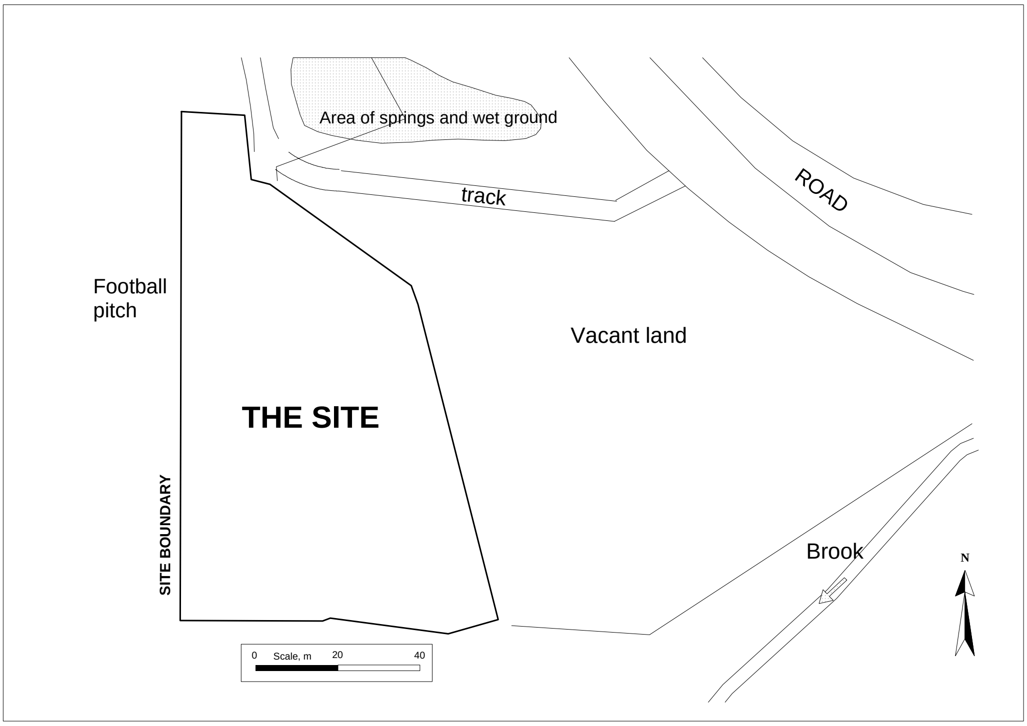
The critical performance indicator for any remediation project is whether the system has achieved the objectives identified in the project design. These objectives should be risk-based, and should aim to protect all relevant receptors (human, groundwater, flora, fauna). Assessment should be based on an EA approved methodology, Contaminated Land Exposure Assessment (DEFRA and EA, 2002a, 2002b; and EA R&D Publication 20, 1999), for specific contaminants in a particular phase. Hence measurement of concentrations of soil / groundwater / vapour contaminants remaining in the subsurface is a more important way of evaluating system performance rather than contaminant mass removal, and may be the critical element in terms of risk reduction.

3. STUDY SITE

3.1 SITE DESCRIPTION

The site is located at the end of a residential street. It is fenced with the southwest corner housing a small gas governor compound.

Land immediately to the northeast, east and south is currently waste ground with unrestricted public access. West of the site is a football pitch. A brook lies at a minimum distance of 50 m southeast of the site, flowing from the northeast to southwest. The brook is approximately 10 m below the level of the site. A topographical depression to the northeast of the site is often wet and fills with water after heavy rain. The site covers an area of approximately 0.7 hectares, and is shown in Figure 3.1 below.

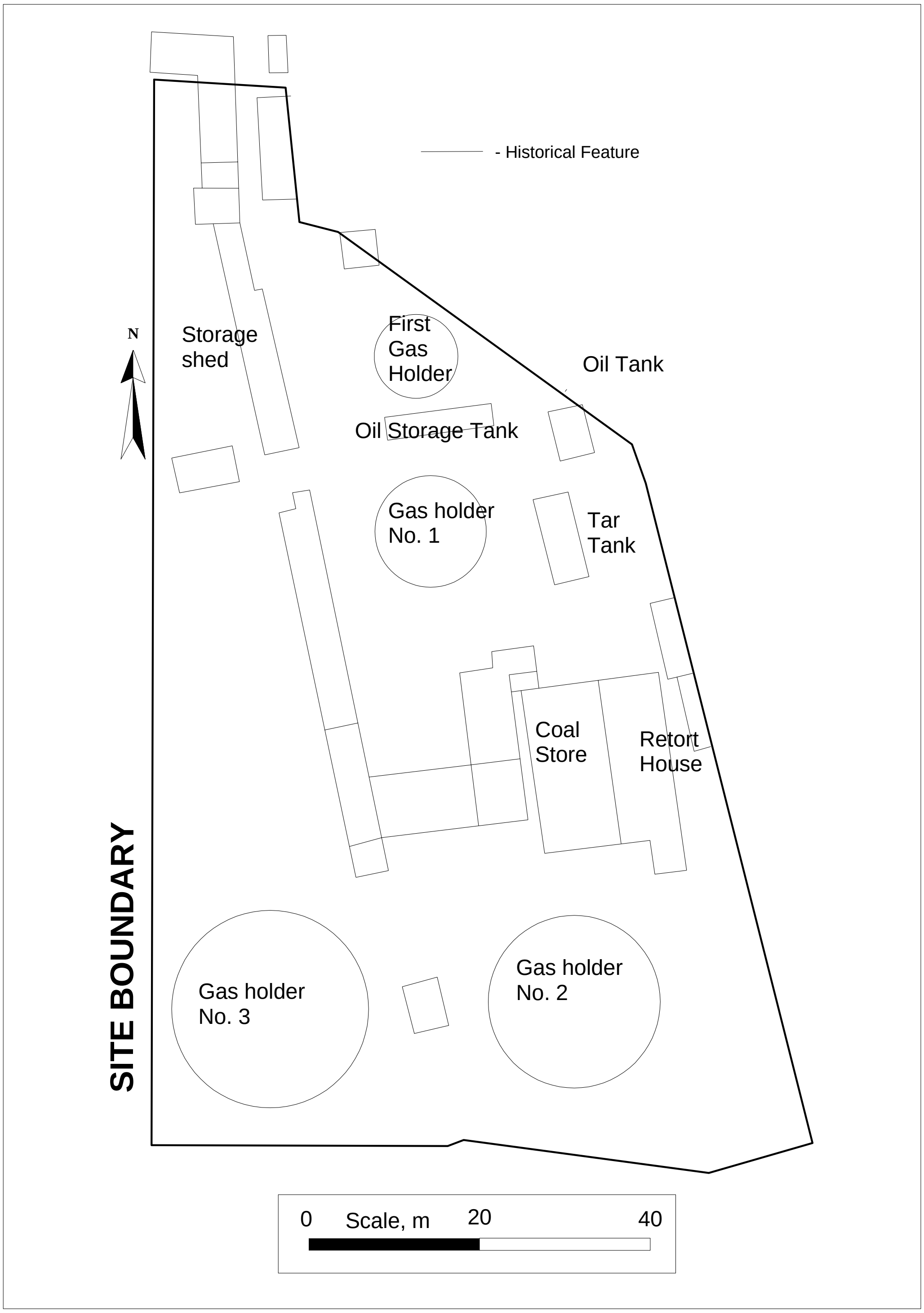


Source: Komex (1998)

Figure 3.1: Site layout

3.2 SITE HISTORY

The site was used to produce town gas (coal gas) between 1850 and 1964. Four gas holders, a retort house, washers, tar and liquor wells, oxide sheds and purifiers were all present on the site for some or all of the time. Figure 3.2 shows the former historical facilities.



Source: Komex (1998)

Figure 3.2: Historical features

3.3 TOPOGRAPHY, HYDROLOGY AND METEOROLOGY

The site is generally flat with an approximate elevation of 63 m above ordnance datum (AOD). The brook which runs approximately 50 m to the southeast of the site is at approximately 53 m AOD and the topographic depression to the northeast of the site is at approximately 57 m AOD.

Although the brook is not classified under the Environment Agency's General Quality Assessment (GQA) scheme, it intersects a river approximately 1.5 km southwest of the site. The river is classified as class B (good) above the intersection and class D (fair) below it.

The site receives a mean annual rainfall of 778 mm (Met Office, 2004). Surface cover is either hardcore (70 %) or unsurfaced (30 %) with no areas of hardcover. Rainfall is therefore able to infiltrate the ground.

3.4 SUMMARY OF ENVIRONMENTAL INVESTIGATIONS AND REPORTS

Between 1986 and 1995 Ove Arup and AEA Technology conducted preliminary site investigations, with associated laboratory testing, to characterise the hydrogeological and contamination conditions at the site (all findings are summarised in Komex, 1998).

The Ove Arup investigation encompassed the site and the adjacent land to the east. The work consisted of 9 boreholes, 5 of which were completed as groundwater monitoring wells, and 27 trial pits.

The AEA Technology investigation comprised a desk study and site investigation including the excavation of 4 boreholes, all of which were completed as groundwater monitoring wells, and 12 trial pits.

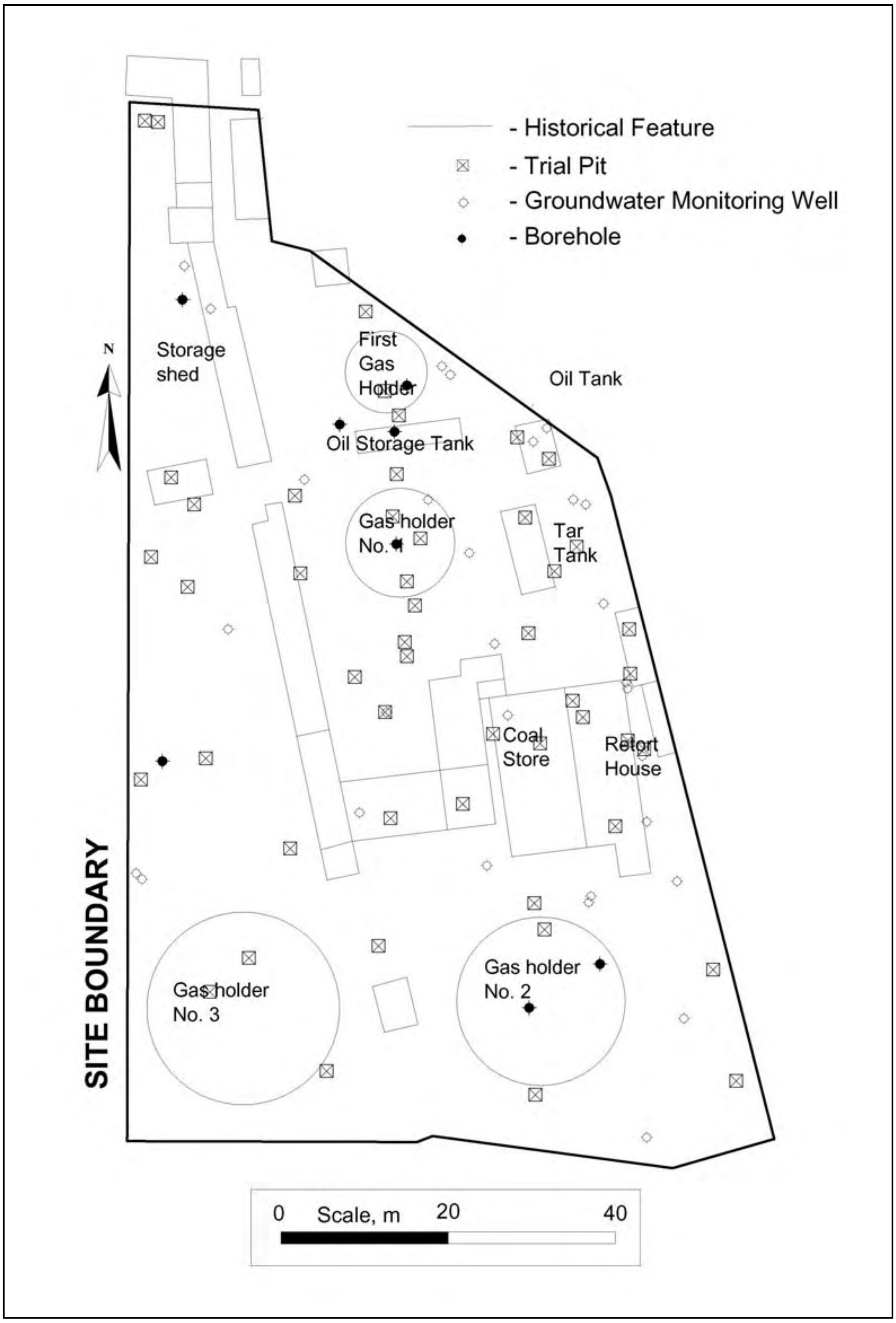
In 1997 the site portfolio was passed to Komex, which carried out a review of the previous work, followed by further site characterisation work. Figure 3.3 summarises the site investigation work carried out by all consultants.

Komex followed site characterisation work by a series of projects for the property owner, SecondSite Property Holdings (SPH). The resulting Komex reports are listed in Table 3.1.

Table 3.1: Komex reports relating to the site

Task	**Report Date**	**Details**
Site Investigation	1998	18 trial pits and 19 monitoring wells and geophysical investigation – Ground Penetrating Radar (GPR) and electromagnetic logging of 9 monitoring wells.
Risk Assessment	1998a	Report focusing on hazards to the surface water features to the east of the site. Groundwater modelling techniques, including contaminant fate and transport, were used to identify site specific clean up criteria for the soil and groundwater on site.
Analysis of Remediation Approaches	1998b	Feasibility and cost-benefit study of all plausible remediation approaches to identify the most suitable remediation strategy. A combined approach including bulk excavation and air sparging proved to be optimum.
Post Remediation Report, Phase I Works	1998c	Summary of Phase I (bulk excavation of contaminant source areas) remediation works.
Phase II Remediation Air sparging System Design	1998d	Detailed design and operational specification for the air sparging curtain system.
Pilot Scale Remediation Trials	1999	Two air sparging pilot trials and one oxygen release compound (ORC^{TM}) pilot trial were carried out.
Air sparging System Interim Performance Review	2002	Review of full scale air sparging system monitoring data from commissioning (July 1999) to October 2001.

Source: Komex



Source: Komex (1998)

Figure 3.3: Site investigation locations

3.5 GEOLOGICAL AND HYDROGEOLOGICAL CONDITIONS

3.5.1 GEOLOGY

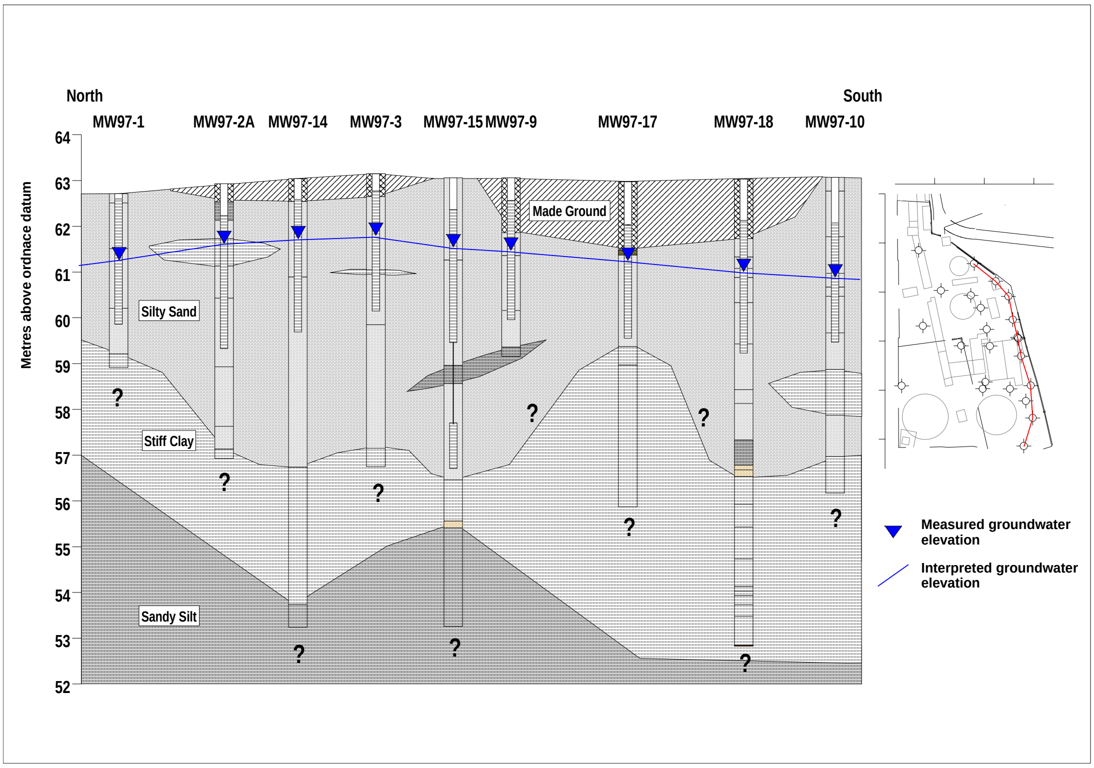
The geology beneath the site can be categorised into 4 distinct horizons:

- 0 m - 2 m of made ground, general demolition rubble including ash and clinker fragments;
- 2 m - 10 m of silty sand with occasional discontinuous thin layers of clay or silt;

- 1 m of stiff red / brown clay with occasional pieces of fine gravel, and;
- 1 m of silt and silty / clayey sands.

The made ground varies in thickness up to a maximum of 2 m and consists generally of demolition rubble. The silty sand which underlies the made ground has occasional thin layers of clay or silt and varies in thickness between 2 m and 10 m. A stiff red/brown clay layer with occasional pieces of fine gravel underlies the silty sand layer. The thickness of this layer was not confirmed during the investigations but was known to be in excess of 1 m. Underlying this layer are silts with silty/clayey sand lenses. Again, the thickness of this layer was not confirmed, but was > 1 m.

A cross section of the geology across the site is shown in Figure 3.4 and selected borehole logs are provided in Appendix 1.



Source: Komex (1998)

Figure 3.4: Cross section across the site

3.5.2 HYDROGEOLOGY

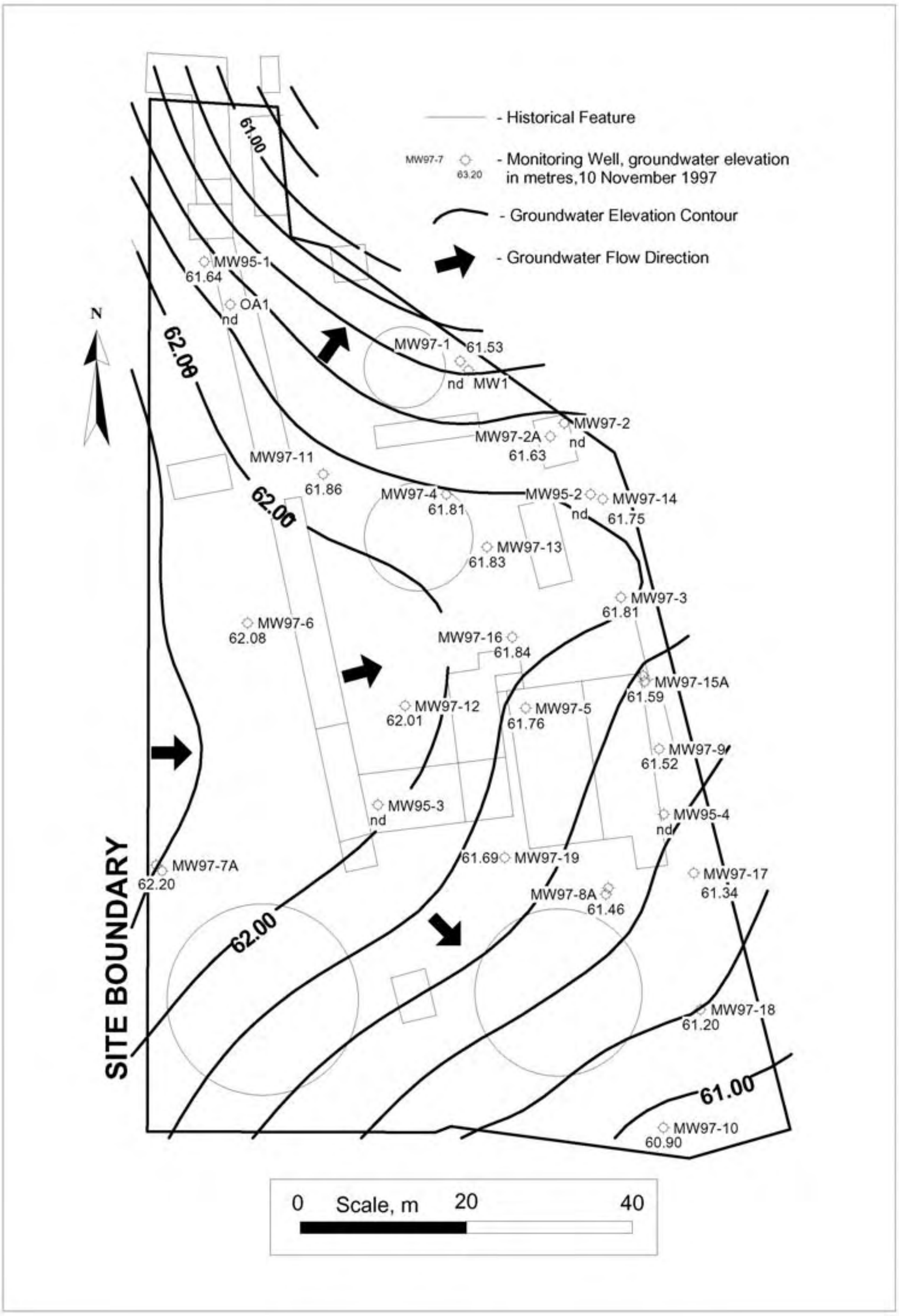
3.5.2.1 Made Ground

The made ground is generally thin, unsaturated, and found only around building foundations.

3.5.2.2 Silty Sand

Silty sand is the principal groundwater-bearing unit below the site. Groundwater levels across the site vary from approximately 0.4 m below ground level (mbgl) to 2.5 mbgl and groundwater levels measured in paired monitoring wells screened at different depth intervals show that there is no significant vertical hydraulic gradient within the silty sand.

Groundwater flow direction is generally to the east, although groundwater in the north of the site flows to the northeast and in the southern half of the site the groundwater flows to the southeast. Hydraulic gradients are approximately 0.03 in the north of the site and 0.02 in the south and Figure 3.5 shows groundwater elevation contours across the site.



Source: Komex (1998)

Figure 3.5: Groundwater elevations and flow direction

Hydraulic conductivity testing has been carried out on wells in the silty sand unit at seven locations. Rising head slug tests were performed, and the data analysed using appropriate analysis techniques (Bouwer & Rice, 1976; Cooper *et al*., 1967).

Hydraulic conductivities calculated for the silty sand aquifer (see Table 3.2) ranged from 1.3 x 10^{-6} ms^{-1} to 6.4 x 10^{-5} ms^{-1}, with most falling in the range 4 x 10^{-6} ms^{-1} to 5 x 10^{-5} ms^{-1}. This range is commonly associated with silts and silty sands (Freeze & Cherry, 1979).

Table 3.2: Hydraulic conductivity measurements in silty sand unit

Monitoring Well	**Hydraulic Conductivity (ms^{-1})**
MW97-13	4.5×10^{-6}
MW97-14	6.4×10^{-6}
MW97-15A	5.4×10^{-5}
MW97-16	6.1×10^{-6}
MW97-17	3.8×10^{-6}
MW97-18	1.3×10^{-6}
MW97-19	4.1×10^{-6}

Source: Komex (1998)

Groundwater flow velocities were estimated using Equation 3.1 below.

$$v = \frac{Ki}{n_e} \qquad \text{Equation 3.1}$$

where			
	v	= average groundwater velocity	ms^{-1}
	K	= hydraulic conductivity	ms^{-1}
	i	= hydraulic gradient	dimensionless
	n_e	= effective porosity	dimensionless, 0.3 for silty sand

Flow velocities were estimated as 6×10^{-7} ms^{-1} to 2×10^{-6} ms^{-1} (20 m to 50 m per year) in the north of the site, and 1.2 ms^{-1} x 10^{-6} to 3×10^{-6} ms^{-1} (40 m to 90 m per year) in the south of the site.

3.5.3 GEOPHYSICAL INVESTIGATION

The geophysical investigation consisted of ground penetrating radar (GPR) and geophysical well logging. The objective of the investigation was to map the sand / clay interface and to determine if lateral, discontinuous clays exist within the sands and gravels.

Eleven GPR profiles were interpreted, from which a topographic high, thought to be the stiff red clay, was identified under the eastern fence line of the site. This high was interpreted as the most likely explanation for the direction of groundwater flow to the northeast and to the southeast of the site.

However, GPR was less successful than had been anticipated. Reflections from surface features (primarily chain linked fences) tended to dominate the received signals and masked the signal from geological interfaces. In addition, interference was caused by buried concrete and metallic structures and other features such as power lines and poles, parked vehicles, and trees may have caused surface reflections. These problems are likely to be encountered at any site with a complex industrial history.

The geophysical well logging consisted of EM39 borehole terrain conductivity logging and borehole gamma logging. The conductivity logging was run down holes with non-metallic casing to measure the electrical conductivity of the surrounding geological material in a cross-sectional format, with the gamma logging intended to correlate stratigraphy between boreholes. Nine monitoring wells were logged using induction and gamma ray tools.

The gamma logs confirmed the observations noted on the borehole logs but did not provide any greater data resolution.

3.5.4 SOIL AND GROUNDWATER CONTAMINATION

Soil and groundwater samples taken from the site were analysed for a range of compounds commonly found at former gasworks facilities, including metals and organics.

3.5.4.1 SOIL CONTAMINATION

Soil contaminant distribution reflected the industrial history of the site. Certain subsurface structures were contaminated with free phase hydrocarbons, whereas other areas of the site, away from historical facilities, exhibited only relatively minor contamination. Two structures in the centre of the site were identified as contaminant 'source' areas. These were gasholder number 1 and a tar tank immediately to the south of it. These structures contained free phase tars and related hydrocarbons both within the foundations and as a halo in material surrounding the structures.

In addition, gasholder number 2 in the south of the site was heavily contaminated with free phase tars.

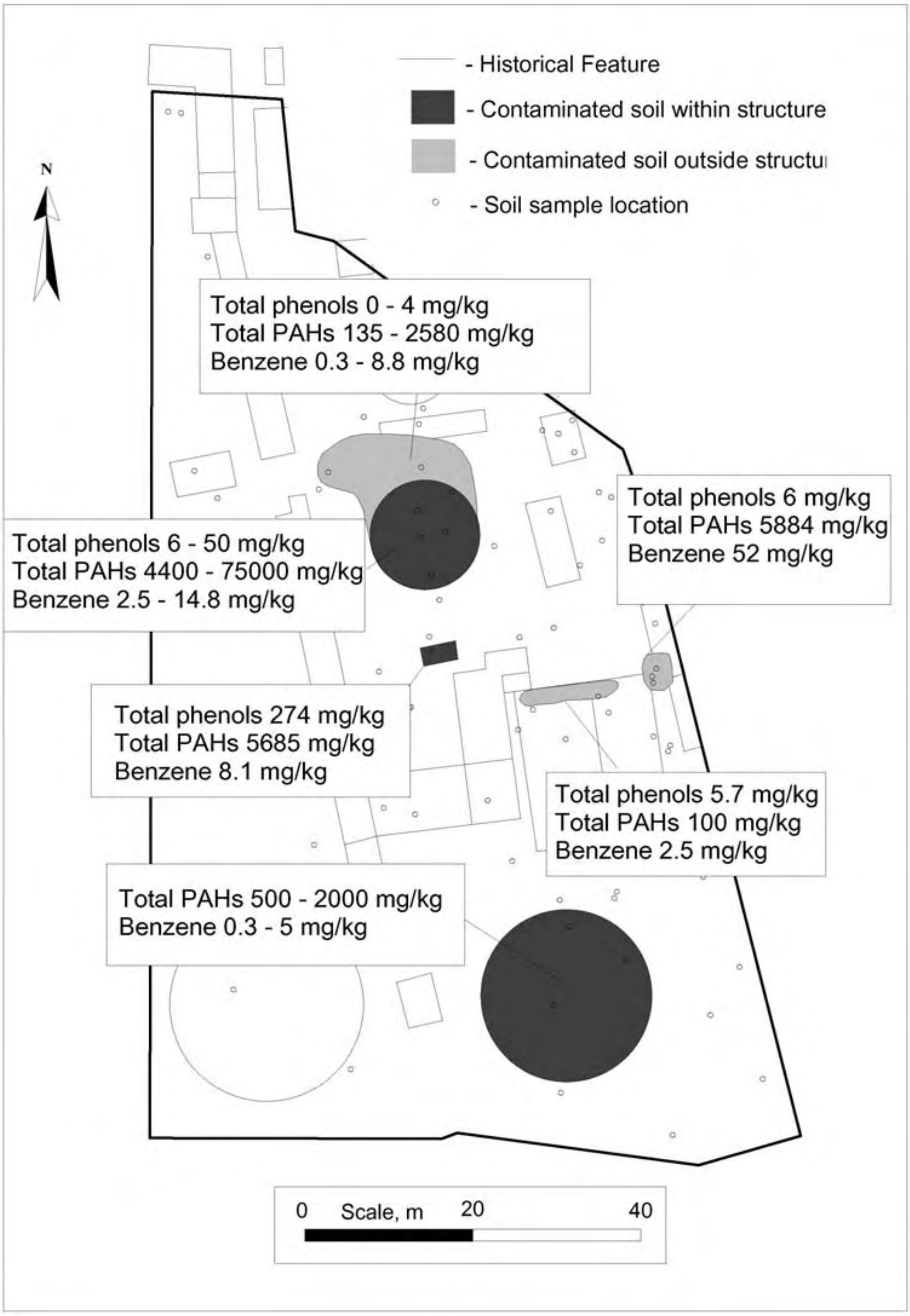
Laboratory analysis of soil samples confirmed the distribution of source structures identified visually. Contamination consisted predominantly of polynuclear aromatic hydrocarbons (PAHs), benzene, toluene, ethylbenzene and xylenes (BTEX) compounds and phenols, with occasional metals. Selected analyses of the main contaminated soil results are provided in Table 3.3. Figure 3.6 summarises key areas of soil contamination on the site.

Table 3.3: Selected soil analysis results

Borehole / trial pit number	**Depth (mbgl)**	**Benzene (mgkg^{-1})**	**Toluene (mgkg^{-1})**	**Xylenes (mgkg^{-1})**	**Phenol (mgkg^{-1})**	**Total PAHs (mgkg^{-1})**
MW97-1-1	2	615	1040	2680	<0.3	382
MW97-4-1	1.2	1880	1410	4620	<0.3	<1
MW97-5-1	2.4	2070	237	1420	<0.3	98
MW97-11-1	0.5	303	1109	24022	<0.3	531
MW97-11-2	1.5	1648	2224	34601	<0.3	309
MW97-15-5	3.9	51689	66369	85309	<0.3	5884
TP97-2-1	0.9	8797	6699	40420	<0.3	2582
TP97-2A-1	0.95	14800	51100	150000	<0.3	4390
TP97-7A-2	1.1	2520	3370	8750	2.7	74390
TP97-9-1	1.2	8120	13100	58100	20.9	5685
TP97-10-1	1.2	2540	181	3196	<0.3	47

Source: Komex (1998)

Bacteria counts were also undertaken on a number of soil samples, from which it was found that bacteria (both total count and total PAH-degrading bacteria) were present in numbers several orders of magnitude above those normally found in fresh soil.



Source: Komex (1998)

Figure 3.6: Key areas of soil contamination

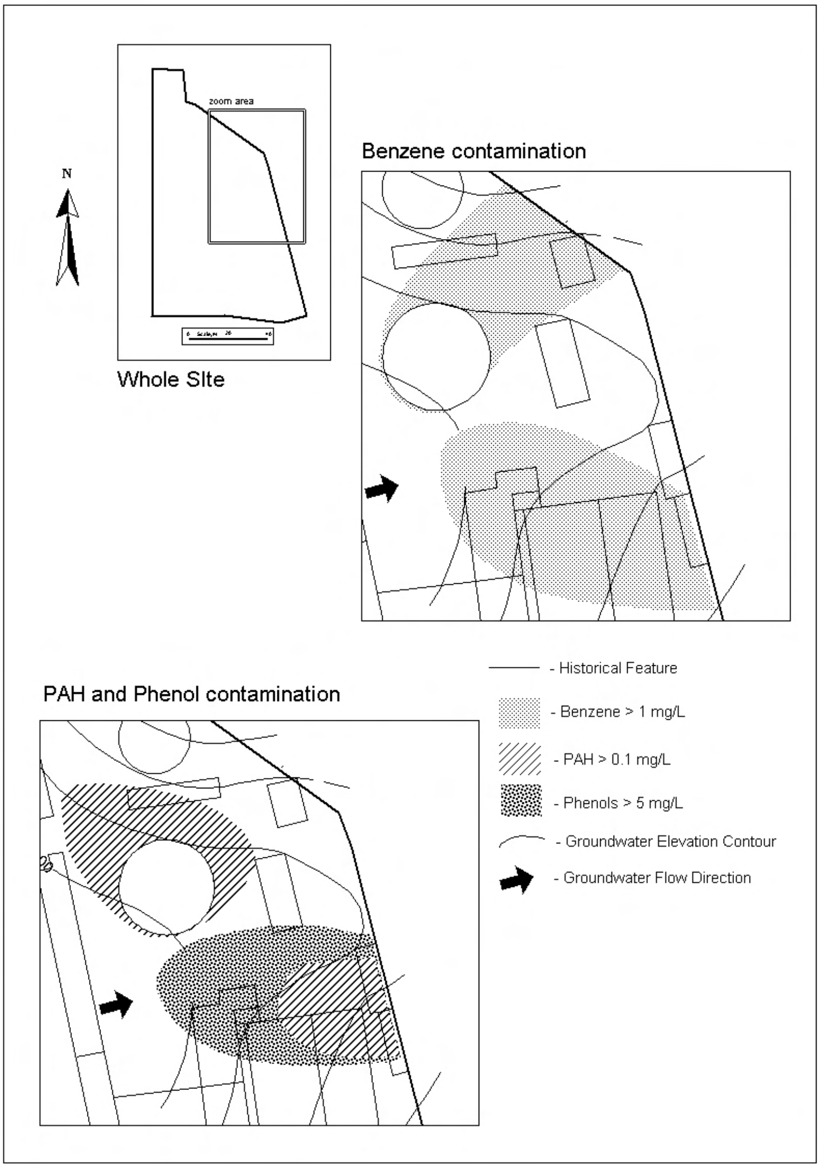
3.5.4.2 GROUNDWATER CONTAMINATION

Groundwater contaminant distribution reflected the soil contaminant sources and the general groundwater flow directions. Principal groundwater contaminants included PAHs, BTEX compounds and phenols. These were found adjacent to the soil contamination source areas in the centre of the site and in two plumes extending to the northeast and to the east of the site. Data for these contaminants are summarised on Figure 3.7, and selected analysis data are shown in Table 3.4 below.

Table 3.4: Selected groundwater analysis results

Monitoring Well Number	**Date**	**Benzene (μgL^{-1})**	**Toluene (μgL^{-1})**	**Ethyl Benzene (μgL^{-1})**	**Xylenes (μgL^{-1})**	**Total Phenol (mgL^{-1})**	**Total PAHs (mgL^{-1})**
MW97-3	Jan 97	10400	54	607	182	6.2	0.2
MW97-4	Jan 97	4880	412	<5	435	0.5	0.56
MW97-4	May 97	4000	1600	520	2130	1.5	8.34
MW97-5	Jan 97	3710	283	37	205	11.1	0.44
MW97-5	May 97	3800	35	34	1220	8.9	0.44
MW97-9	Jan 97	6360	21	56	177	1.2	1.02
MW97-9	May 97	2200	8	17	102	0.86	0.10
MW97-13	Nov 97	700	332	263	1160	<4.2	<2.87
MW97-15B	Nov 97	1039	361	346	590	<7.7	<4.8
MW97-16	Nov 97	1923	978	210	1050	47.5	<0.76

Source: Komex (1998)



Source: Komex (1998)

Figure 3.7: Groundwater contamination

3.6 SUMMARY

Leaking structures were the main source of the contamination in soil and groundwater. The major sources of PAH, BTEX and phenol contamination were gasholder number 1, a tar tank immediately to the south, and the soil surrounding these structures. The contents of both structures and the surrounding soil contained free phase hydrocarbons and Komex suggested that the contamination associated with these structures has continued to provide a source of dissolved phase contaminants leading to the two groundwater contamination plumes.

3.7 INTERPRETATION OF SITE CHARACTERISATION RESULTS

At the time of the site characterisation works (i.e. in 1997), standard practice was to compare soil and groundwater contamination results with established numerical criteria to identify areas requiring remediation and where they were available and relevant, Komex used UK guidelines (ICRCL, 1987), but these guidelines covered only a narrow range of compounds. Other chemicals of concern were compared with a combination of Dutch guidelines (Ministerie van Vrom, 1994 a and b) and Canadian guidelines (CCME, 1991).

Because no UK guideline values existed for groundwater contamination, and the evaluation predated the publication of R&D Publication 20 (Environment Agency, 1999) , the Dutch and Canadian values were again used as initial guidelines for certain contaminants. UK drinking water standards did exist, however, no limits were available for the particular species of organic contaminants that were present on the site.

Once the site characterisation was complete, the remediation strategy, and hence the remediation criteria, were established by adopting a risk-based strategy. This is discussed in detail in Section 5.2.

4. TECHNOLOGY DEMONSTRATION SUPPORT ISSUES

4.1 INTRODUCTION

This section discusses support issues associated with the initial site investigation work, selection, installation and operation of the air sparging curtain system, including:

- Regulatory approval and compliance and licensing;
- Contract agreement and health and safety;
- Work plan;
- Licensing;
- Fieldwork and sampling;
- Laboratory analytical methods; and,
- Quality assurance/quality control.

4.2 REGULATORY APPROVAL, COMPLIANCE AND LICENSING

The characterisation, development and implementation of the remediation strategy was commissioned by SPH and undertaken by Komex as part of SPH's nationwide voluntary programme of soil and groundwater contamination assessment and remediation. Although there were no regulatory requirements to undertake remediation, the regulators (both the Environment Agency (EA) and local council) were consulted at all stages and the EA agreed to the remediation strategy. The local council has maintained an interest in site activities.

The air sparging component of the project was carried out under a Mobile Plant Licence granted to Komex by the EA.

4.3 CONTRACT AGREEMENT AND HEALTH AND SAFETY

4.3.1 CONTRACTS

Komex, retained by SPH under a Term Contract agreement for environmental services, acted as Principal Contractor for all work phases (including air sparging), except for the Phase I remediation bulk excavation works, for which VHE Construction was retained by SPH, with Komex acting as the site Engineer. Komex therefore maintained a supervisory presence on site for the duration of the Phase I works.

4.3.2 CDM REGULATIONS

All work phases were carried out under Construction, Design and Management (CDM) Regulations, 1994. Regulations were complied with by the appointment of PCM Project Management Services as Planning Supervisor. A Pre-Construction Health & Safety Plan was prepared in accordance with the requirements of Regulation 15 (1) - (3) of the CDM Regulations and Appendix 4 of "Managing Construction for Health and Safety - Approved Code of Practice" for each work phase by the Principal Contractor. The Plan was approved by the Planning Supervisor and used by the Principal Contractor to develop the Construction Phase Health and Safety Plan. The Health and Safety Executive was notified of the project in accordance with Regulation 7 of the CDM Regulations by submission of Form F10.

4.3.3 HEALTH AND SAFETY INCIDENTS

No health and safety incidents were recorded relating to any phase of the project.

4.4 WORK PLAN

A three phase remediation programme was proposed and undertaken (see Section 5 for further details). Phase I comprised the bulk excavation and removal of major hydrocarbon contamination sources, such as tar tanks and gas holder bases. Phase II involved the installation of an air sparging treatment curtain along the east and northeast site boundaries to treat contaminated groundwater prior to its migration beyond the site boundary. If required, a third phase of remediation would be implemented as a 'polishing phase'. The requirement for this is yet to be determined.

This report focuses on the air sparging component of the remediation programme.

The air sparging system was developed and designed by Komex, which is responsible for all aspects of the project, including commissioning and testing the system to ensure functionality, operation and maintenance of the system for a period of three years, and for evaluation of the effectiveness of the system over its design life.

4.5 FIELDWORK AND SAMPLING

Earlier site characterisation was carried out by Ove Arup and AEA Technology (see Section 3.4 for details). Further site characterisation was carried out by Komex in 1997 from 18th August to 4th September, 27th October to 5th November and 9th to 11th December.

4.5.1 TRIAL PITS

The following information was recorded during trial pit excavation:

- Material descriptions;
- Groundwater presence;
- Visual evidence and extent of contamination; and,
- Olfactory evidence of contamination.

Trial pits were dug using a machine excavator. Geological layers were described from visual inspection of the pit walls and from the spoil pile and particular attention was paid to any evidence of contamination, visual or olfactory, in soil or water. The number of soil samples taken depended upon the variability of materials encountered and the perceived level of contamination. Samples were taken from spoil which had not directly contacted the excavator, to prevent cross-contamination between samples. Upon completion, trial pits were photographed and immediately backfilled with arisings, as far as possible in reverse order to that in which they had been removed. Backfilled material was compacted at surface level using the excavator bucket.

4.5.2 BOREHOLES AND GROUNDWATER MONITORING WELLS

During the Komex investigation, boreholes were drilled using a hollow stem auger rig operated by Boart Longyear Ltd. The geology and evidence of contamination was logged from the continuous sampler core obtained during drilling and any evidence of contamination was recorded. Samples were collected either to delineate the extent of the contamination or to identify visible contamination.

The drilling equipment was steam cleaned as required after each hole had been drilled, to minimise the possibility of cross-contamination.

All monitoring wells were completed with 50 mm Internal Diameter (ID) PVC casing with 0.5 mm slotted well-screens. Filter packs of 0.7 mm to 2 mm diameter washed silica sand were installed around the screens and a hydraulic seal of hydrated bentonite pellets was placed between the sand and ground level to prevent the well annulus acting as a pathway for surface contamination to migrate into deeper layers. The monitoring wells were capped at surface using lockable steel covers.

Monitoring wells were commonly screened across the groundwater table. At some locations, a second monitoring well was drilled and a screen installed at depth to evaluate any vertical hydraulic gradient. Where two wells were installed, shallow screened monitoring wells were identified by an ‘A’ suffix, e.g. MW98-15A. Deeper screened wells were identified by a ‘B’ suffix, e.g. MW98-15B.

Monitoring wells typically had 2.9 m long screens installed to allow the upper part of the screen to lie adjacent to the unsaturated zone to allow the ingress of any mobile light non aqueous phase liquids (LNAPL) into the well.

All monitoring wells were then developed. Development involved the removal a minimum of three well volumes (one well volume equates to the volume of the well pipe and sandpack), of groundwater from the well using a high density polyethylene (HDPE) bailer. Development of each well was concluded when the fines in the water removed from the well (sand and silt particles) had diminished to a minimum.

Prior to each groundwater sampling event, monitoring wells were purged by removal of three well volumes before sampling was carried out. Purging and sampling was also carried out using an HDPE bailer, with separate bailers used for each well to prevent cross-contamination.

4.5.3 VAPOUR MONITORING WELLS

Two vapour monitoring wells were installed in three locations. At each location vapour wells were installed at approximately 0.5 m intervals between ground level and the water table. Each well had a 0.3 m screened section in a sand filter pack, a plain pipe to the surface and a 0.15 m bentonite seal between each screened section.

4.6 LABORATORY ANALYTICAL METHODS

The laboratory used for chemical analysis of soil and groundwater samples was accredited (UKAS) for the analytical methods requested. Field QA/QC procedures can be found in Appendix 2.

4.6.1 SOIL ANALYTICAL METHODS

Soil samples were tested for the analytes shown in Table 4.1:

Table 4.1: Site characterisation - soil sample analysis suite

Analytes

pH
Loss on Ignition
Stone Content
Moisture Content

Cresols[3]
Xylenols[3]
Phenol[3]
Trimethylphenols[3]
Total Phenols[3]

Naphthalene[1]
Acenaphthene[1]
Acenaphthylene[1]
Fluorene[1]
Phenanthrene[1]
Anthracene[1]
Fluoranthene[1]
Pyrene[1]
Benzo(a)anthracene[1]
Chrysene[1]
Benzo(b)fluoranthene[1]
Benzo(k)fluoranthene[1]
Benzo(a)pyrene[1]
Dibenzo(ah)anthracene[1]
Indeno(123-cd)pyrene[1]
Benzo(ghi)perylene[1]
Total PAHs[1]

Chloride[7]
Total Cyanide[4]
Complex Cyanide[4]
Easily Liberable Cyanide[4]
Elemental Sulphur[5]
Water soluble sulphate[7]
Ammonium as N[8]
Arsenic[4]
Cadmium[4]
Chromium (total)[4]
Lead[4]
Mercury[4]
Selenium[4]
Copper[4]
Nickel[4]
Zinc[4]
Boron[6]

Notes on analysis methodology:
1 Gas chromatograph-mass spectrometry
2 Gas chromatograph-flame ionization detector
3 High performance liquid chromatography
4 Acid extraction
5 Dichloromethane extraction, liquid chromatography
6 Colourimetry
7 Water extraction, ion chromatography
8 Distillation and titration

Source: Komex (1998)

In addition, some samples were submitted for Total Petroleum Hydrocarbons[2] (TPH), Diesel Range Organics[2] (DRO), BTEX[1], nitrate, and phosphate analysis and also for hydrocarbon-degrading bacteria.

Some samples were also submitted for hydraulic parameter testing, including porosity, permeability, particle size distribution, grain density and water saturation.

4.6.2 GROUNDWATER ANALYTICAL METHODS

Groundwater samples were tested for the analytes shown in Table 4.2:

Table 4.2: Site characterisation - groundwater sample analysis suite

Analytes

pH
Total Organic Carbon[1]
Conductivity

Total Dissolved Solids
Bicarbonate Alkalinity[9]
Carbonate Alkalinity[9]
Total Alkalinity[9]
Ammoniacal Nitrogen[9]
Chloride[6]
Nitrate[6]
Total Sulphur[6]

Cresols[2]
Xylenols[2]
Phenol[2]
Trimethylphenols[2]
Total Phenols[2]

Benzene[3]
Toluene[3]
Ethyl Benzene[3]
Xylenes[3]

Aluminium
Arsenic[4]
Barium
Cadmium[4]
Calcium
Chromium[4]
Copper[4]
Easily Liberable Cyanide
Total Cyanide[5]
Iron
Lead[4]
Magnesium
Manganese
Mercury[4]
Nickel[4]
Phosphate
Potassium
Selenium[4]
Sodium
Strontium
Free Sulphide
Thiocyanate[7]
Zinc[4]

Naphthalene[2]
Acenaphthene[2]
Acenaphthylene[2]
Fluorene[2]
Phenanthrene[2]
Anthracene[2]
Fluoranthene[2]
Pyrene[2]
Benzo(a)Anthracene[2]
Chrysene[2]
Benzo(b)Fluoranthene[2]
Benzo(k)Fluoranthene[2]
Benzo(a)Pyrene[2]
Dibenzo(ah)Anthracene[2]
Indeno(123-cd)Pyrene[2]
Benzo(ghi)Perylene[2]
Total PAH[2]

Source: Komex (1998)

Notes on analysis methodology:
1 Oxidation
2 High performance liquid chromatography (HPLC)
3 Gas chromatography mass spectrometry (GCMS)
4 Atomic absorption spectroscopy
5 Acid extraction
6 Ion chromatography
7 Spectrophotometry
8 Ammonium selective electrode
9 Titration

In addition, some samples were submitted for TPH and DRO .

4.7 QUALITY ASSURANCE/QUALITY CONTROL (QA/QC)

4.7.1 FIELD PROCEDURES

Soil samples were collected from each soil boring. Each sample was split into four portions, and each portion was stored either in a 1 L HDPE plastic container (for metals analysis) or a 250 mL glass jar containing methanol and water (for phenol analysis), or two glass jars for BTEX and TPH analysis.

Core samples on which to measure physical hydraulic parameters were also collected. These were cut from HDPE core liners and sealed with plastic end caps immediately after removal and sent to the laboratory for testing.

Water samples were collected in 1 L amber glass bottles (for phenol and PAH analysis), two 1 L bottles (for major ions, metals, biological oxygen demand (BOD) and chemical oxygen demand (COD), a 250 mL plastic bottle (for cyanide analysis), a 50 mL glass vial (for BTEX analysis) and, for sulphide analysis, a 50 mL plastic bottle containing sodium hydroxide with ethylene diamine tetraacetic acid (EDTA).

4.7.2 LABORATORY QA/QC

A detailed analysis of the laboratory quality assurance/quality control (QA/QC) data associated with the soil and groundwater samples taken as part of the site characterisation phase is presented in Appendix 2. This assessment has incorporated data from soil duplicates, reference materials (RMs), blank spikes, blanks and surrogate recoveries.

4.8 RESEARCH SUPPORT

The project is the subject of a collaborative research project jointly funded by the Engineering and Physical Sciences Research Council (EPSRC), SPH and Komex. The research team includes members from Komex, SPH, Imperial College London and King's College London. The research project title is "Hydro-biologic Controls on the Transport and Remediation of Organic Pollutants". Research interests include the development, installation and testing of the air sparging treatment curtain (Komex), the development of techniques for identification of aerobic and anaerobic mineralisation rates (King's College London), and the development of a variably saturated groundwater flow model with multi-species contaminant transport capabilities, incorporating coupled biochemical and geochemical reactions (Imperial College London).

5. REMEDIATION DESIGN

5.1 INTRODUCTION

The remediation design was supported by the following work elements:

- Site specific risk assessment;
- Analysis of remedial approaches;
- Phase I (bulk excavation) remediation design;
- Pilot scale trials using air sparging techniques and oxygen release reagent; and,
- Phase II (air sparging) remediation design.

Site specific risk assessment and evaluation of remedial approaches are described in this chapter. Phase I remediation and pilot scale trials are described in Chapter 6 and Phase II remediation is described in Chapter 7.

5.2 SITE SPECIFIC RISK ASSESSMENT

The purpose of the site specific risk assessment was to establish, using a risk framework, whether there was, at that time, an unacceptable risk to receptors from contamination on site. Secondly, the assessment sought to identify remediation criteria for the key risk driving contaminants.

5.2.1 CONCEPTUAL ASSESSMENT

An initial screening of potential source, pathway, receptor combinations indicated that plausible exposure pathways were via dust and vapours to personnel on-site during excavations, and via groundwater carrying contaminants off site to the two nearby surface water bodies (Figure 3.1).

5.2.2 NUMERICAL MODELLING

Simple numerical models (Farmer *et al*., 1980; USEPA, 1985; and APIDSS, 1994) showed that even under worst case conditions, airborne contaminant concentrations were below the appropriate Occupational Exposure Limits (OELs), and that therefore there was negligible risk to receptors from airborne contaminants, given the site’s current use. For evaluating risks to the surface water features, groundwater modelling was undertaken using MODFLOW (McDonald and Harburgh, 1988) based Groundwater Vistas software (Environmental Simulations International Ltd, 1998). This work identified that these receptors were potentially at risk from contaminants originating from the site.

Chemicals of concern present on site fell into three groups: phenols, PAH, and BTEX compounds. Because chemicals in each of these groups have similar properties, a single contaminant was chosen from each of these groups to represent the behaviour of the group. Contaminants were screened according to their available (source) concentrations, relative mobility (solubility and attenuation), human health effects and potential ecological effects (by considering established guidelines).

In all cases the chemical thought to constitute the greatest risk in each group was chosen and these were benzene, cresol and naphthalene.

The major pathway under consideration was groundwater migration in the dissolved phase. For this reason, PAHs such as benzo(a)pyrene were not considered, because they have a particularly low solubility and high retardation potential. Derivation of site specific groundwater remediation criteria required the selection of acceptable contaminant concentrations at the receptor. The most appropriate guidelines available in 1998 were the Dutch Intervention groundwater quality standards. Adoption of these criteria was generally accepted by the EA as normal practice at the time.

Groundwater modelling was then undertaken for the three representative contaminants with reference to the acceptable contaminant concentrations at the receptors. The calculated remediation criteria are shown in Table 5.1 below:

Table 5.1: Maximum allowable contaminant concentrations in groundwater on site

Surrogate Contaminant	**Maximum allowable concentration on-site to achieve criteria at receptors (mgL^{-1})**
Benzene	0.045
Cresol	0.3
Naphthalene	0.11

Source: Komex (1998a)

5.3 ASSESSMENT OF POTENTIAL REMEDIAL APPROACHES

Six different remediation approaches were evaluated both from feasibility and cost perspectives. These are shown in Table 5.2 below.

Table 5.2: Comparison of potential remedial approaches

Approach		**Comments on Feasibility**	**Cost**
1	Excavate contaminated soil; treat contaminated groundwater.	High cost. Excavation volume > 8000 m^3 (15,000 tonnes). Large groundwater volumes from dewatering excavations up to 5 m deep.	£1.1M
2	Excavate major sources; natural attenuation (NA) of groundwater contaminant plume	Not achievable in a realistic timescale. Modelling, (Komex, 1998a), suggests that NA would take > 100 yrs to achieve objectives, even after removal of the major sources (gasholder 1, tar tank).	NR
3	Leave sources; capture mobile contaminants at eastern site boundary.	Contaminants left *in situ* would contaminate groundwater. Modelling (Komex, 1998a), suggests that groundwater migrating across the eastern site boundary will have benzene, phenols and PAHs.	NR
4	Excavate major sources and worst areas of residual LNAPL; remediate residual contamination using pump and treat.	Effective immediately, but pump and treat system would be required for > 50 years because of the residual LNAPL in the soil.	NR
5	Limited excavation of major sources, capture residuals at boundary	Effective, but time to capture residuals may be great (high cost) because dispersed LNAPL remaining in soil will continue to act as a source.	£991K
6	Larger excavation around sources & areas of dispersed LNAPL; capture mobile contaminants at boundary, implement site wide residuals cleanup only if required.	Goals are achieved in shorter timescale but excavation volume increased. Excavation costs higher, but offset by shorter projected operation and maintenance (O&M) time for boundary capture technology	£747K

Notes: NR Not recommended from a technical / timescale perspective

Source: Komex (1998b)

On the basis of the above, Option 6 was selected as the most cost-effective feasible approach. Bulk excavation of sources was carried out as Phase I remediation works. Incorporated in this phase of works was a series of pilot remediation trials to evaluate alternative technologies to be applied at the site boundary to capture residual contaminants.

6. PHASE I REMEDIATION WORKS

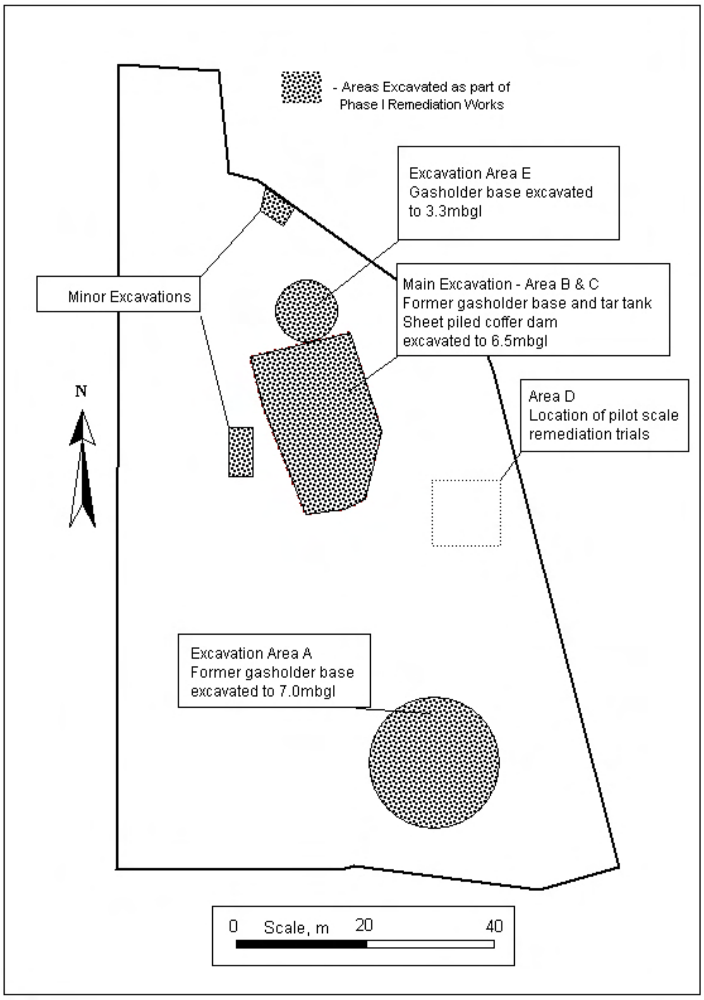
6.1 INTRODUCTION

Phase 1 remediation works comprised excavation of the major source areas. During these works, pilot scale remediation trials of *in situ* treatment technologies commenced.

6.2 EXCAVATION WORKS

Phase I remediation works were undertaken between 8th June and 28th August, 1998. A total of 5,380 tonnes of Special Waste and 2,791 tonnes of Difficult Waste were removed from site and sent to an appropriately licensed landfill. A total of 8,667 tonnes of clean granular material was brought onto site as backfill material. The following works were undertaken (Area locations are detailed in Figure 6.1):

- Area A. Removal of contaminated soil from within gasholder base.
- Area B/C. Removal of contaminated soil from within tar tank and gasholder base; complete removal of the structures.
- Area D. Area designated for pilot scale remediation trials.
- Area E. Removal of contaminated soil from within gasholder base.

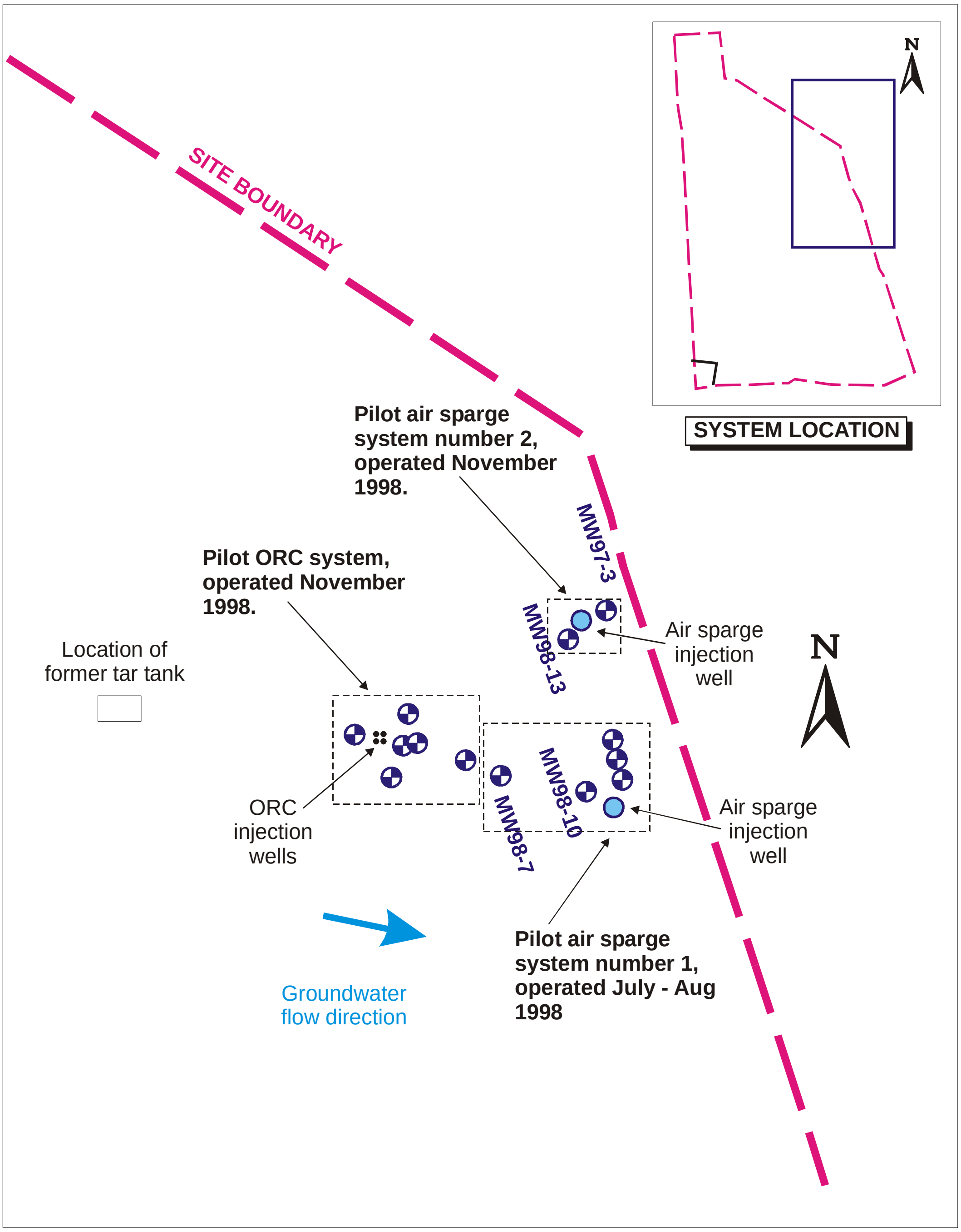


Source: Komex (1998c)

Figure 6.1: Excavation areas, Phase I remediation

6.3 PILOT SCALE TRIALS

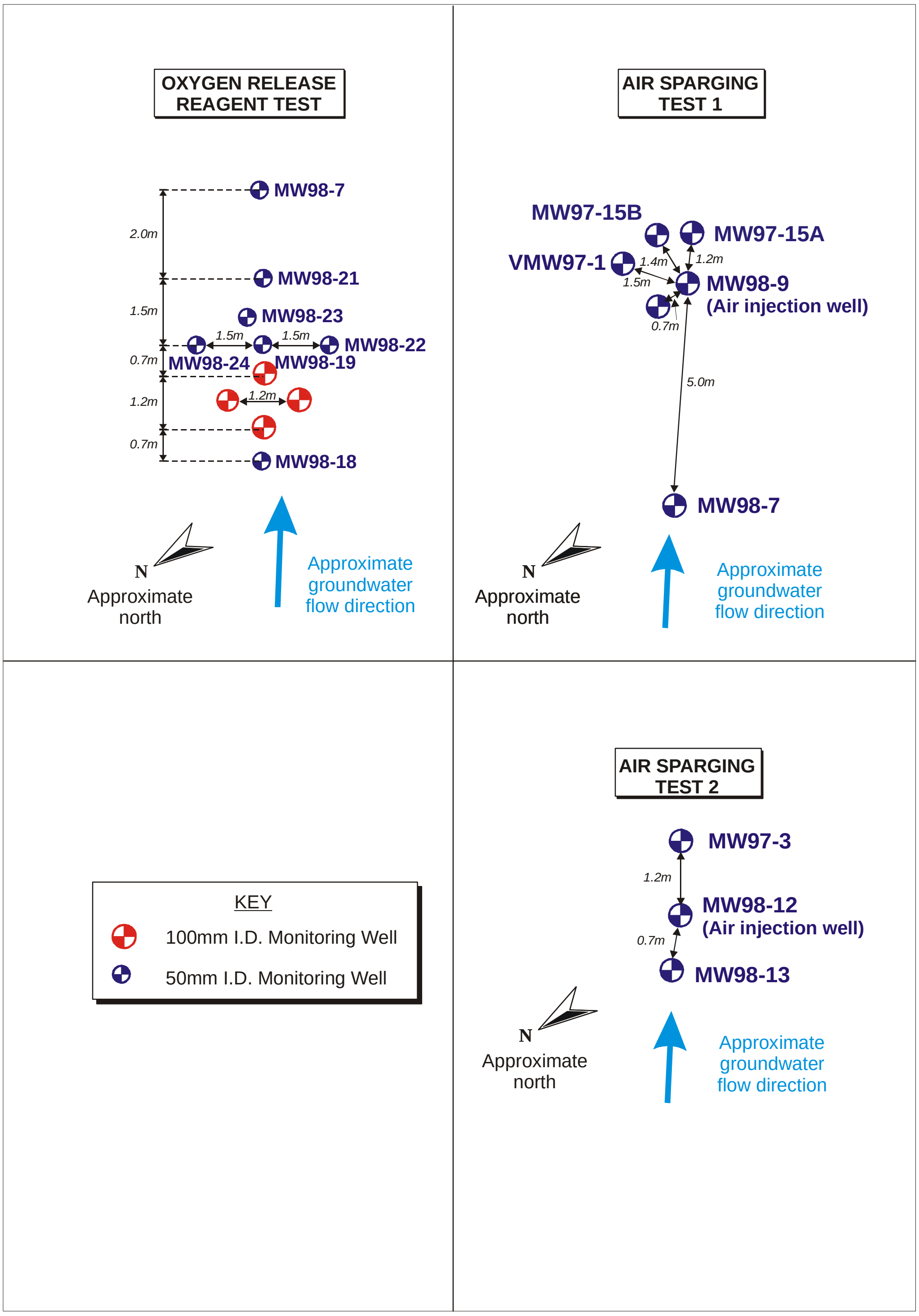
Three pilot trials (two air sparging trials and one using Oxygen Release Compound^{TM} (ORC^{TM})) were undertaken between June and November 1998 during and after the Phase I remediation work. Test locations are shown on Figure 6.2 and selected pilot scale test results are presented in Appendix 3.



Source: Komex (1999)

Figure 6.2: Pilot scale remediation trial locations

The monitoring well configurations used for each test are shown in Figure 6.3 .



Source: Komex (1999)

Figure 6.3: Pilot test monitoring well configurations

6.3.1 AIR SPARGING TEST 1

6.3.1.1 Methodology

Air sparging Test 1 was undertaken during July and August, 1998, to provide information on the physical behaviour of the subsurface environment during air sparging. The parameters of concern were:

1. Achievable air injection pressures and flow rates;
2. Radius of influence; and,
3. Groundwater table mounding.

Air was injected into a 50 mm well screened between 6.0 mbgl to 6.5 mbgl. Adjacent monitoring wells were used to take water and vapour samples to evaluate the system's performance. A series of respiration tests were carried out. The tests comprised a period of air injection followed by a recovery period when the compressor was turned off. During this period, water level, dissolved oxygen (DO), conductivity and pH were measured using a water quality probe.

Adjacent monitoring wells were sampled to evaluate changes in the dissolved hydrocarbon concentrations and inorganic chemistry. Ten water samples were taken and the following analytes were measured:

pH
Total Organic Carbon
Conductivity
Total Dissolved Solids
Phenols
16 USEPA Polynuclear Aromatic Hydrocarbons (PAHs)
Cyanide
Arsenic
Cadmium
Chromium
Lead
Copper
Nickel
Zinc
Benzene, toluene, ethylbenzene, xylene (BTEX)
Total Petroleum Hydrocarbons (TPH)
Bicarbonate alkalinity as $CaCO_3$
Carbonate alkalinity as $CaCO_3$
Total alkalinity as $CaCO_3$
Main ion suite: Cl^-, SO_4^{2-}, NO_3^-, HCO_3^-, Na^+, K^+, Mg^{2+}, Ca^{2+}, $Fe_{(aq)}$, $Fe_{(total)}$, $Mn_{(aq)}$, $Mn_{(total)}$

Eight vapour samples were taken and analysed for volatile organic compounds. Of the eight, two were also analysed for phenol.

6.3.1.2 Results

Results are presented in 4 sections; observations and *in situ* measurements, hydrocarbon vapour data, groundwater data, and soil data.

1. Observations and *In Situ* Measurements
Observations and *in situ* measurements are summarised in Table 6.1 below.

Table 6.1: Observations during air sparging Test 1

Parameter	Observation	Comment
Air injection pressures required (above atmospheric)	55 kPa - 62 kPa (8psi - 9 psi)	This is only 7 kPa - 12 kPa (1 psi - 2 psi) above hydrostatic head. Formation entry pressure is therefore minimal
Air flow rates	1 Ls^{-1} (2.1 scfm)	Reasonable flows are possible
Radius of influence	>1.45 m	Bubbling noticed in well 1.45 m away from injection well
Groundwater mounding	<0.25 m	Mounding evident but temporary
Dissolved oxygen measurements	8 mgL^{-1} during sparging, dropping to zero when sparging ceases	Sparging increases DO, but there is a substantial subsurface DO demand
O_2 and CO_2 measurements in vapour	After sparging, O_2 declines, CO_2 increases	Microbial activity consumes O_2 and generates CO_2

Source: Komex (1999)

2. Hydrocarbon Vapour Data

Hydrocarbon vapour data are presented in Table 6.2 below.

Table 6.2: Hydrocarbon vapours evolved during air sparging Test 1

		Hydrocarbon Vapours (μgL^{-1})					
Monitoring Well	**Days after sparging commenced**	**benzene**	**toluene**	**ethylbenzene**	**xylene**	**1,2,4-trimethyl benzene**	**naphthalene**
VMW97-1	2	19	-	3	3	2	2
	7	-	1	3	2	2	-
MW98-7	2	-	-	-	-	-	-
	7	-	-	-	-	-	-
MW98-10	2	44	3	2	5	1	-
	7	-	-	-	-	-	-
MW97-15B	2	101	5	8	12	1	-
	7	-	-	-	-	-	-

Notes Source: Komex (1999)

Entries marked "-" indicate measurements below detection limit of 1 μgL^{-1}

The maximum vapour concentration in the off-gas from the system was measured in MW97-15B two days after sparging commenced. Vapour concentration measured was 126 μgL^{-1} total BTEX.

3. Groundwater Data

There was a marked decrease in target dissolved contaminant concentrations over the 7 day test period, although some monitoring wells exhibited an increase in these concentrations when measured 2 days after commencement of air injection. The initial increase is likely to have been due to mobilisation of residual Non Aqueous Phase Liquid (NAPL) due to the physical disturbance caused by air creating, and then flowing through, channels in the saturated zone. However, these increases were mitigated over the latter 5 days of the sparging test.

Maximum mass removal rates recorded over the latter 5 days of the test were 1.3 $mgL^{-1}day^{-1}$ total BTEX (MW98-10), 1.5 $mgL^{-1}day^{-1}$ naphthalene (MW98-10), 0.23 $mgL^{-1}day^{-1}$ cresol (MW98-10) and 46 $mgL^{-1}day^{-1}$ TPH.

4. Soil Data

Samples of the soil in the sparged area were analysed to determine whether significant precipitation of iron had occurred. Air sparging can have a significant effect on inorganic species in the subsurface environment, particularly oxidation, which can result in formation of precipitates, which could clog air movement channels. The most commonly documented problem of this type relates to the precipitation of iron minerals.

Concentrations of iron and manganese compounds in soil did not appear to be significantly elevated above those in soil samples from unaffected areas of the site, which suggested that a long term sparging project would not be compromised by iron or manganese precipitation.

6.3.2 AIR SPARGING TEST 2

6.3.2.1 Methodology

Air sparging Test 2 was carried out in November 1998. This test was used to confirm the information gained during Test 1 and to obtain additional information relating to:

1. Greater resolution of variation of field monitoring parameters (FMPs) during and after air injection, particularly redox potential (Eh);

2. Confirmation of the trend in groundwater contaminant concentrations observed during Air sparging Test 1, and further evaluate the organic species present in groundwater; and,

3. Carrying out of high-resolution respiration testing.

Air was injected into MW98-12 which was a 50 mm ID monitoring well, screened from 7.0 mbgl to 7.5 mbgl. Air injection was carried out over 3 days, followed by a further 4 days of monitoring. Two adjacent monitoring wells were used to obtain water and vapour samples from each. One respiration test was carried out over 1 week. The same tests were undertaken as in Air sparging Test 1, with the addition of Eh. Four groundwater samples were taken for laboratory analysis.

A data logging water quality probe, equipped with a flow cell, was used to monitor the field parameters. Wells were sampled using a peristaltic pump attached to the flow cell. The pump operated at a flow rate of approximately 0.4 $Lmin^{-1}$ which was relatively low compared to the hydraulic conductivity of the aquifer, so no drawdown occurred. This allowed the monitoring wells to be pumped continuously and the field parameters to be measured intensively.

One water sample was taken to represent baseline conditions, followed by 2 samples during air injection and 1 sample taken after completion of the injection phase. The sample suite was similar to Test 1, although cyanide, arsenic, cadmium, chromium, lead, copper, nickel and zinc were omitted and a combination of TPH and Gasoline Range Organics (GRO) analyses were used in place of BTEX and USEPA PAH analyses.

6.3.2.2 Results

1. Observations and *In Situ* Measurements

Observations and *in situ* measurements are summarised in Table 6.3.

Table 6.3: Observations during air sparging test 2

Parameter	Observation	Comment
Air injection pressures required (above atmospheric)	83 kPa - 90 kPa (12 psi -13 psi)	This is 21 kPa – 28 kPa (3 psi - 4 psi) higher than measured in test 1, suggesting some variability in aquifer properties
Air flow rates	1.4 Ls^{-1} (3 scfm)	Reasonable flows are possible
Radius of influence	<1.5 m	Well at 1.5 m distance from injection well showed no increase in DO
Dissolved oxygen measurements	8 mgL^{-1} during sparging, dropping to zero when sparging ceases	Sparging can increases DO, but there is a substantial subsurface DO demand. See Figure 6.4 for details
Temperature measurements	Water temperature increases from 9.5 °C to 12 °C on air injection	Possibly attributable to exothermic microbiological activity, supporting evidence for biodegradation – although may also be a result of heat transfer from injected air.
Conductivity measurements	Gradual increase during sparging from 1000 μScm^{-1} to 1350 μScm^{-1}	Possibly due to precipitation of inorganic species such as iron – this type of precipitation could cause fouling over long operational periods
pH measurements	Stable at 7.0 – 7.5	Relatively neutral pH
Redox potential (Eh) measurements	Increased during sparging from -160 mV to -40 mV	Air sparging successfully increased the oxidating potential in the subsurface

Source: Komex (1999)

2. Groundwater Quality – Organic Compounds

An open scan gas chromatograph mass spectrometry (GCMS) analysis was taken from monitoring well MW98-19, approximately 10 m away from the air sparging location. The purpose of this was to identify all hydrocarbon components present in the groundwater. Results are shown in Table 6.4.

Table 6.4: Hydrocarbon components present in groundwater

Compound Type	Compound	
monoaromatic	benzene	o, p & m xylenes
	toluene	trimethylbenzene
	ethylbenzene	
phenols	phenol	2,6-dimethylphenol
	2-methylphenol (2-cresol)	2,5-dimethylphenol
	3 & 4-methylphenol (3 & 4-cresol)	2-ethylphenol
	2,4-dimethylphenol	2,4,6-trimethylphenol
naphthalenes	naphthalene	2-methylnaphthalene
	1-methylnaphthalene	2,3-dimethylnaphthalene
	acenaphthylene	pyrene
	acenaphthene	benzo(a)anthracene
	fluorene	chrysene
other PAHs	phenanthrene	benzo(b)fluoranthene
	anthracene	benzo(k)fluoranthene
	fluoranthene	benzo(a)pyrene
aliphatics	2,2,4,6,6-pentamethylheptane	
	2,6,10-trimethylpentadecane	
other	benzofuran	1,8-naphthalic anhydride
	2,6-dimethyphenylisocyanate	indene
	1,2-isoquinolinone	

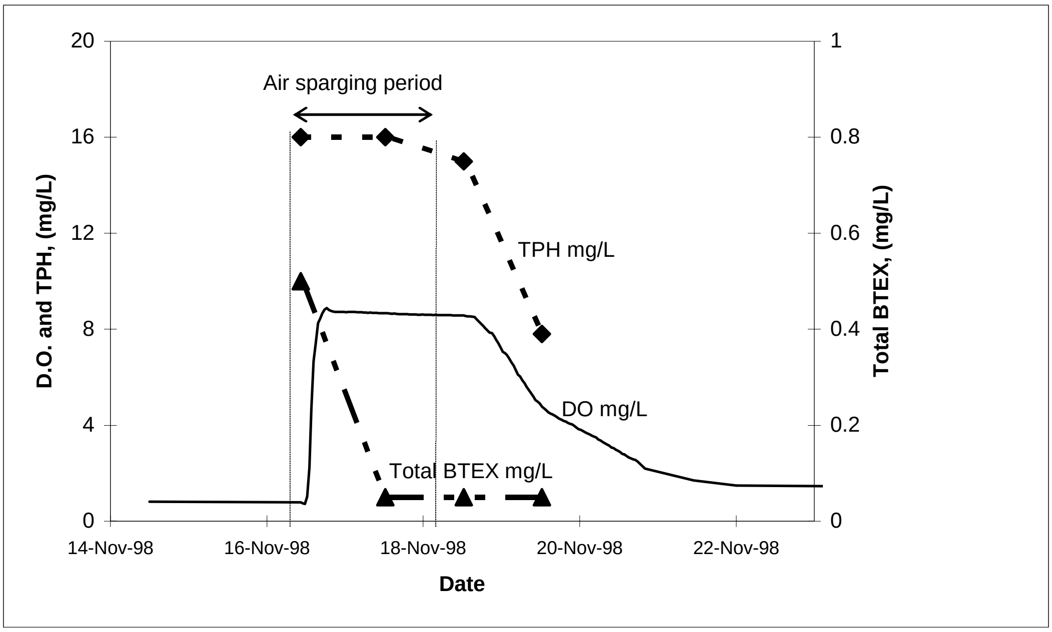
Source: Komex (1999)

The dominant hydrocarbon species present were monoaromatic and polyaromatic hydrocarbons. Only two aliphatic species were detected, at relatively low concentrations. Had the composition of the sample been dominantly aliphatic, air-sparging may have been less effective at remediating the target contaminants (benzene, cresols and naphthalene), because aliphatic hydrocarbons are commonly more easily biodegraded than aromatics. They would therefore be consumed first, leaving the aromatic compounds to be degraded much later in the process.

TPH analyses and GRO analyses were taken over time during and after air sparging. Results showed a decrease in both GRO and TPH concentrations over the air sparging test. GRO concentrations decreased from 0.5 mgL^{-1} to <0.1 mgL^{-1} in less than one day, corresponding to a mass removal rate in excess of 0.5 mgL^{-1}day^{-1}. TPH concentrations were reduced at a rate of 7.2 mgL^{-1}day^{-1}. Interpretation of TPH chromatograms showed naphthalene and cresol concentrations reduced from 0.44 mgL^{-1} and 0.11 mgL^{-1} respectively, to below detection limits over 4 days.

3. Respiration Testing

A respiration test was carried out over the period 14th - 24th November 1998. A data logging water quality probe was deployed in a monitoring well 0.7 m from the air injection point. Over the course of the test, groundwater samples were taken and analysed for total BTEX and TPH concentrations. Results are shown in Figure 6.4.



Source: Komex (1999)

Figure 6.4: Respiration test, air sparging test 2

The data confirm the observations made in respiration testing carried out in Air sparging Test 1. Dissolved oxygen concentrations are raised by sparging, but once sparging ceases, concentrations decline, indicating a significant subsurface oxygen demand. In addition, the data show that BTEX and TPH concentrations are reduced over the duration of the test.

6.3.3 OXYGEN RELEASE COMPOUND^{TM} (ORC^{TM}) TRIAL

6.3.3.1 Methodology

An ORC^{TM} trial was carried out in order to evaluate the suitability of ORC^{TM} filter socks for use as a long term dissolved oxygen supply to promote bioremediation and hence positively impact groundwater contaminant concentrations. ORC^{TM} is a commercially available magnesium peroxide based reagent, designed to produce oxygen on contact with water. Aims were to:

1. Evaluate variations in key dissolved phase organic parameters - TPH, BTEX, phenol, cresol, naphthalene and identify mass removal rates if possible;

2. Evaluate variations in dissolved phase inorganic chemistry.

Monitoring wells were drilled for this trial between 3rd and 10th November, 1998. Four 100 mm ID monitoring wells were installed to approximately 7 mbgl and screened across their full length in a 1 m square area.

The filter socks were tied together and placed in the wells from the base of the wells to ground level. The socks are shown laid out at surface in Plate 6.1.

Source: Komex (1999)

Plate 6.1: ORC^{TM} filter socks

Seven 50 mm ID monitoring wells were installed surrounding the ORC^{TM} wells. These wells were suitably orientated to monitor changes in field parameters and groundwater contamination immediately adjacent to the ORC^{TM} wells (Figure 6.2), and also down hydraulic gradient. The ORC^{TM} was placed into the saturated zone of the aquifer.

Prior to emplacing the ORC^{TM}, water was sampled from the seven satellite monitoring wells to establish baseline measurements (monitoring event 1). Following emplacement, water samples were taken at 7 days, 11 days, 28 days and 91 days (monitoring events 2, 3, 4 and 5 respectively). The samples were analysed for the same analytes as Air sparging Test 2, but with no volatile organic compound (VOC) or semi-volatile organic compound (SVOC) analyses.

6.3.3.2 Results

1. Dissolved Oxygen (DO) Measurements

In all wells, DO concentrations remained below 2 mgL^{-1}, and in most cases, measurements showed no significant departure from background. However, in MW98-19, DO concentrations increased sharply for approximately 16 hours following emplacement of the ORC^{TM} reagent, reaching 2.9 mgL^{-1}. Concentrations then decreased rapidly back to background levels, and remained lower. It is interpreted that the observed increase indicates elevated DO reaching the monitoring well, but that the stimulated biological oxygen demand (BOD) and chemical oxygen demand (COD) rapidly exceeded the supply, hence concentrations dropped.

2. Groundwater Quality - Organic Contaminants

Analysis of BTEX range organics in the seven satellite monitoring wells adjacent to the ORC^{TM} emplacement wells showed no persistent downward trend over the course of the test. In two cases (MW98-7, MW98-24), BTEX concentrations increased.

Two monitoring wells, MW98-18 and MW98-19 did exhibit some depletion in BTEX concentrations between monitoring events 3 and 4. After monitoring event 4, no further drop in contaminant concentration was observed. This behaviour was generally mirrored by TPH concentrations.

The limited effect of ORC^{TM} on groundwater quality may be due to the presence of residual phase hydrocarbon in the subsurface. If residual phase is present, then it will dissolve due to equilibrium processes as aerobic bacteria consume dissolved phase hydrocarbons. Hence, although ORC^{TM} may be promoting aerobic biodegradation, it would not be discernible by the analysis of dissolved phase contaminant concentrations.

Dissolved oxygen generated by ORC^{TM} is not produced at a constant rate but “peaks” after a short time and then decays as reagents are used up. The limited downward trends in BTEX concentrations seen in MW98-18 and MW98-19 may correspond to the peak DO supply. As the DO supply decays and aerobic biodegradation slows, the rate of dissolution of residual phase material exceeds the rate of biodegradation and so no further favourable effects on groundwater quality are discernible.

This therefore suggests that, under prevailing site conditions, an ORC^{TM} filter sock would be expected to have a limited useful lifespan.

A significant drop in dissolved phase contaminant concentrations was observed in wells 0.7 m from the ORC^{TM} emplacement wells, but not in wells over 1.5 m away. The zone of observable effect was therefore very limited, and did not appear to migrate down hydraulic gradient over time.

6.3.4 SUMMARY AND CONCLUSIONS

The purpose of the pilot scale trials was to identify the suitability of air sparging and ORC^{TM} as a full scale remediation technique. The main conclusions are outlined below.

6.3.4.1 Air Sparging

Both air sparging trials were successful, leading to reductions in a range of contaminants including BTEX, phenols and low molecular weight PAHs. Mass removal rates were such that the technique could be suitable for application at full scale, given the aims and target criteria of the Phase II remediation programme. Results also suggested that the technique was suitable despite the presence of residual phase hydrocarbons.

6.3.4.2 ORC^{TM} Reagent

Use of the ORC^{TM} reagent at the site produced less conclusive results. Although some hydrocarbon mass removal was exhibited within 0.7 m of the emplacement wells, this effect appeared to be very limited in extent. The presence of dissolved phase hydrocarbons, likely residual phase hydrocarbons, and an elevated COD, combined to create a demand for oxygen in the subsurface which exceeded the supply.

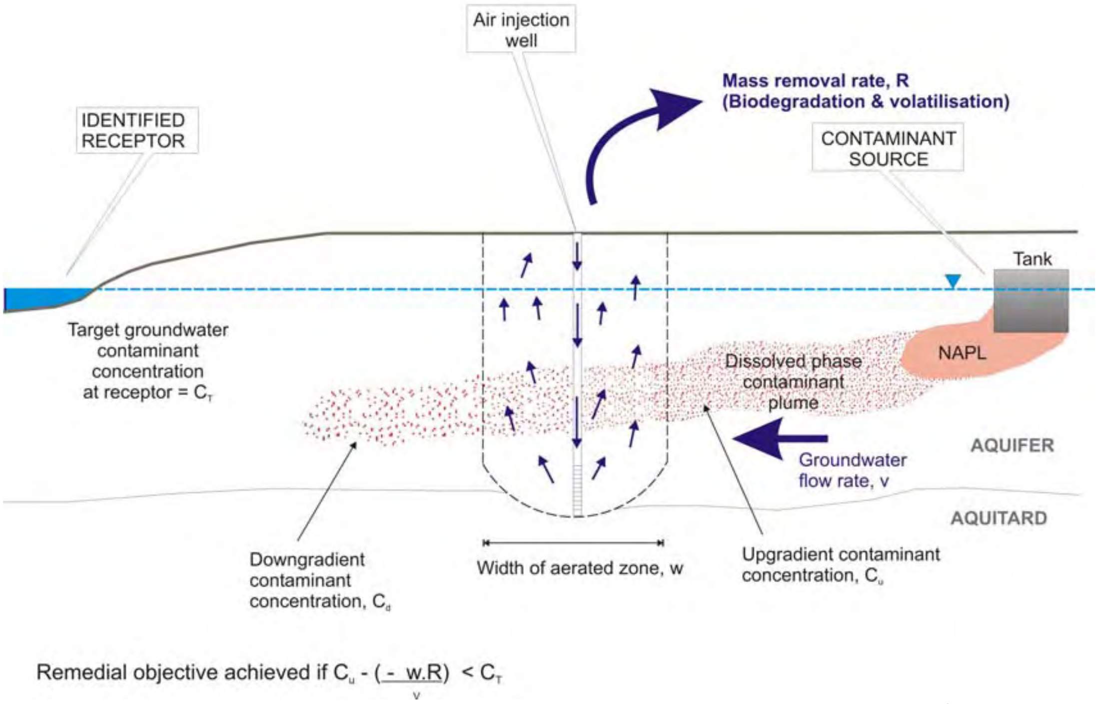
The use of ORC^{TM} at this site was therefore not considered suitable as a full scale remediation technique.

Further details of the pilot scale trials can be found in Shields *et al*., (2000).

7. DESIGN, INSTALLATION AND OPERATION OF AIR SPARGING SYSTEM

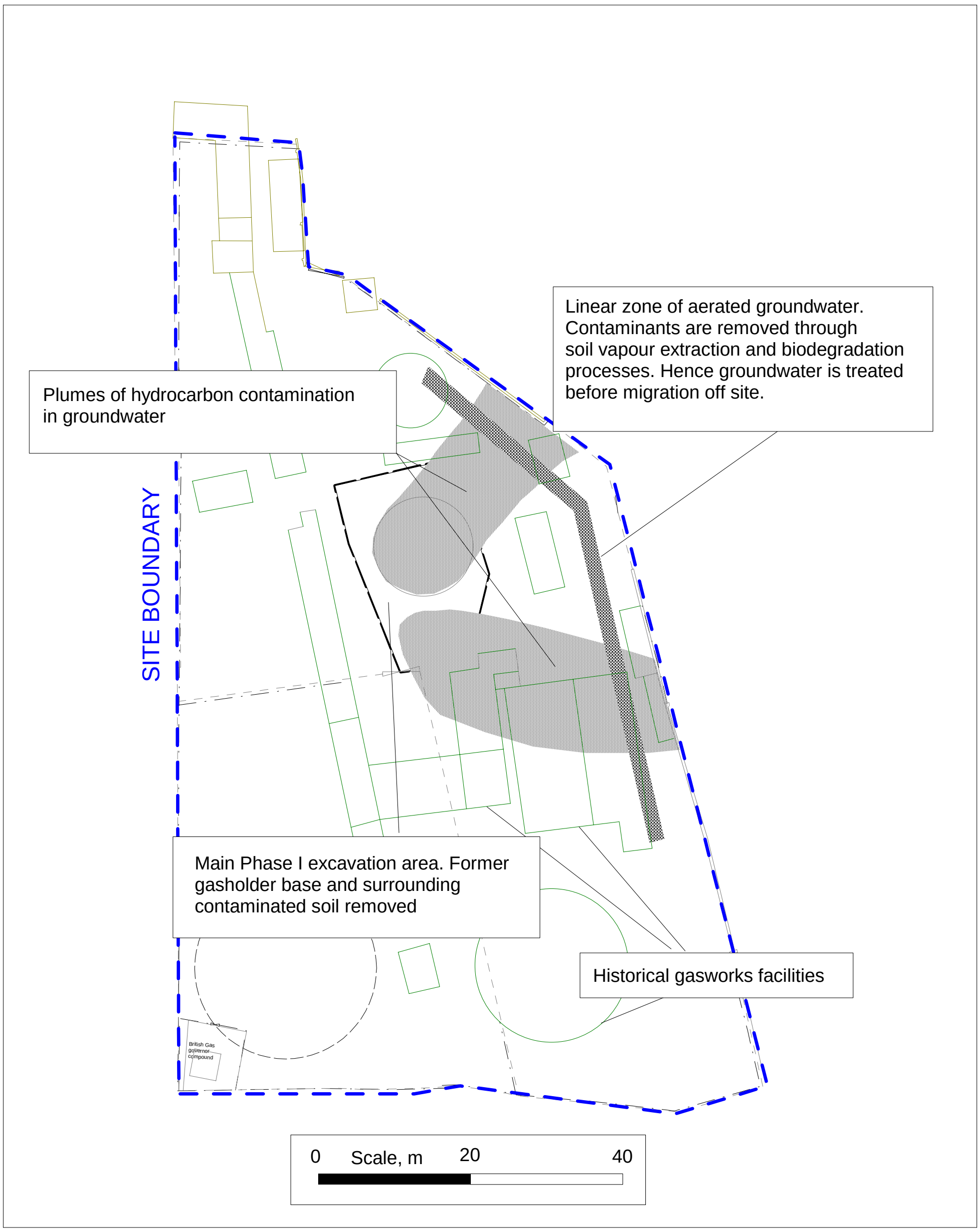
7.1 DESIGN OBJECTIVES

Although Phase I remediation works had removed the main contaminant sources, contaminated groundwater remained beneath the site. The air sparging system was designed to mitigate any residual risk by reducing the concentrations of aqueous phase contaminants along a key section of the eastern site boundary. As groundwater flows east and passes through the area affected by the air sparging system, so contamination levels would be reduced prior to the groundwater crossing the site boundary. The system is not designed to contain or divert flow, rather it is intended to treat contaminants with minimum disturbance to the natural groundwater flow. The remediation concept is shown in Figure 7.1 and its application to the site is shown in Figure 7.2.



Source: Komex

Figure 7.1: Air sparging curtain remediation schematic



Source: Komex (2002)

Figure 7.2: Site remediation concept

An additional benefit to the adjacent site may be realised, because the effects of air sparging may propagate several metres downgradient of the injection point. Therefore contaminant concentrations in groundwater beneath the adjacent site may also be reduced over time.

Numerical remediation objectives for key contaminants are shown in Table 5.1.

7.2 SYSTEM SPECIFICATION

The sparge system comprised a compressor providing air to 22 vertical injection wells spaced at 3 m intervals, approximately 5 m within the eastern site boundary. Air extraction from the unsaturated zone was achieved via horizontally laid slotted pipework completed in the unsaturated zone. This was attached, via an air/water separator, to a vacuum pump. The extracted vapour was treated by means of carbon filters and vented to atmosphere. Major system components are specified in Sections 7.2.1 and 7.2.2. To facilitate vapour sampling, a short section of vertically orientated slotted screen was nested at each air injection point.

7.2.1 SUBSURFACE COMPONENTS

7.2.1.1 Air Injection Points

Twenty-two vertical air injection points spaced at 3.0 m intervals were drilled at a 5 m distance from the eastern site boundary, with a well spacing of 2.5 m giving overlapping areas of influence (Figure 8.1). Each air injection point comprised two wells, one screened from 3.0 mbgl - 3.5 mbgl and the other from 6.5 mbgl - 7.0 mbgl.

7.2.1.2 Air Injection Pipework

Air injection and extraction pipework was 150 mm ID HDPE, reducing to 50 mm HDPE to the wellheads. All pipework was buried to a minimum depth of 0.2 m below current ground level to prevent vandalism. Installation of the air injection pipework is shown in Plate 7.1 below.

Source: Komex

Plate 7.1: Air injection pipework connected to wellhead

7.2.1.3 Soil Vapour Extraction (SVE) System

The SVE system comprised lengths of 50 mm ID HDPE pipe laid horizontally, with 0.5 mm width slots (as for TRILOC^{TM} type well screen), running the full length of the system, buried to minimum cover (approximately 0.2 m). These pipes were connected to the SVE vacuum pump via solid 50 mm ID HDPE pipe, also buried to minimum cover. All SVE pipework was selected to be phenol resistant. The SVE pipework can be seen in Plate 7.2, prior to covering.

Source: Komex

Plate 7.2: SVE extraction pipework laid horizontally

7.2.1.4 Monitoring Wells

Eleven boreholes were drilled surrounding the sparge system, completed as 50 mm ID monitoring wells. Installation depth of each monitoring well varied, depending on local hydrogeological conditions, with 0.5 mm slotted screens no longer than 3 m, screened with 0.5 mm – 1 mm diameter inert graded sand and sealed to surface with hydrated bentonite. The monitoring wells were completed with 0.3 m above ground level, completed with a gas monitoring port, and were protected by 0.5 m high lockable steel well covers with cement surface seals. Locations of all key monitoring wells and all sparge wells are shown in Figure 8.1.

7.2.1.5 Surface Completion of Injection / Extraction System

The injection / extraction system was covered with a 5 m wide by 0.2 m thick layer of clay, placed to effect an airtight cover to the area. This was covered with a 0.1 m thick layer of gravel to facilitate pedestrian access.

7.2.1.6 Wellhead Connection and Fittings

Each injection / extraction point was fitted with a 600 mm square watertight lockable steel manhole cover to allow access for sample collection, air flow regulation and measurement (Plate 7.3).

Source: Komex

Plate 7.3: Wellhead detail

The manhole covered the wellhead and incoming air supply pipe. The air supply pipe was fitted with a 0 Ls^{-1} - 4.7 Ls^{-1} (0 scfm - 10 scfm) flow gate valve and a 0 kPa - 140 kPa (0 psi - 20 psi) regulator with dial. An inlet facility was also provided such that flow measurement could be made using a hotwire flowmeter.

A 19 mm diameter slotted pipe for collection of unsaturated zone vapour samples was also located within each manhole. The pipe was completed with a sampling port, such that samples could be collected through a 6 mm flexible hose.

7.2.2 SURFACE SYSTEM

7.2.2.1 Air Injection Supply

A pump capable of supplying 70 Ls^{-1} (150 scfm) at up to 125 kPa (18 psi) above atmospheric pressure was used to provide injection air (Plate 7.4). A specification which would not introduce oil into the air stream was chosen.

Source: Komex

Plate 7.4: Air injection compressor

7.2.2.2 SVE Pump Specification

An SVE pump capable of drawing 95 Ls^{-1} (200 scfm) was used (Plate 7.5). The system was designed so that the SVE pump would start a minimum of 5 minutes before the air injection compressor to ensure efficient capture of vapours.

Source: Komex

Plate 7.5: Soil vapour extraction pump

7.2.2.3 Electrical Supply Specification

A 3-phase 415 V, 60 kVA supply was installed to the site boundary specifically for the project. All cables within the site were laid in HDPE ducting, a minimum of 0.2 m below ground level.

7.2.2.4 Air-Water Separator

An air-water separator with a 300 L capacity was installed directly upstream of the SVE blower to protect it from damage in the event that water was drawn into the air extraction pipes (Plate 7.6).

Source: Komex

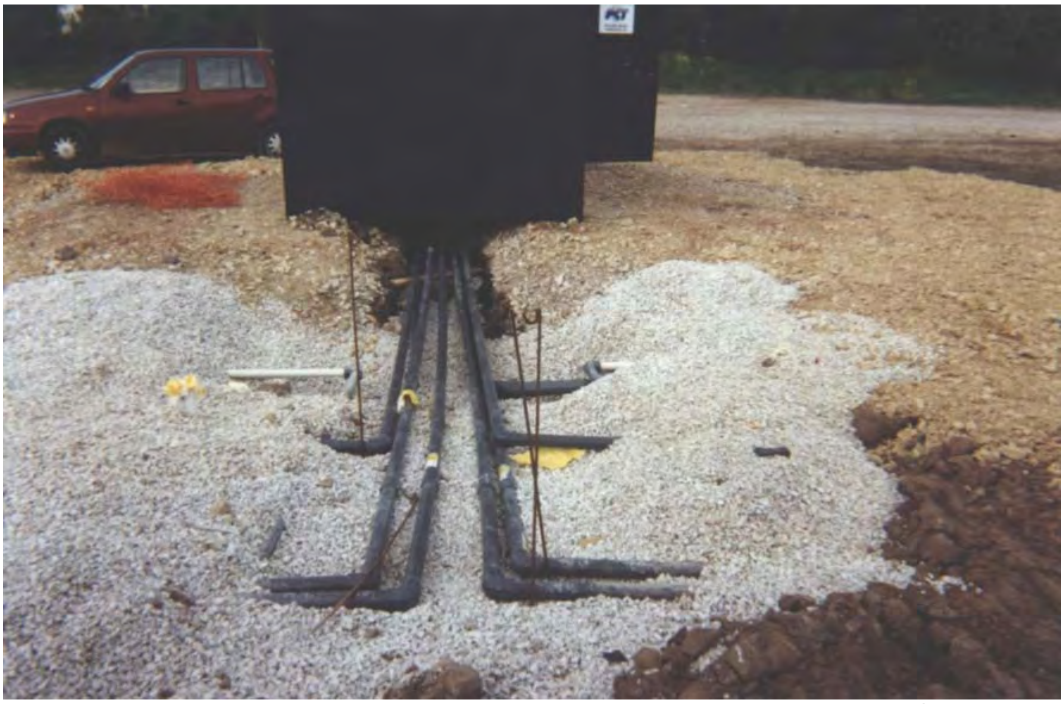
Plate 7.6: Air-water separator

7.2.2.5 LEL Detector

A Lower Explosive Limit (LEL) detector for benzene was linked to the system power, such that the system would shut down if the LEL concentration for benzene were exceeded.

7.2.2.6 Secure Container

A secure ventilated container housed all surface equipment to protect against vandalism. All subsurface pipework entered the container from below, ensuring no equipment was exposed at surface (Plate 7.7).



Source: Komex

Plate 7.7: All pipework entering unit from below

7.3 INSTALLATION WORKS

Phase II of the remediation programme, the installation of the air sparging curtain along the northeastern site boundary, was implemented in the summer of 1999. Drilling and associated groundworks were carried out between April and July, with testing and commissioning in late July and early August.

7.4 OPERATION OF FULL SCALE SYSTEM

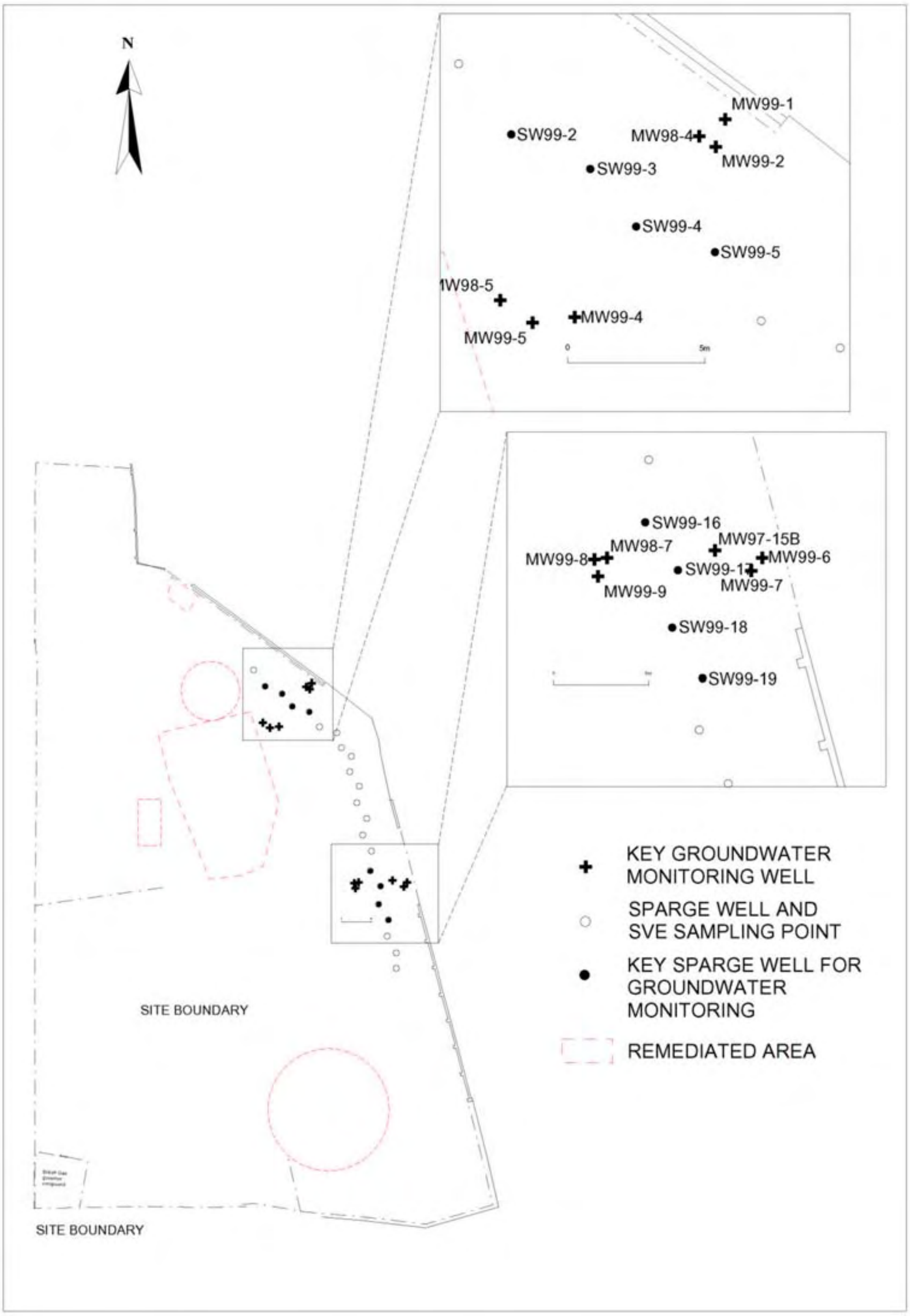
The system became fully operational on 20 August 1999. Air flow rates applied were limited to approximately 1.4 Ls^{-1} - 1.9 Ls^{-1} (3 scfm - 4 scfm) at each injection point, giving a total air delivery of 28 Ls^{-1} - 42 Ls^{-1} (60 scfm – 90 scfm).

The system was operated on an 8 hour pulse cycle. Pulsing the injected air has a number of beneficial effects. It helps prevent permanent mounding of the groundwater table around the air injection points, which could potentially alter groundwater flow across the site, and so divert contaminant migration around the sparge system. In addition, the alteration of air movement helps to minimise the generation of preferential flow pathways in the soil, and hence increases treatment efficiency. The system was designed so that the 11 northernmost injection wells were pulsed alternately with the 11 southernmost wells. This achieved the desired objectives and reduced the peak air demand of the system, allowing a less powerful and more cost-effective air delivery system to be used.

8. PERFORMANCE MONITORING

8.1 PERFORMANCE MONITORING METHODOLOGY

To demonstrate whether the performance criteria had been met, monitoring of soil vapour, groundwater, and field monitored parameters such as dissolved oxygen were carried out over the course of the project. Monitoring protocols are outlined in Appendix 2. Key monitoring locations are shown on Figure 8.1.



Source: Komex

Figure 8.1: Key monitoring well and sparge well locations

8.1.1 SAMPLING SCHEDULES

Sampling was carried out on a broadly logarithmic timescale, with the highest sampling rate immediately after system startup, becoming less frequent as the project progressed. Table 8.1 and 8.2 show the sampling schedules to date for both soil vapour and groundwater.

8.1.2 SOIL VAPOUR SAMPLING

At each sparge wellhead a shallow vapour monitoring well allowed vapour samples to be taken from the unsaturated zone. Both real and temporal variations in volatilisation could then be monitored. Sampling locations are shown on Figure 8.1.

During the commissioning phase, a number of the SVE wellheads were sampled to confirm likely off-gas concentration ranges, to ensure that the selected SVE treatment technology (activated carbon) was appropriate.

Following full-scale startup of the system, soil vapour samples were taken from all 22 wellheads for the first three sampling events. Photoionisation detector (PID) readings were taken at the same time. Regression analysis of PID readings and volatile organic compound (VOC) concentrations in vapour samples showed a positive correlation, and therefore on the fourth and subsequent monitoring event, vapour samples for laboratory analysis were taken only if PID readings over 5 ppm were recorded. Table 8.1 shows the vapour sampling schedule.

Table 8.1: Soil vapour sampling schedule

Well I.D.	**DATE**									
	13/7/99	**27/7/99**	**1/9/99**	**15/9/99**	**5/11/99**	**7/1/01**	**22/6/01**	**29/11/01**	**10/5/01**	**11/10/01**
SW99-1	S	S	S	S	**	**	**	**	**	**
SW99-2	S	S	S	S	**	**	**	**	**	**
SW99-3	S	S	S	S	**	**	**	**	**	**
SW99-4	S	S	S	S	**	**	**	**	**	**
SW99-5	S	S	S	S	**	**	**	**	**	**
SW99-6	S	S	S	S	**	**	**	**	**	**
SW99-7	S	S	S	S	**	**	**	**	**	**
SW99-8	S	S	S	S	**	**	**	**	**	**
SW99-9	S	S	S	**	**	**	**	**	**	**
SW99-10	S	S	S	**	**	**	**	**	**	**
SW99-11	S	S	S	**	**	**	**	**	**	**
SW99-12	S	S	S	**	**	**	**	**	**	**
SW99-13	S	S	S	**	**	**	**	**	**	**
SW99-14	S	S	S	**	**	**	**	**	**	**
SW99-15	S	S	S	**	**	**	**	**	**	**
SW99-16	S	S	S	S	**	**	**	**	**	**
SW99-17	S	S	S	S	**	**	**	**	**	**
SW99-18	S	S	S	S	**	**	**	**	**	**
SW99-19	S	S	S	S	**	**	**	**	**	**
SW99-20	S	S	S	**	**	**	**	**	**	**
SW99-21	S	S	S	**	**	**	**	**	**	**
SW99-22	S	S	S	**	**	**	**	**	**	**

Notes: Source: Komex (2002)

S - sample taken for laboratory analysis, PID reading also taken.
** - PID reading only

At each sampling event shown above, soil vapour concentrations were monitored at the outlet of each carbon treatment drum. These data provided information on vapour concentrations vented to atmosphere, which were a requirement of the Mobile Plant Licence.

8.1.3 GROUNDWATER SAMPLING

Groundwater sampling points were split into 6 different categories, shown in Table 8.2 below.

Table 8.2: Groundwater sampling schedule

	Well type	Well I.D.	DATE								
			13-Jul-99	01-Sept-99	15-Sept-99	5-Nov-99	7-Jan-00	22-Jun-00	29-Nov-00	10-May-01	11-Oct-01
1	Northern plume, upgradient of treatment curtain	MW98-5 MW99-5 MW99-4	S	x	x	x	x	S	x	x	S
2	Northern plume, within treatment curtain	SW99-2 SW99-3 SW99-4 SW99-5	S	S	S	S	S	S	S	S	S
3	Northern plume, downgradient of treatment curtain	MW98-4 MW99-1 MW99-2	S	S	S	S	S	S	S	S	S
4	Southern plume, upgradient of treatment curtain	MW98-7 MW99-8 MW99-9	S	x	x	x	x	S	x	x	S
5	Southern plume, within treatment curtain	SW99-16 SW99-17 SW99-18 SW99-19	S	S	S	S	S	S	S	S	S
6	Southern plume, downgradient of treatment curtain	MW97-15B MW99-6 MW99-7	S	S	S	S	S	S	S	S	S

Notes

Source: Komex (2002)

S - sample taken for laboratory analysis

x - no sample taken

Samples were taken from within, and downgradient of, the treatment curtain at each monitoring event. Samples were taken on the upgradient (western) side of the treatment curtain less frequently. These samples were taken to monitor contaminant concentrations influent to the treatment zone. All groundwater monitoring results are shown in Appendix 4.

9. PERFORMANCE EVALUATION

9.1 INTRODUCTION

System performance is subdivided into three sections:

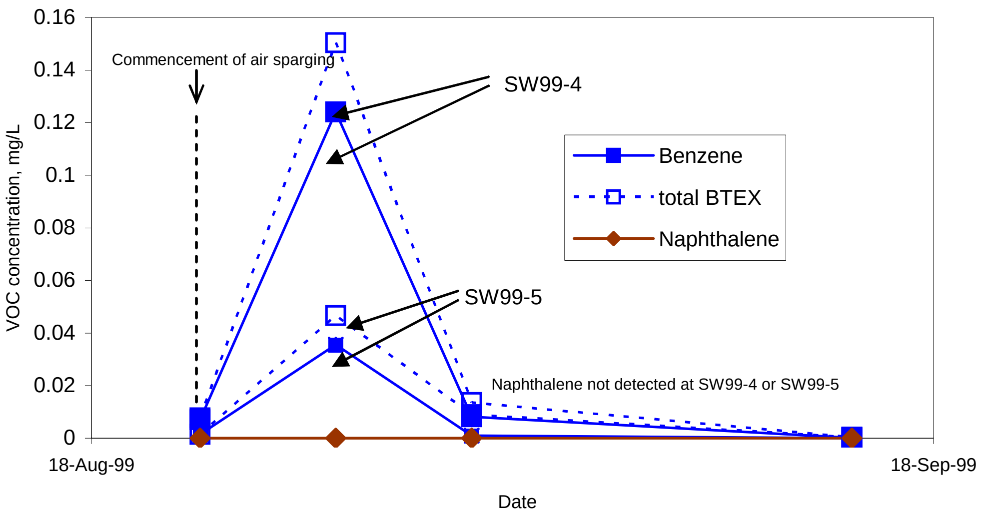
1. Soil vapour extraction and volatilisation processes;
2. Groundwater contaminant concentration changes; and,
3. Post shutdown monitoring.

9.2 SOIL VAPOUR EXTRACTION

The air sparging system incorporated a soil vapour extraction (SVE) system which extracted vapour from the full length of the air sparging curtain at a total flow rate which exceeded the air injection rate. This ensured full capture of hydrocarbon vapours.

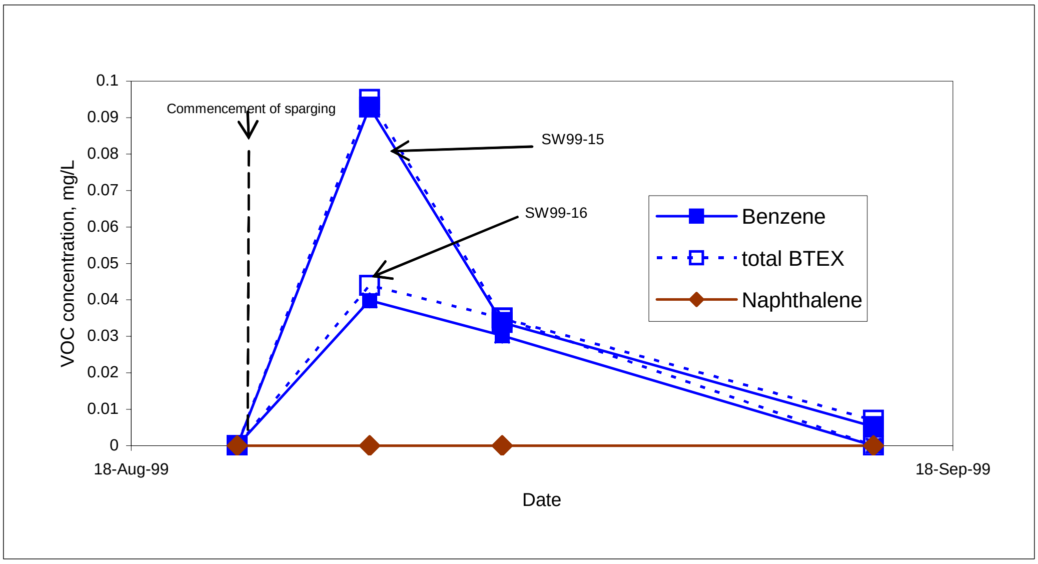
Prior to the commencement of air sparging, vapour samples were taken from each sparge wellhead. These initial results, together with corresponding photoionisation detector (PID) readings indicated that only a minor amount of hydrocarbon vapour was present in the unsaturated zone. During system commissioning, additional vapour samples were taken from four wells, two in the northern area (SW99-3 and SW99-4), and two in the southern area (SW99-14 and SW99-15). These samples exhibited highly elevated volatile organic compound (VOC) concentrations, benzene in particular. Given the relatively low concentrations of VOCs initially detected in the unsaturated zone, the results indicate that VOCs were being volatilised from the saturated zone.

VOC results taken following full system startup (August 20th 1999) exhibited an initial 'pulse' of VOC mass in the off-gas, followed by a decline over the following month, a characteristic of most locations along the air sparging curtain. Data for SW99-4, SW99-5, SW99-15 and SW99-16 are displayed on Figure 9.1 and Figure 9.2.



Source: Komex (2002)

Figure 9.1: Initial vapour concentrations, northern plume



Source: Komex (2002)

Figure 9.2: Initial vapour concentrations, southern plume

9.2.1 SOIL VAPOUR COMPOSITION

Results showed that the main hydrocarbon species present in the vapour was benzene. Toluene, ethlylbenzene and xylene were also commonly detected, but in lower concentrations. Naphthalene was analysed for, but was never detected at any location. Cresol was not analysed for in vapour samples. Cresol is less volatile than naphthalene (the cresol Henry's Constant is 1.2 atm.m^{3}mol^{-1} whereas naphthalene's is 3.6 atm.m^{3}mol^{-1} - 12.2 atm.m^{3}mol^{-1} (Montgomery, 1997). As naphthalene was not detected in the vapour, detection of cresols would not be expected, given the same aqueous phase concentration. Hydrocarbon species proportions are shown in Table 9.1 below.

Table 9.1: Hydrocarbon vapour composition

Contaminant	**Proportion of vapour, %**
Benzene	84.8
Toluene	5.1
Ethylbenzene	2.1
Xylenes	8.1
Naphthalene	0.0

Notes Source: Komex (2002)

Results calculated from the sum of contaminant concentrations at all locations measured over the first four vapour monitoring events.

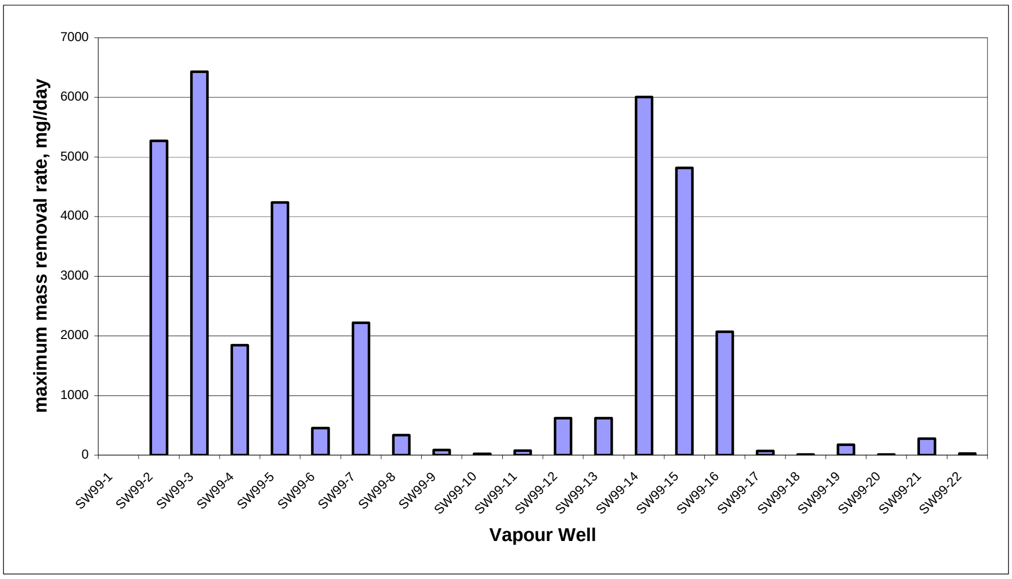
9.2.2 MASS REMOVAL

Analysis of Figure 9.1 and Figure 9.2 suggests that mass removal by volatilisation was greatest in the first two weeks after the air sparging system was switched on, and declined thereafter. By the end of the first month, almost no hydrocarbon mass was detected at the wellheads. Maximum mass removal rates were calculated for benzene using Equation 9.1, and these rates are shown for each air sparging wellhead on Figure 9.3. The equation is shown below.

$$MR_x = \frac{F_x.C}{t} \qquad \text{Equation 9.1}$$

Where MR_x = maximum mass removal rate of benzene at wellhead *x* (µgL^{-1}day^{-1})
C = benzene concentration sampled (µgL^{-1})
t = time interval (days)
F_x = SVE air flow rate at wellhead *x* (Lday^{-1}).

The calculation yields mass removal rates of up to 6,433 mgday^{-1} (SW99-3), although significant variation is exhibited along the length of the air sparging curtain. Two distinct areas yield the greatest mass, SW99-2 to SW99-7 and SW99-14 to SW99-16. These areas correspond closely with the groundwater contamination plumes.



Source: Komex (2002)

Figure 9.3: Maximum mass removal rates for benzene

Based on 27th August 1999 data (Figure 9.1), initial mass removal rates immediately after sparging commenced are likely to have been higher than the calculated values. VOC concentrations measured at selected wells during commissioning were up to 10 times higher than those measured on 27th August, corresponding to probable order of magnitude higher initial mass removal rates.

9.2.3 TREATMENT OF SOIL VAPOUR OFF-GAS

As required by the Mobile Plant Licence, soil vapour off-gas was treated using activated carbon before venting to atmosphere. Monthly monitoring was carried out by laboratory analysis of samples and by use of a PID. Initial laboratory samples indicated that off-gas vapour concentrations were below laboratory and PID detection levels. Once this had been established, monitoring was carried out using a PID alone (see Table 8.1), laboratory samples being taken only when the PID detected vapours > 5 ppm.

9.3 GROUNDWATER RESULTS

The primary goal of the air sparging curtain was to reduce contaminant concentrations in the groundwater migrating off site. Wells used for groundwater monitoring are shown on Figure 8.1, and are outlined in Table 9.2.

Table 9.2: Monitoring wells used to monitor groundwater contaminant concentrations

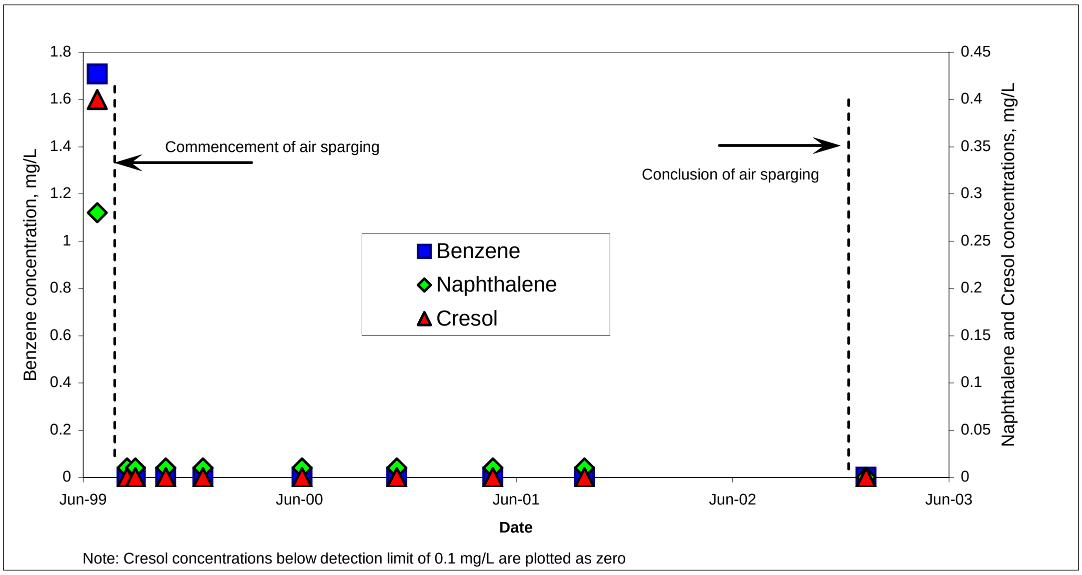
Monitoring Wells	Monitoring rationale
SW99-2, SW99-3, SW99-4, SW99-5	Zone of air sparging, across northern plume of contamination.
SW99-16, SW99-17, SW99-18, SW99-19	Zone of air sparging, across southern plume of contamination.
MW99-1, MW99-2, MW98-4	Zone of air sparging, southern plume of contamination.
MW98-5, MW99-4, MW99-5	Zone of air sparging, across northern plume of contamination.
MW97-15B, MW99-6, MW99-7	Zone of air sparging, southern plume of contamination.
MW98-7, MW99-8, MW99-9	Zone of air sparging, across southern plume of contamination.

Source: Komex (2002)

As discussed in Section 5.2, risk assessment work (Komex, 1998a), was used to derive site specific remediation criteria for principal risk driving contaminants (Table 5.1). These criteria formed the numerical targets for groundwater passing through the treatment zone (SW99-2 to SW99-5, and SW99-16 to SW99-19). Concentrations in the wells downgradient of the treatment zone were also compared against these criteria to identify whether the beneficial effects of air sparging propagated downgradient of the injection point. This could potentially lead to contamination levels in groundwater beneath the adjacent site reducing over time. Results of groundwater contamination monitoring are discussed below.

9.3.1 KEY ORGANIC CONTAMINANTS IN GROUNDWATER

Key organic groundwater contaminant data are shown in Appendix 4. Within the aerobic zone of air sparging (SW99-2 to SW99-5 and SW99-16 to SW99-19), benzene, naphthalene and cresol contaminant mass was rapidly removed at all monitoring locations. Commonly, all three key contaminants exhibited declines to below the cleanup criteria within 1 to 2 weeks of commencement of air sparging and the rate of mass removal suggests that, in these areas, the dominant mass removal mechanism was volatilisation. An example of this behaviour is shown in Figure 9.4.



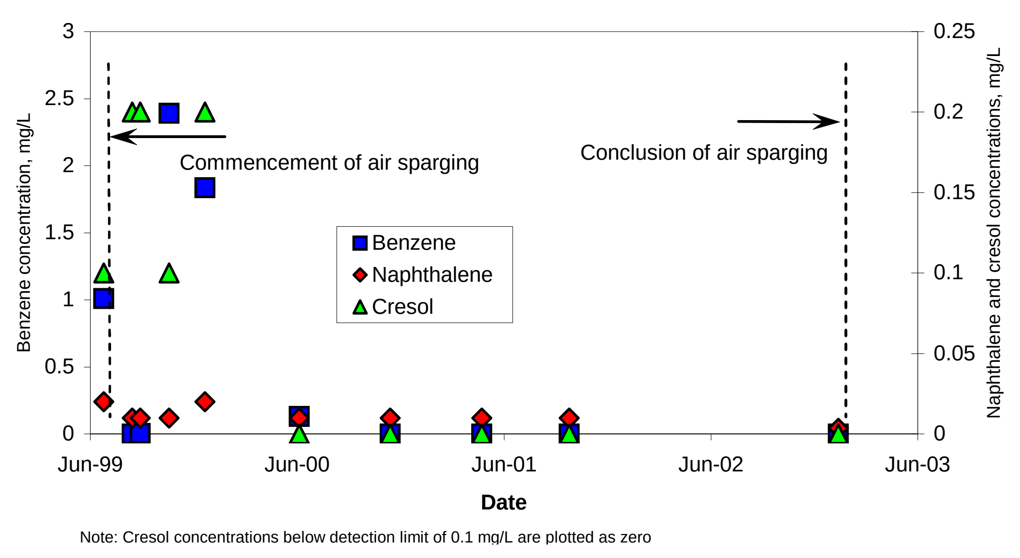
Note: Cresol concentrations below detection limit of 0.1 mg/L are plotted as zero

Source: Komex

Figure 9.4: Variation in key organic contaminants, SW99-2

This is further substantiated by the elevated contaminant concentrations recorded in soil vapour samples over the first 2 weeks (see Section 9.1).

Downgradient of the air sparging curtain and outside the area of air movement, similar trends were exhibited, although contaminant mass removal was commonly slower than within the zone of air movement. This is likely to be due to a difference in the dominant mass removal mechanism. In the absence of air movement in this area, volatilisation will have been minimal. However, aerobic biodegradation will have taken place as groundwater flow brought dissolved oxygen to this area. An example of this behaviour is shown in Figure 9.5.

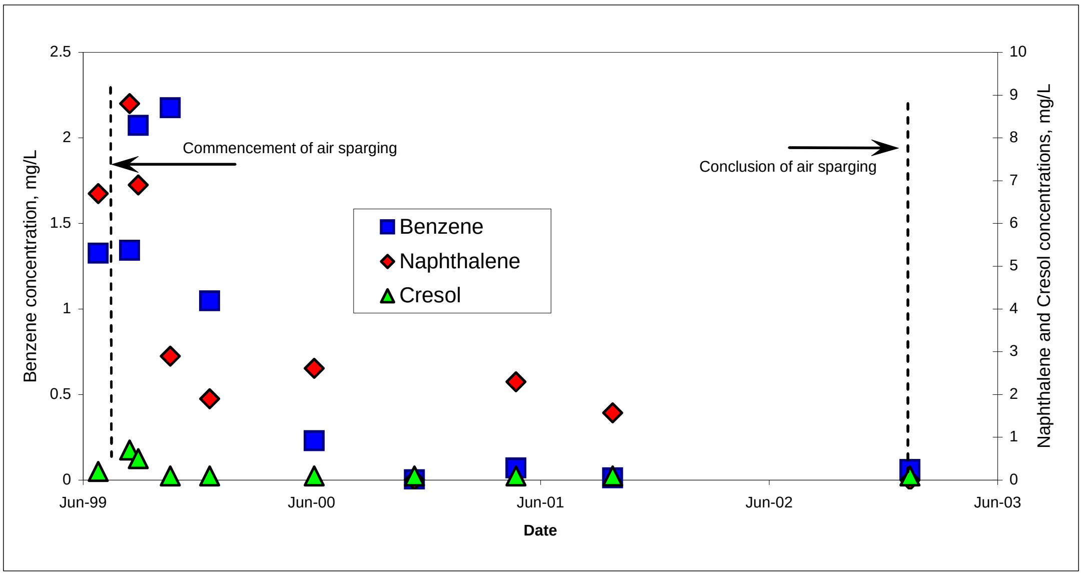


Note: Cresol concentrations below detection limit of 0.1 mg/L are plotted as zero

Source: Komex

Figure 9.5: Variation in key organic contaminants, MW98-4

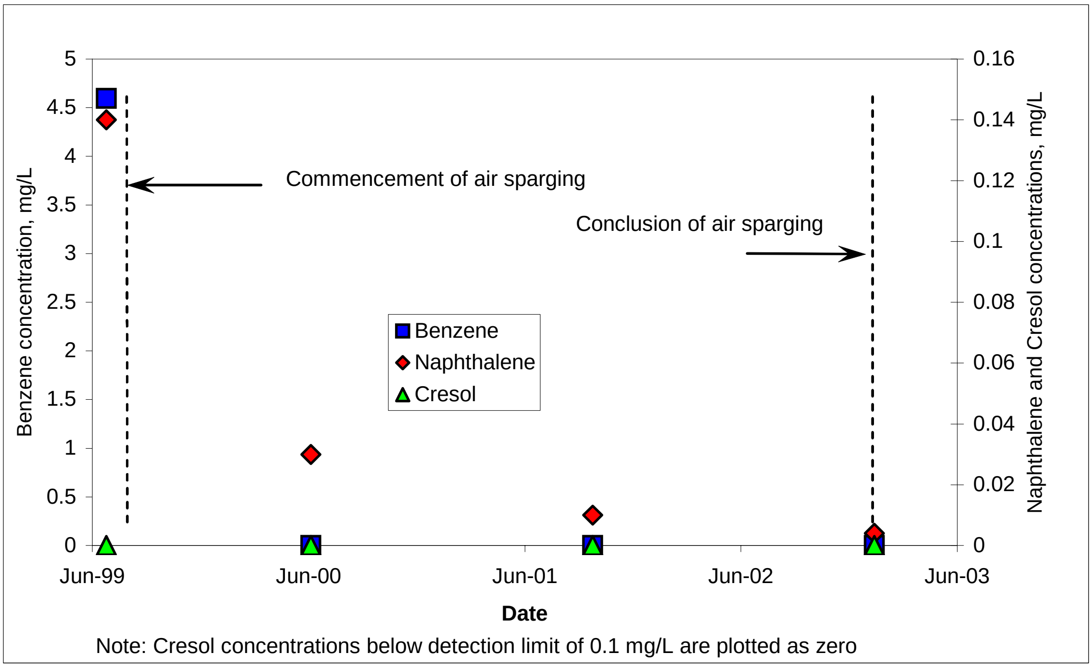
During the final monitoring event (October 2001) the target cleanup criteria were met at all downgradient monitoring locations except MW97-15B (Figure 9.6). However, significant reductions in key contaminant concentrations were exhibited at MW97-15B, and both benzene and cresol concentrations were below their target criteria in the final monitoring event. Although naphthalene also fell from a maximum concentration of 8.8 mgL^{-1} (1st September 1999) to 0.7 mgL^{-1} (October 2001), and although there is evidence of anaerobic biodegradation at this location, the target concentration of 0.11 mgL^{-1} was not met. It is likely that the persistence of naphthalene is due to the presence of residual phase hydrocarbon mass in the immediate vicinity of the monitoring well.



Source: Komex

Figure 9.6: Variation in key organic contaminants, MW97-15B

Monitoring at the upgradient locations was carried out less frequently than at the other locations. All these locations saw a decline in contaminant concentrations over the length of the project (July 1999 to October 2001). In particular, benzene concentrations declined significantly at all locations (e.g. from 4500 ugL^{-1} to <5 ugL^{-1} at MW99-5, Figure 9.7). This effect is likely to be linked to the first phase of remediation, in which contaminant sources upgradient of the sparge curtain were removed and replaced with clean fill.



Note: Cresol concentrations below detection limit of 0.1 mg/L are plotted as zero

Source: Komex

Figure 9.7: Variation in key organic contaminants, MW99-5

9.3.2 EVIDENCE FOR BIODEGRADATION

Biodegradation processes were evaluated by two approaches. Firstly, respiration tests carried out at a number of the air sparging wellheads were used to calculate subsurface oxygen demands. Although part of that demand can be attributed to inorganic reactions, a proportion of it is likely to be due to biodegradation. Secondly, work carried out by King's

College London on subsurface material from the site has yielded mineralisation rates for naphthalene.

9.3.2.1 Respiration Tests

A number of the air sparging wellheads were dual completions, comprising a deep screen adjacent to the base of the aquifer, and a shallow screen at between 2 mbgl – 4 mbgl. Respiration tests were carried out at these wellheads during the commissioning phase, prior to commencement of continuous sparging. Sparging commenced with air directed through the lower screen and into the formation. Dissolved oxygen was monitored using a datalogging probe located in the nested shallow-screened monitoring well. Dissolved oxygen decay rates varied from wellhead to wellhead, from 7.2 $mgL^{-1}h^{-1}$ (SW99-20) to 22.3 $mgL^{-1}h^{-1}$ (SW99-12). This decay rate can be converted to a biodegradation rate using equation 9.2 below:

$$BR = \frac{\Delta^{DO}.RMM_{hc}}{x.RMM_{oxygen}} \qquad \text{Equation 9.2}$$

Where *BR* = biodegradation rate ($mgL^{-1}h^{-1}$)
Δ^{DO} = dissolved oxygen decay rate ($mgL^{-1}h^{-1}$)
x = number of moles O_2 to biodegrade 1 mole hydrocarbon (see below)
RMM_{hc} = relative molecular mass of hydrocarbon (g)
RMM_{oxygen} = relative molecular mass of oxygen (g)

It is assumed that one of the principal contaminants undergoing biodegradation is benzene, hence the following (simplified) reaction can be said to be occurring:

$$C_6H_{6(aq)} + 7.5O_{2(aq)} \longrightarrow 3H_2O_{(l)} + 6CO_{2(aq)} \qquad \text{Equation 9.3}$$

This gives a value for *x* of 7.5, and an RMM for the hydrocarbon of 78 $gmol^{-1}$.

Alternatively, assuming that the principal hydrocarbon undergoing biodegradation is naphthalene, the appropriate reaction is:

$$C_{10}H_{8(aq)} + 4O_{2(aq)} \longrightarrow 4H_2O_{(l)} + 10CO_{2(aq)} \qquad \text{Equation 9.4}$$

giving a value for *x* of 4 and a hydrocarbon RMM of 128 $gmol^{-1}$.

Appendix 4 summarises the dissolved oxygen decay rate data and shows benzene and naphthalene biodegradation rates calculated using the above method.

It should be noted that three key assumptions/observations are made to reach these results:

1. All the observed oxygen decay is due to hydrocarbon degradation by respiring aerobic bacteria.
2. The hydrocarbon food source as a whole is equivalent to benzene or naphthalene (the actual organic matter is likely to be a complex mixture of aromatic and aliphatic hydrocarbons).
3. Groundwater flow, which could also account for attenuation of dissolved oxygen concentrations, is too slow to account for more than 5 % of the observed decline.

Calculated values of the biodegradation rate vary between 2.35 $mgL^{-1}h^{-1}$ and 12.22 $mgL^{-1}h^{-1}$ assuming benzene is being degraded, and between 2.41 $mgL^{-1}h^{-1}$ and 12.54 $mgL^{-1}h^{-1}$ assuming naphthalene is being degraded.

9.3.2.2 Mineral Assays

As part of the parallel research project, supporting work on biodegradation at the site was carried out by King's College London. Only the conclusions of the work are presented herein. The resulting papers (Jones *et al*., 1999 and Jones *et al.,* 2001) are listed in the References section. The conclusions of the work broadly indicated that aerobic biodegradation was promoted by the sparge curtain. Specifically:

1. Naphthalene biodegradation rates average 5.7 $\mu g h^{-1} kg^{-1}$ soil in the upper 4 m of the subsurface.
2. Naphthalene biodegradation can be demonstrated at all locations tested other than the control well.
3. Biodegradation rates are generally higher upgradient of the sparge curtain, probably as a result of the Phase I remediation works, in which 5,000 tonnes of clean fill material was placed upgradient of the sparge curtain (heavy contamination can limit the ability of microorganisms to function).
4. Mineralisation rates increased markedly after commencement of air sparging.
5. Mineralisation rates decreased approximately 4.5 months after sparging commenced, probably due to scarcity of hydrocarbon mass.

However, it should be noted that these conclusions are based on laboratory experiments, and therefore can only be regarded as approximate field values.

9.4 POST SHUTDOWN MONITORING

Air sparging, together with similar *in situ* remediation processes, can be susceptible to ‘rebound’ of groundwater concentrations following termination of the remediation process. Rebound is a well-known effect, resulting from the presence of minor volumes of residual phase hydrocarbon mass in the subsurface. Once air injection ceases, contaminant concentrations may gradually increase again, hence the term ‘rebound’. As a result, a crucial element in evaluating the success of *in situ* groundwater remediation is the continuation of monitoring for a suitable period beyond the end of active remediation works.

9.4.1 POST SHUTDOWN MONITORING STRATEGY

Prior to system shutdown, agreement was reached with the Environment Agency to implement the following post shutdown monitoring strategy.

1. Immediately prior to shutdown, take a complete set of groundwater samples from the key monitoring wells.
2. Wait for a period of 3 months or more, then take a final complete set of groundwater samples.

The 3 month delay period was calculated to ensure that groundwater in the sparge zone was completely replaced with groundwater from the upgradient area. This would ensure that the system had reached equilibrium and any rebound of contaminant concentrations would have occurred. The equation is as follows:

$$T = \frac{w}{v} \qquad \text{Equation 9.5}$$

Where T = time to equilibration (days)
w = width of sparge zone (m)
v = groundwater flow velocity ($mday^{-1}$)

Given that the width of the sparge zone was 5 m, and using a conservative estimate for the groundwater flow velocity of 0.054 $mday^{-1}$ (Komex 1998), time to equilibrium was calculated at 92 days. This was rationalised to 3 calendar months.

The sparge system was shut down on 29th January 2003. Groundwater sampling was undertaken on this date, and again on 27th May 2003. Hence the actual period between shutdown and final monitoring was almost 4 months. The additional month represents further conservatism, to ensure that equilibrium had been reached in the subsurface.

9.5 POST SHUTDOWN MONITORING RESULTS

Monitoring results following system shutdown are discussed for the former northern plume and southern plume areas separately.

9.5.1 NORTHERN PLUME

Contaminant concentrations in the northern plume measured on 27th May 2003 were all below the identified target criteria (Table 5.1). Hence the remediation was concluded to have been successful, and no rebound of contaminant concentrations had occurred over the 4 months since shutdown.

9.5.2 SOUTHERN PLUME

Three of the ten locations monitored showed exceedences above target remediation criteria on 27th May 2003. Benzene was recorded at MW98-7 and SW99-18 at 1.88 mgL^{-1} and 0.58 mgL^{-1} respectively. MW97-15B also showed benzene above the target criterion, at 0.10 mgL^{-1}, and naphthalene at 2.1 mgL^{-1} (see Figure 9.8)

The following key observations can be made:

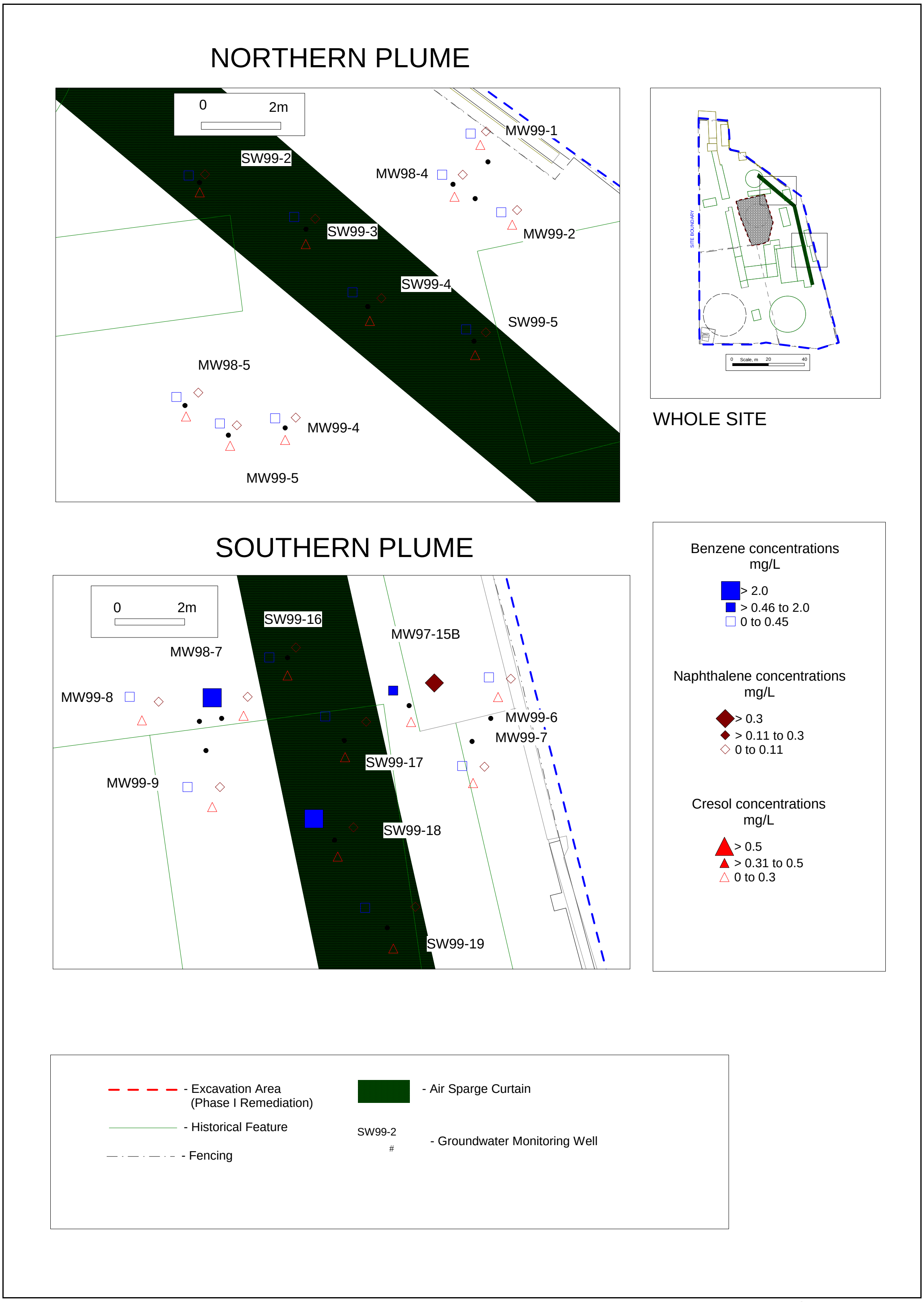
1. In July 1999, 12 exceedences were recorded in the southern plume (at 7 different locations). This was reduced to 4 exceedences at 3 different locations by May 2003.
2. All final contaminant concentrations were lower than initial concentrations taken on 13th July 1999.
3. All concentrations recorded in May 2003 were lower than those recorded in January 2003, indicating that contaminant concentration rebound had not occurred, and that trends suggested that concentrations were declining over time, not increasing.
4. Cresol, which was recorded prior to, and during sparging, had been reduced to below remediation criterion at all locations.
5. Contaminant concentrations from July 1999 suggested that residual hydrocarbon mass may have been present across the whole of the southern plume study area. Concentrations from May 2003 suggested that the area affected by residual hydrocarbon had been greatly reduced, and that residual hydrocarbons was likely to be restricted to the immediate vicinity of MW98-7, SW99-18 and MW98-15B.

9.6 EVALUATION OF RESIDUAL RISK

Residual risks are discussed separately for the northern and southern former plume areas. Factors under consideration include final groundwater contaminant concentrations, area distribution of contaminant concentrations, and evidence for attenuation processes.

9.6.1 NORTHERN PLUME

As final groundwater concentrations measured on 27th May 2003 did not exceed remediation criteria, the remediation achieved its objectives in this area. The residual risk can therefore be regarded as negligible.



Source: Komex

Figure 9.8: Post shutdown groundwater concentrations

9.6.2 SOUTHERN PLUME

In the southern plume area, 10 monitoring wells were sampled and data were compared with the 3 key contaminants at each location. Hence 30 comparisons were made with remediation criteria. Four exceedences were recorded (13 %), compared with 26 non-exceedences (87 %). These data do not suggest broad-front dissolved phase migration of elevated contaminant concentrations off site, but that only limited, discrete areas of elevated contaminant concentrations remained.

Furthermore, it should be noted that monitoring wells closest to the site boundary (MW99-6 and MW99-7) did not show exceedences. This also suggested that off-site contaminant migration was much reduced, and if occurring, was limited in extent.

9.6.3 RISK ASSESSMENT

The original remediation criteria were developed through groundwater modelling which incorporated advection and dispersion processes, but did not incorporate degradation (Komex, 1998a). This was a conservative approach reflecting the fact that no information was available at the time relating to the degradative potential of the subsurface. Since the criteria were developed, research work has highlighted a number of lines of evidence to show that both aerobic and anaerobic biodegradation processes were active in the subsurface (Komex, 2004). In light of this, the risk assessment could be refined to incorporate degradation processes.

Although the research work did not provide site specific decay constants, it provided sufficient evidence for the incorporation of biodegradation into the model through the use of published first order decay rates. For conservatism, the (faster) aerobic processes were ignored and the subsurface was assumed to be anaerobic in the absence of the air sparging system. Evidence suggested that significant sulphate-facilitated biodegradation processes were occurring; hence decay constants relevant to sulphate were used where available.

Table 9.3 below shows the rate constants used in the calculation and the predicted contaminant concentrations at the southern receptor (the river). For modelling purposes, the source area was defined as the whole of the northeastern area of the site (a conservative approach), with source concentrations fixed at the maximum measured residual concentrations (1.88 mgL^{-1} for benzene and 2.10 mgL^{-1} for naphthalene). All other parameter values remained unchanged from the original risk assessment (Komex, 1998a).

Table 9.3: Modelled contaminant concentrations at southern receptor

Contaminant	Maximum residual concentration on site (mgL^{-1})	First order decay rate (day^{-1})	Modelled concentration at river (mgL^{-1})	UK EQS, (mgL^{-1})	Dutch Intervention Criteria (mgL^{-1})
Benzene	1.88	125$^{(a)}$	2 x 10^{-4}	0.03	0.03
Naphthalene	2.10	33$^{(b)}$	1 x 10^{-7}	0.01	0.07

Notes: Source: Komex (2004)

(a) Suarez and Hanadi, 1999. Mean average first order decay rate for benzene degradation using sulphate as principal electron acceptor

(b) USEPA, 1999

The table shows that modelled concentrations were below both UK Environmental Quality Standards (EQS) and Dutch criteria concentrations for both benzene and naphthalene. Furthermore, the modelled concentration for benzene was two orders of magnitude below its EQS and the modelled concentration for naphthalene was five orders of magnitude below its EQS. These data suggested that the residual risk posed to the river by residual concentrations on the site was negligible.

10. REGULATOR LIAISON AND PROJECT CLOSURE

The overall remediation programme was designed to protect off-site receptors from contaminated groundwater originating from the site. The design life of the air sparging element of the project was 3 years. It was anticipated that over the 3 year period, upgradient groundwater contaminant concentrations would gradually decline due to the Phase I source removal works, and the requirement for the air sparging curtain would eventually be mitigated. However, a third phase of remediation (a ‘polishing’ phase) was built into the overall strategy, to be implemented in the event that groundwater contaminant concentrations still required treatment or further risk assessment at the conclusion of the air sparging phase.

Meetings were held with the EA in autumn 2002 to agree suspension of sparging operations and post shutdown monitoring. These works were concluded in May 2003. Refinement of the original risk assessment showed that the remaining risks to receptors from residual concentrations on site were negligible. Results have not been formally presented to the EA, but it is anticipated that liaison will be concluded in the near future. Agreement on final project closure will depend on the outcome of the discussions with the EA.

11. SUMMARY

The air sparging / SVE system operated from 20th August 1999 to 29th January 2003. The system operated for 3 years 5 months (compared with a design life of 3 years). At the conclusion of sparging, performance criteria were met at 13 out of 14 key monitoring locations. Key points on system performance are outlined below.

11.1 SOIL VAPOUR EXTRACTION

- Soil vapour was encountered in two principal areas corresponding closely with the conceptualised locations of the contaminated groundwater contamination plumes.
- The system successfully removed, and appropriately treated, contaminated soil vapours from the subsurface.
- Testing of the SVE system off-gas shows that VOC concentrations vented to atmosphere were below laboratory detection limits.
- Over 80 % of the hydrocarbon mass removed by soil vapour extraction was benzene.
- Contaminant mass removal rates reached a peak within the first week of system operation, and then rapidly declined thereafter. After 9 weeks of operation, all monitoring points exhibited soil vapour contaminant concentrations below detection limits, and this was maintained for the duration of the project.

11.2 GROUNDWATER RESULTS DURING SPARGING

- The groundwater remediation criteria were achieved at most of the key locations within the zone of air movement within one month of system startup. Contaminant concentrations remained below the target criteria for the duration of the project at most locations.
- At monitoring locations downgradient of the sparge curtain, target criteria (Table 5.1) have been achieved, although concentrations were reduced more slowly than in the zone of air movement. Only one location, MW97-15B, has exhibited contaminant concentrations outside the target criteria on more than two occasions since June 2000. This may be due to the presence of residual phase contamination at this location.
- Overall, target criteria have been achieved on 155 out of a possible 168 occasions since June 2000.

11.3 BIODEGRADATION

- Respiration testing has shown that a significant oxygen demand exists in the subsurface. This is likely to be a combination of biological oxygen demand and chemical oxygen demand.
- Microbiological work carried out by King's College London indicate the following:
    - Naphthalene mineralisation rates averaging 5.7 $\mu g h^{-1} kg^{-1}$ soil in the upper 4 m of the subsurface.
    - Naphthalene biodegradation can be demonstrated to occur at all locations tested.
    - Mineralisation rates are generally higher upgradient of the sparge curtain, probably as a result of the Phase I remediation works, in which 5000 tonnes of clean fill material was placed upgradient of the sparge curtain.
    - Mineralisation rates increased markedly after commencement of air sparging activities.

- Mineralisation rates decreased approximately 4.5 months after sparging commenced, probably due to scarcity of hydrocarbon mass.

11.4 GROUNDWATER RESULTS – POST SHUTDOWN MONITORING

Because all contaminant concentrations in the northern plume were below the remediation criteria, no further action was recommended in this area.

Exceedences of the remediation criteria developed in 1998 (Komex, 1998a) were recorded at three locations in the former southern plume area on 27th May 2003. However, the groundwater modelling exercise used to develop the 1998 criteria was re-evaluated, incorporating anaerobic biodegradation processes. The results of this update demonstrated that, given current groundwater contaminant concentrations on site, concentrations of benzene and naphthalene at the southern receptor would be two and five orders of magnitude below the UK EQS respectively.

Results from the southern plume area can therefore be summarised as having shown significant reductions in contaminant concentrations with negligible concern over post shutdown rebound. The majority of locations exhibited contaminant concentrations below remediation criteria, although three locations showed exceedences. These exceedences indicated that a limited volume of residual phase hydrocarbon mass is likely to be present in the subsurface in the vicinity of these locations, but that the area of ground affected by residual phase had been much reduced over the course of the project. In addition, an update to the original risk assessment work (Komex, 1998a) demonstrated that risks to the identified receptor from the residual contaminants on site are negligible.

11.5 RELIABILITY

The system was operational for a total of 864 days out of 975 since commissioning. This represents a reliability of 89 %.

12. ECONOMIC CONSIDERATIONS

Outlined in Table 12.1 below is a cost breakdown for the design, installation and operation of the air sparging system over 3 years.

Table 12.1: Cost breakdown for air sparging / SVE system

Operation	Cost	% of total cost
System design	£14,000	5
Well and subsurface pipework installation	£76,250	29
Surface equipment installation	£38,125	15
Operation and Maintenance (3 years)	£39,200	15
Health & Safety, site infrastructure	£2,500	1
Monitoring	£52,550	20
Project Management	£17,500	7
Compliance with CDM regulations, acquisition of licences	£3,000	1
Compliance with Licensing requirements of the Environment Agency over 3 years (management and licence fees)	£12,725	5
Contingency	£4,000	2
TOTAL	**£259,850**	**100**

Source: Komex

The whole remediation programme (including Phase I source removal works) is shown in Table 12.2 below.

Table 12.2: Overall remediation project costs

Remediation Phase	Works	Cost
I	Source Removal	£420,000
II	Air Sparging / SVE	£259,850
TOTAL		**£679,850**

Source: Komex

These costs compare favourably with the other technically feasible remediation options outlined in Table 5.2. Estimated costs for remediation by excavation alone were approximately £1.1 M. Hence the air sparging project has reduced overall remediation costs by approximately £400,000.

Remediation costs are commonly broken down into a cost per unit treated, £tonne^{-1} or £m^{-3}. The air sparging / SVE curtain remediation system is less easily analysed by this method, as treatment volumes, and hence unit costs, are of secondary importance to whether receptor protection was achieved.

13. LESSONS LEARNED

13.1 INTRODUCTION

The overall project was successfully executed and completed on budget. However, certain elements required unexpectedly greater attention and effort to complete. The following comments represent issues which proved to be key, and are divided into regulatory, technical and financial issues.

13.2 REGULATORY ISSUES

At the time of project conception, the current Mobile Plant Licensing (MPL) regime had not been introduced. Discussion with the EA at this initial stage concluded that the project could commence without an MPL, but that one should be pursued. Although an MPL was finally acquired for the air sparging system, this took longer than anticipated because the MPL regime was new both for the regulator and the operator, and care was therefore taken on both sides to ensure it was implemented correctly.

In situ remediation systems such as air sparging do not fit comfortably within the MPL regime. The MPL was originally conceived to cover the treatment of waste soil. Although air sparging can be said to have a positive impact on soil in the subsurface (contaminant mass is removed), it is not always implemented with this as the primary goal. It is possible that authorisations covering this type of system will ultimately be covered by the proposed Single Regeneration Licence (Remediation Permit Working Group, 2002).

13.3 TECHNICAL ISSUES

Site specific pilot scale testing was a crucial part of the project. Not only does pilot testing demonstrate whether sparging is applicable to site conditions, it also provides information which is immediately transferable into the design process (well spacing, treatment zone width etc). Pilot scale testing costs totalled approximately £25,000, which is 10 % of the total cost of the air sparging phase of the remediation.

The SVE system was a significant part of the mass removal process for the initial period of operation, but its importance diminished over time. It was operated for the duration of the project because vapour capture was a principal criterion in the Mobile Plant Licence although, with hindsight, operational costs could have been reduced if the SVE system was switched off when it was no longer needed, although this would have required negotiation with the EA as it would have constituted a departure from the agreed MPL conditions.

13.4 FINANCIAL ISSUES

A financial breakdown of the project is shown in Section 12. However, a number of cost issues are considered to be worth additional emphasis. Other than installation, the two greatest cost elements are operation and maintenance, and monitoring (35 % of the Phase II budget in total).

The operation and maintenance budget covered costs for replacement parts, scheduled maintenance visits and unscheduled visits to restart the system following automatic shutdowns. These costs can be minimised by robust design but should not be underestimated. The sparge system comprises a number of high cost items (sparge compressor, SVE pump, complex telemetry) and the system design successfully ensured that none of these items became irreparably damaged.

GLOSSARY OF TERMS

Biodegradation	The consumption (degradation) of matter by microorganisms.
Coal gas	Also ‘town gas’. Gas produced from the processing of coal at a gasworks. Prior to the discovery of North Sea gas, this was the principal source of municipal heating and lighting gas.
Gasholder	Tank, commonly circular, used to store gas. At former gasworks sites gasholders contained the end product gas.
Liquor tank / liquor well	Tank used to contain ammonia rich liquids which were produced as a by-product of the coal gas manufacturing process.
Oxide shed	Also ‘purifiers’. Building in which cyanides and sulphides were removed from the gas stream during the coal gas manufacturing process.
Retort house	Building in which the coal carbonisation process was carried out as part of the coal gas manufacturing process. The retort house contained ‘retorts’ or ovens in which coal was heated in the absence of oxygen to drive off volatile components.
Tar tank / tar well	Tank used to contain heavy tars which were produced as a by-product of the coal gas manufacturing process. Tar tanks were often below-ground structures.

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APPENDICES

Appendix 1	Representative Borehole Logs
Appendix 2	QA/QC and Monitoring Protocols
Appendix 3	Selected Pilot Scale Remediation Trial Data
Appendix 4	Air Sparging Performance Data – Groundwater and Respiration Test Results

APPENDIX 1
REPRESENTATIVE BOREHOLE LOGS

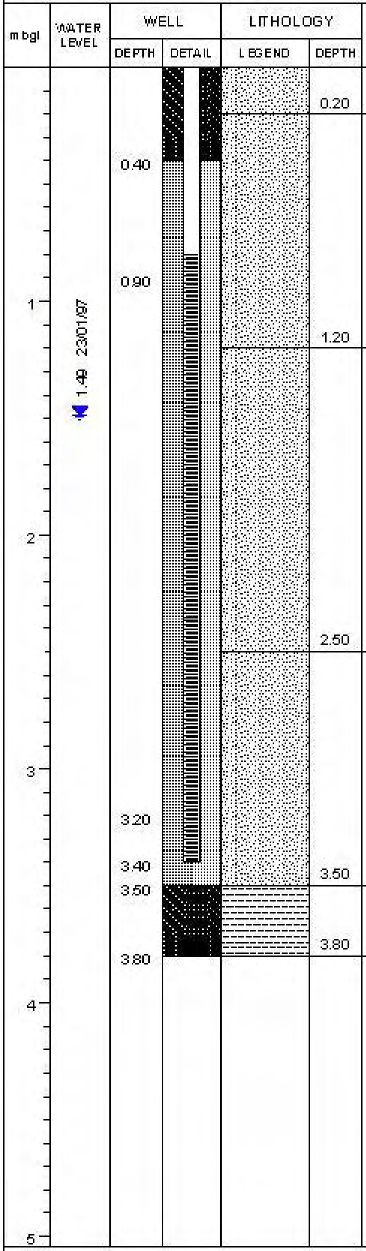
KOMEX EUROPE
ENVIRONMENTAL AND WATER RESOURCES

MONITORING WELL LOG

MW97-1

Sheet 1 of 1

PROJECT No: 50173-1	**DATE:** 23/01/97	**EASTING:**
SITE:	**LOGGED BY:** GMH	**NORTHING:**
CLIENT:	**CONTRACTOR:**	**ELEVATION:** 62.71



LITHOLOGY DEPTH	DESCRIPTION	PID	SAMPLE LABEL	SAMPLE DEPTH
0.20	Very loose brown SAND, damp. No HCO. Poor recovery.			
1.20	Loose red brown silty SAND.	00		0.50
2.50	SAND: Strong organic odour at 1.2m, changes with depth. Becoming black at 1.2-2m.	5		1.20
		0.5	MW971-1	2.00
3.50	SAND:At 2.5m clayey band 0.1m thick.			
3.80	Firm red CLAY. No HCS, HCO.			
	End of Borehole at 3.8 m			

NOTES

HCO- Hydrocarbon Odour. HCS- Hydrocarbon Staining.

Descriptions are based on observations and hand testing of grab samples.
Mechanical tests were not performed unless otherwise stated.

▽ Water Strike
▼ Rest Groundwater Level

Drilling Method: Hollow stem auger
Borehole Diameter: 120mm
Screen Material: MDPE
Screen Diameter: 50mm
Screen Slot Size: 0.5mm
Sand Particle Size: 1-2mm
All depths shown in metres below ground level.

120 Cumberland Road, Bristol BS1 6UY. Tel. (0117) 925-1304

Reviewed By:

FILE:

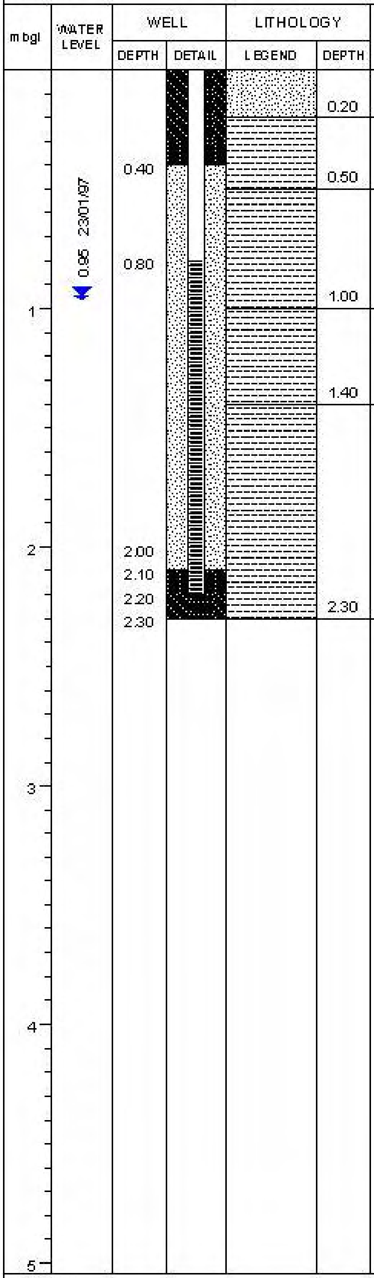
KOMEX EUROPE
ENVIRONMENT AND WATER RESOURCES

MONITORING WELL LOG

MW97-4

Sheet 1 of 1

PROJECT No:	50173-1	**DATE:**	23/01/97	**EASTING:**	
SITE:		**LOGGED BY:**	GMH	**NORTHING:**	
CLIENT:		**CONTRACTOR:**		**ELEVATION:**	62.66



LITHOLOGY DEPTH	DESCRIPTION
0.20	Black SAND with pieces of brick and clinker. Slight HCO.
0.50	Black very Silty CLAY. Strong HCO.
1.00	Firm red CLAY, black along fractures (Free phase HC on augers).
1.40	Soft grey very silty CLAY. Strong HCO.
2.30	Firm red brown CLAY. No HCS. Possibly no HCO.
	End of Borehole at 2.3 m

PID	SAMPLE LABEL	SAMPLE DEPTH
58		0.30
71		0.50
13		1.00
53	MW974-1	1.20

NOTES

HCO- Hydrocarbon Odour. HCS- Hydrocarbon Staining. Freephase HC noted on auger. Green/brown in colour.

Descriptions are based on observations and hand testing of grab samples.
Mechanical tests were not performed unless otherwise stated.

▽ Water Strike
▼ Rest Groundwater Level

Drilling Method: Hollow stem auger
Borehole Diameter: 120mm
Screen Material: MDPE
Screen Diameter: 50mm
Screen Slot Size: 0.5mm
Sand Particle Size: 1-2mm

All depths shown in metres below ground level.

120 Cumberland Road, Bristol BS1 6UY. Tel. (0117) 925-1304

Reviewed By:

FILE:

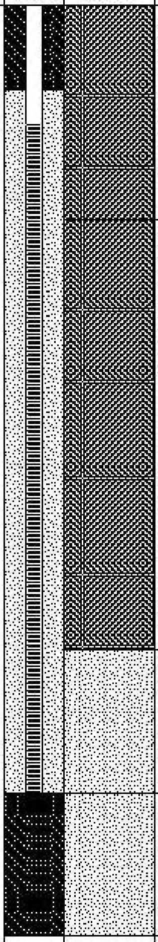
KOMEX EUROPE
ENVIRONMENTAL AND WATER RESOURCES

MONITORING WELL LOG

MW97-5

Sheet 1 of 1

PROJECT No:	50173-1	**DATE:**	23/01/97	**EASTING:**	
SITE:		**LOGGED BY:**	GMH	**NORTHING:**	
CLIENT:		**CONTRACTOR:**		**ELEVATION:**	62.92



m bgl	WATER LEVEL	WELL DEPTH	LITHOLOGY DEPTH	DESCRIPTION	PID	SAMPLE LABEL	SAMPLE DEPTH
		0.35 0.50	0.90	MADE GROUND: Brown, medium grained sand with pieces of ash, brick and concrete rubble. No HCO, No HCS. Dry.	0.3		0.50
1 2	1.15 23/01/97		2.70	MADE GROUND: Little recovery. Mostly concrete rubble, strong HCO, wet from 1.2m.	26.5	MW975-1	2.40 2.50
3		3.10 3.30	3.30	Loose grey silty SAND, noticable HCO.	13		2.90
		3.90	3.90	Loose red silty SAND, slight HCO. No staining.	14.5		3.40
4 5				End of Borehole at 3.9 m			

NOTES

HCO- Hydrocarbon Odour. HCS Hydrocarbon Staining. Obstruction encountered at 0.3m on 1st attempt, hole relocated 0.5m away.

Descriptions are based on observations and hand testing of grab samples. Mechanical tests were not performed unless otherwise stated.

▽ Water Strike
▼ Rest Groundwater Level

Drilling Method: Hollow stem auger
Borehole Diameter: 120mm
Screen Material: MDPE
Screen Diameter: 50mm
Screen Slot Size: 0.5mm
Sand Particle Size: 1-2mm
All depths shown in metres below ground level.

120 Cumberland Road, Bristol BS1 6UY. Tel. (0117) 925-4304

Reviewed By:

FILE:

KOMEX EUROPE
ENVIRONMENTAL AND WATER RESOURCES

MONITORING WELL LOG

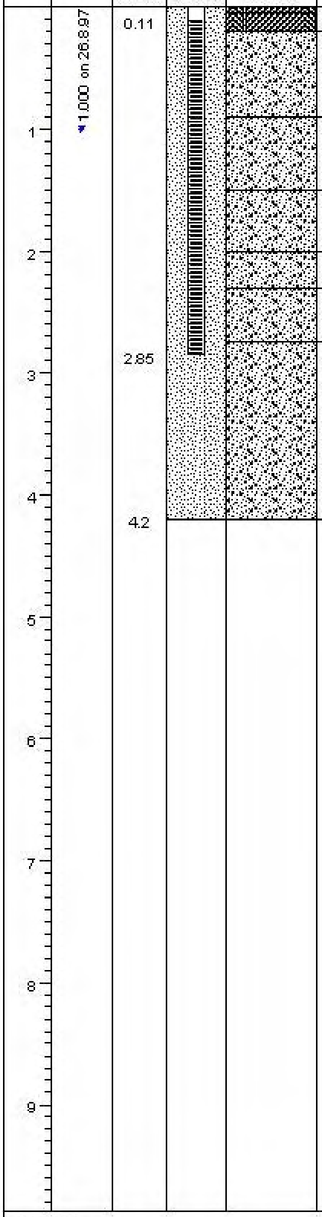
MW97-11

Sheet 1 of 1

PROJECT No: 50173-3
SITE:
CLIENT:

DATE: 26 August 1997
LOGGED BY: M Hall
CONTRACTOR:

EASTING:
NORTHING:
ELEVATION: 62.49



WELL DEPTH	LITHOLOGY DEPTH	DESCRIPTION	PID	SAMPLE LABEL	SAMPLE DEPTH
0.11	0.20	MADE GROUND: Hand dug to clear services.			
		MADE GROUND: Gravel track and sub-base.			
	0.90	Dense, black, silty SAND with pieces of concrete and clinker, 0 - 3 cm diameter. Free phase hydrocarbon?		MW97-11-1	0.50
	1.50	Dense, black, silty SAND with pieces of brick. Clay layers 2.5cm thick at 0.9m, 1.1m and 1..4 mbgl. Black staining, especially 0.9m - 1.2m.			
	2.00	Loose, dark grey, moist, silty SAND. Strong hydrocarbon odour.		MW97-11-2	1.50
	2.30	Dense, red brown and black, moist, silty SAND. Thin layer of clay at 2.15m (1cm thick).			
	2.75	Brown, moist, silty SAND. Possibly with free phase hydrocarbon, no staining.			
2.85	4.20	Red brown, moist, silty SAND. No obvious odour, occasional pieces of clay 3.4 - 3.6 m. Stained black, no difference in composition.			
4.2		End of Borehole at 4.2 m			

NOTES
Running sand below 3.5m bgl - very difficult drilling.

Descriptions are based on observations and hand testing of grab samples.
Mechanical tests were not performed unless otherwise stated.

▽ Water Strike
▼ Rest Groundwater Level

Drilling Method:
Borehole Diameter:
Screen Material:
Screen Diameter:
Screen Slot Size:
Sand Particle Size:
All depths shown in metres below ground level.

120 Cumberland Road, Bristol BS1 6UY. Tel. (0117) 925 4304
Reviewed By:
FILE:

APPENDIX 2
MONITORING PROTOCOLS AND QA/QC

SOIL VAPOUR AND GROUNDWATER SAMPLING PROTOCOLS

This document sets out sampling protocols for groundwater and soil vapour, in order to maximise the representativeness of the collected data. Rigorously following an accepted protocol ensures the comparability of future monitoring results. The document describes the field sampling plan for the works at the site. Sampling locations are shown on Figure 8.1.

To demonstrate that the performance criteria have been met, monitoring of soil vapour, groundwater, and field monitored parameters such as dissolved oxygen has been carried out over the course of the project. Monitoring protocols are outlined below.

SOIL VAPOUR SAMPLING

At each sparge wellhead a shallow vapour monitoring well allows vapour samples to be taken from the unsaturated zone. Both areal and temporal variations in vapour evolution can then be monitored.

Vapour Sampling Protocol

Extreme care needs to be taken when vapour sampling from installed sampling points to avoid:

1. The possibility of mixing with atmospheric air when sampling.
2. Partitioning effects possibly induced by reducing the pressure in the soil matrix during vapour pumping.

The following procedure was adopted to minimise, or at least account for these effects.

Sampling Method

The high compressibility and high mobility of soil vapour (compared to groundwater) means obtaining representative vapour samples is more problematic than with groundwater samples. Because of the greater chemical stability of groundwater, field measured parameters can be relied upon to indicate sample integrity. In vapour sampling, field measured parameters such as volatile organic carbon (VOC), oxygen (O_2) and carbon dioxide (CO_2) content cannot readily be used to determine sample stability. However, they can assist in that determination.

The primary concern when sampling soil vapour is that the induced vapour gradient from pumping may cause atmospheric air to be pulled from surface into the sample. If this ‘short-circuiting’ occurs, it will cause dilution of the contaminant in the sample. To reduce the possibility of this effect, purging is kept to a minimum, especially in shallow wells (<3 m) with no surface confining layer. Real time monitoring of field measured parameters can be used to indicate if short-circuiting is occurring. If short-circuiting is taking place, O_2 concentrations will usually increase, while hydrocarbon and CO_2 concentrations will usually decrease. If this effect is noticed, the sample integrity is lost.

The second problem is caused by the compressibility of vapour. As vapour is withdrawn from the subsurface through pumping, the localised subsurface pressure can be significantly reduced. This effect will change the vapour equilibrium concentration that is being measured, i.e., the act of sampling the vapour changes the vapour concentration. Significant pressure reductions in the subsurface will cause vaporisation of organic contaminants that are sorbed on to soil particles, as well as volatilisation of dissolved phase organic contaminants from groundwater. Both these phenomena increase vapour contaminant concentrations. This effect may not be significant in high permeability zones, but in lower permeability zones, it can cause significant variation in the composition of the soil vapour. The effect can best be minimised by reducing the induced pressure gradient by pumping more slowly, creating a smaller pressure gradient.

To maximise the usefulness of the information obtained from the vapour sampling, the following framework is followed when sampling the soil vapour monitoring points:

1. An inspection of the well is made, noting any irregularity with the well condition.

2. New polytetrafluoroethene (PTFE) tubing is attached from the sampling point to a vapour analysis pump, which measures field-measured parameter concentrations and differential pressure.
3. Initial field conditions are assessed by pumping until field measured parameters stabilise (commonly 1 - 2 minutes). The vapour sample box is attached to the PTFE tubing and sampling commences. A new 1 L Tedlar bag with PTFE vapour tap, is flushed (~0.5 L) with sample vapour twice to ensure no residual vapour from the sample tubing or Tedlar bag remains (see notes on purging below). VOC concentrations are measured with a Photovac Microtip Photo Ionisation Detector from each bag. The bag is then filled 2/3 full for transport to the laboratory for analysis.
4. The sample bags are placed in a uniquely labelled cool box, at ambient temperature to reduce effects of photo-ionisation and condensation. All samples are analysed for VOC concentrations.

Notes on Purging:

A 1 L Tedlar bag should be purged twice, with at least 0.5 L of sample each time. This is to allow the complete purging of the sampling piping and allow the sample vapour to equilibrate with the Tedlar bag (to allow any active sites on the bag to be saturated with the sample gases). The volume of vapour pipework purge required, assuming 3 purge volumes for a 2 m pipe length, can be calculated from:

Volume of vapour pipework, Vvp = (pipe internal diameter / 2)^2 x π x length of pipe
Vvp = (6 mm/2)^2 x π x 2 x10^3 mm
Vvp = 56 mL
Required purge = Vvp x 3 = 0.17 L

The volume required to purge the piping (0.17 L) is much less than the 1 L that is required to purge the Tedlar bags. Therefore, a total purge of ~ 1 L should be adequate for the pumping equipment.

GROUNDWATER SAMPLING PROTOCOL

When sampling groundwater, a number of concerns need to be addressed. Most significant of these are:

1. Ensuring that the sampled groundwater is representative of formation groundwater.
2. Ensuring that the sampled groundwater is not mixing significantly with atmosphere, causing chemical changes.
3. Ensuring transportation to the lab does not induce chemical changes to the sample.

A sampling procedure has been adopted to address these concerns.

Sampling Method

The following is the proposed groundwater sampling methodology based on experience gained in North America:

1. An inspection of the well is made, noting any irregularities in the well condition.

2. The static groundwater level in the well is measured. This is confirmed to be a static level by taking measurements over 5 minutes and verifying the variation in measurements is minimal (<5 %).

3. The total depth of the well is measured. This is done to confirm the well's depth integrity and to check for the presence of dense non-aqueous phase liquid.

4. The wells are sampled with a disposable plastic bailer. Each bailer is used only once, to ensure that cross contamination is eliminated.

5. Seven bottles are filled for each type of analysis. All bottles have PTFE lined caps. VOC samples are collected in amber glass 50 mL septum top vials. Mineral and BOD/COD samples are collected in 1 L HDPE bottles. The sulphide analysis requires a preservative addition of 60 mL of a mixture containing ethylenediamenetetracetic acid, ascorbic acid and sodium hydroxide in a 120 mL HDPE bottle. PAH and TPH samples are collected in 1 L amber glass bottles. Phenol samples are collected in a 250 mL amber glass bottle. The laboratory supplies all sample containers. All bottles are filled with zero headspace.

SAMPLE PREPARATION/STORAGE/TRANSPORT

Samples are sealed, labelled and placed in a cool box equipped with ice packs to maintain a sample temperature of approximately 4 ^{o}C. The cool box contains a bottle of deionised water from which the temperature is measured and recorded on receipt at the laboratory. All samples are wrapped in packing material to reduce the likelihood of breakage.

LABORATORY QA/QC

Laboratory analysis and internal laboratory QA/QC are discussed below. The laboratory implemented the following controls to ensure analytical quality is of the highest order.

- All laboratory equipment is serviced regularly, according to manufacturer recommendations.
- The analytical methods used are fully validated and based on published industry accepted methods. (EPA, Bluebook or ASTM).
- Method blanks are run before and after each sample batch to ensure that contamination carryover does not take place.
- Equipment is calibrated according to the calibration schedule for each instrument and continuing calibration checks are run before and after each sample batch.
- If method blanks or continuing calibration checks fail the QC check, the instrument is reblanked / recalibrated, and the previous batch is reanalysed.

Data validation is carried out to ensure the reliability of the data and that an audit trail has been developed, from sampling to reporting of the data. Data and sampling information requiring transcription from the lab reports and field proformas into summary tables is verified by checking the table against the raw data. A review of QA/QC data, sample records and results is undertaken. This includes such information as chain of custody data, dilution factors, detection limits, quantification limits, field notes, field data, laboratory results, spike recovery data, blank data, calibration data and duplicate data. Care is taken interpreting data that do not meet QA/QC checks.

QA/QC – GROUNDWATER

Matrix Spikes and Matrix Spike Duplicates

Matrix spike and matrix spike duplicates (ms and msd) are taken periodically. VOC ms & msds are analysed after being spiked with a known quantity of EPA8260 calibration solution. The response of the compounds of interest in the actual matrix gives useful information on the robustness of the analyses.

Sample Storage, Custody and Handling – Groundwater

One reusable ice pack is frozen and placed in each cool box prior to using that cool box for sample storage. Samples are labelled and placed in a cool box for storage. A small container filled with deionised water travels with each cool box as a temperature check. This temperature is measured on arrival at the laboratory. Prior to despatch, the cool box is sealed and a chain of custody form completed. The cool boxes and the chain of custody are inspected and any damage or discrepancies are recorded and reported to Komex so that appropriate action can be taken. The temperature should remain at 4 ^{o}C ± 2 ^{o}C to minimise volatilisation of volatile components and biological activity in the samples. This is maintained at the laboratory by storing the samples in refrigeration units with temperature control and temperature logging.

Equipment Calibration – Groundwater

All equipment used to measure field measured parameters is calibrated and operated as per the manufacturers specification.

Reporting – Groundwater

All field measurements, observations and calibrations are recorded on the groundwater pro forma.

ANALYSIS QA/QC – GROUNDWATER

Data collected from the contract laboratory include:

- continuing calibration check data for all sample batches;
- method blank data for all sample batches;

- reference material data for all SVOC and ICP metals batches;
- surrogate and internal standard data for all VOC and SVOC analyses; and,
- reagent blank data for all ICP metals batches.

These data are used to assess the precision and accuracy of the analyses. If any analyses are problematic for any reason (broken sample bottles, difficult matrix, warm cool box etc.) this is communicated to Komex as soon as practicable, to arrange for corrective action (e.g. re-sampling).

In addition to the internal laboratory checks, the following data are used to help assess data quality for groundwater samples.

Inorganic Chemistry

Ion balances are calculated for the major inorganic ions. The results should be within 5 % of balance. Additionally, pH and electrical conductivity (EC) are measured in both the field and laboratory. These values have been compared to assess if significant chemical changes occur in the groundwater sample during transportation. Values should be within 5 % variation.

Organic Chemistry

For the volatile organic carbon (VOC) analysis, several checks are carried out to assess the analytical performance. The method of analysis being used is based on the EPA 8260 GC/MS Purge and Trap method. Internal standards and surrogates are added to the purge vessel along with the sample water. The internal standard recoveries are then used to correct the surrogate recoveries. These corrected surrogate recoveries are compared against performance criteria to assess the laboratory and matrix effects on the analysis. The performance criteria from the EPA 8260 method are shown in Table A2.1 below.

Table A2.1 - Surrogate Spike Recovery Limits for Water - VOC

Surrogate Compound	Low/High Water (%)
Dibromofluoromethane	86/118
Toluene-d8	88/110
Dichloroethane-d4	80/120

These limits represent expected method performance for a simple matrix. If the surrogate recoveries fall significantly outside this range, it likely represents analytical difficulties with the matrix. In order to confirm matrix related problems with analyses outside this range, any sample with a surrogate recovery lower than 70 % recovery is reanalysed.

The semi-volatile organic carbon (SVOC) analysis, based on EPA 8270 GC/MS Purge and Trap method with acetone and dichloromethane extraction, has very similar internal QA/QC criteria. The significant difference between SVOC and VOC methodology is that the surrogate is added at the extraction step, and the internal standards are added into the purge reservoir. Internal standards are used to correct the surrogate recoveries. These corrected surrogate recoveries are then compared against performance criteria to assess laboratory and matrix effects on the analysis. The performance criteria for SVOCs have a wider tolerance than VOCs. The criteria are shown in Table A2.2.

Table A2.2 - Surrogate Spike Recovery Limits for Water - SVOC

Surrogate Compound	Low/High Water (%)
Nitrobenzene-d5	35/114
2-Fluorobiphenyl	43/116
Terphenyl-d14	33/141
Phenol-d5	10/94
2-Fluorophenol	21/100
2,4,6 - Tribromophenol	10/123

Source Contract Laboratory Program

These limits represent expected method performance for a simple matrix. If the surrogate recoveries fall significantly outside this range, it likely represents analytical difficulties with the matrix. The analysis of

SVOCs is more complex than that for VOCs, so larger variations are expected in surrogate recoveries. In order to confirm matrix related problems with any analyses outside the ranges above, any sample with one of the acid surrogates (phenol-d5, 2-fluorophenol and 2,4,6-tribromophenol) and one of the neutral surrogate (nitrobenzene-d5, 2-fluorobiphenyl and terphenol-d14) recoveries below 40 % is reanalysed. Additionally, any sample with three surrogates below 40 % recovery is reanalysed.

QA/QC – VAPOUR

Sample Storage, Custody and Handling – Vapour

Samples are labelled and placed in a cool box for storage. The cool box is left at ambient temperature to minimise condensation of vapour in the bags. Care is taken to ensure the bags are stored in the dark to minimise photodegradation. Prior to despatch, the cool box is sealed and a chain of custody form completed. At the laboratory, the cool boxes and the chain of custody are inspected and any damage or discrepancies recorded and reported to Komex so that appropriate action can be taken.

Equipment Calibration – Vapour

All equipment used to measure field measured parameters is calibrated and operated as per the manufacturers specification.

Reporting – Vapour

All field measurements, observations and calibrations are recorded on the soil vapour pro forma.

ANALYSIS QA/QC – VAPOUR

Organic Chemistry

For the volatile organic carbon (VOC) analyses, there are several checks on analytical performance. The method of analysis being used is based on the EPA 8260 GC/MS Purge and Trap method. Internal standards and surrogates are added to the purge reservoir along with the sample vapour. The internal standard recoveries are then used to correct the surrogate recoveries. These corrected surrogate recoveries are then compared against performance criteria to assess the acceptability of the analysis.

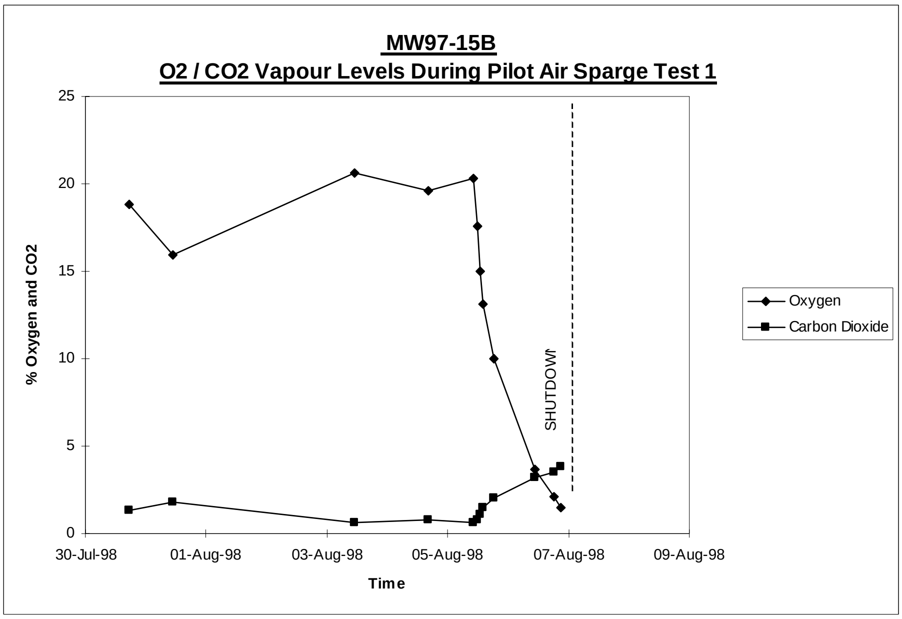
For the vapour samples the same surrogates are used as for groundwater analyses. The criterion used in determination of vapour sample quality is 80 % - 105 % in all cases. If any vapour analysis has surrogate recoveries that are outside this range, the sample is reanalysed.

APPENDIX 3

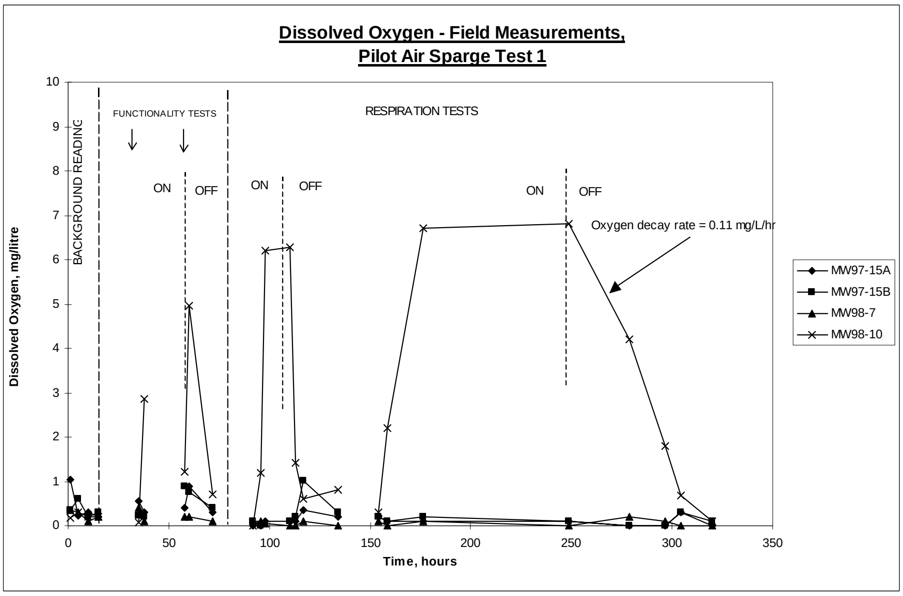
SELECTED PILOT SCALE REMEDIATION TRIAL DATA

AIR SPARGING TEST 1

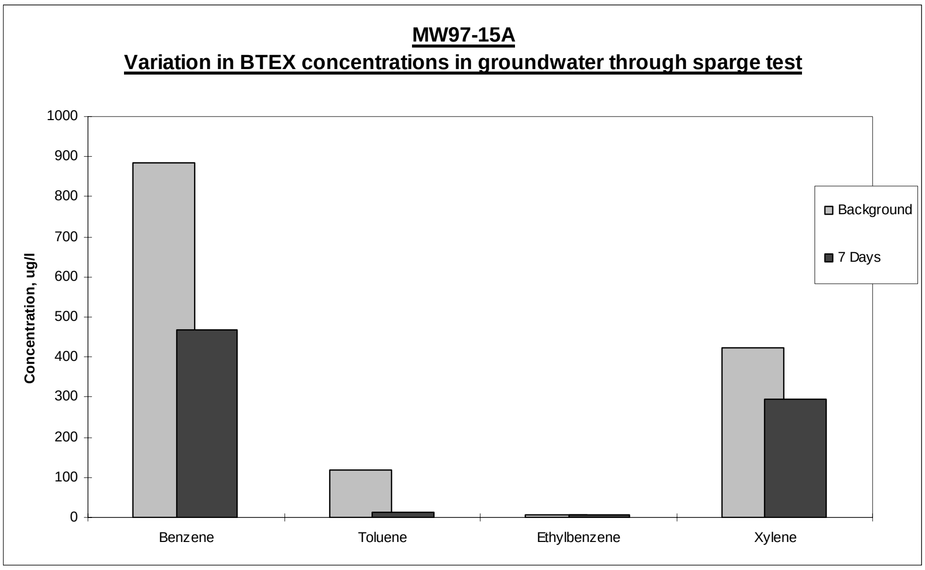
Respiration Testing



MW97-15B
O2 / CO2 Vapour Levels During Pilot Air Sparge Test 1

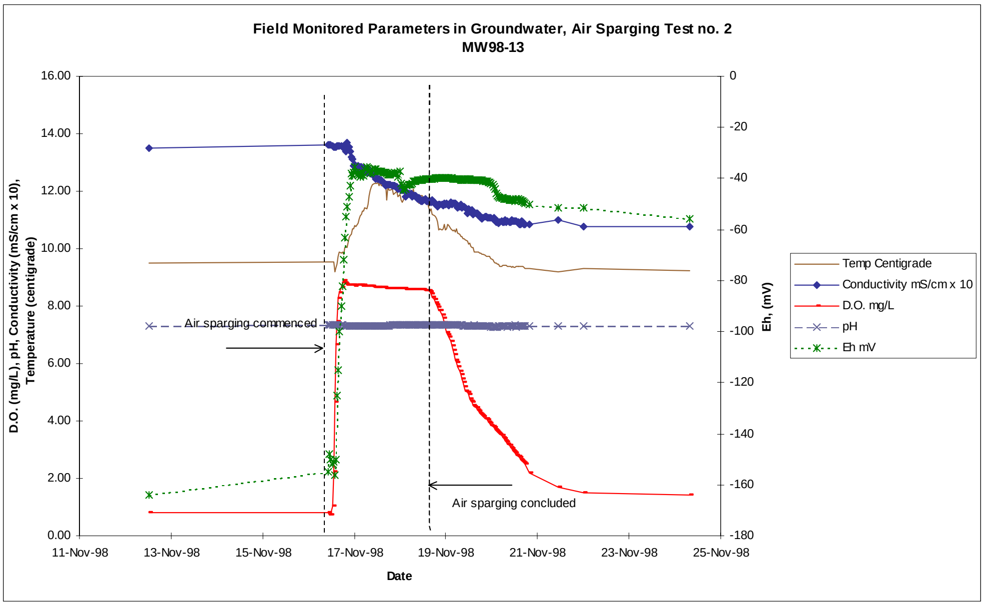


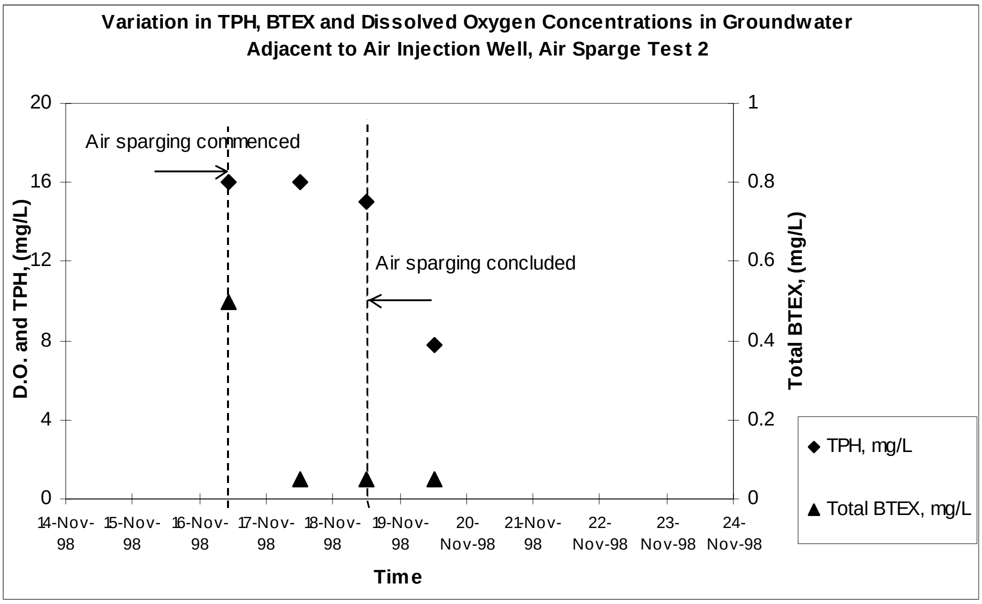
Dissolved Oxygen - Field Measurements,
Pilot Air Sparge Test 1



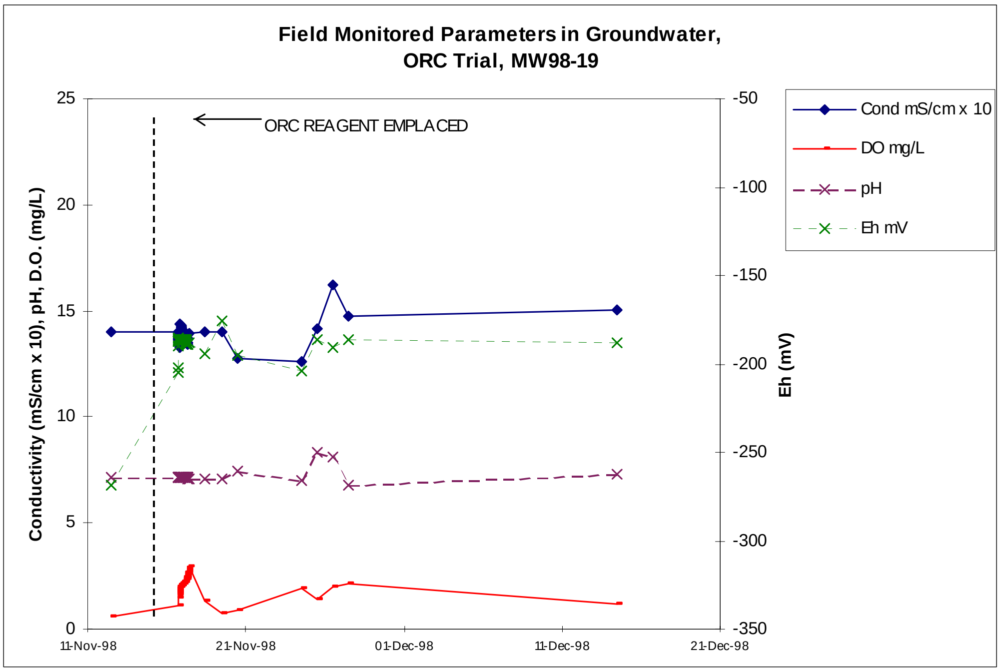
MW97-15A
Variation in BTEX concentrations in groundwater through sparge test

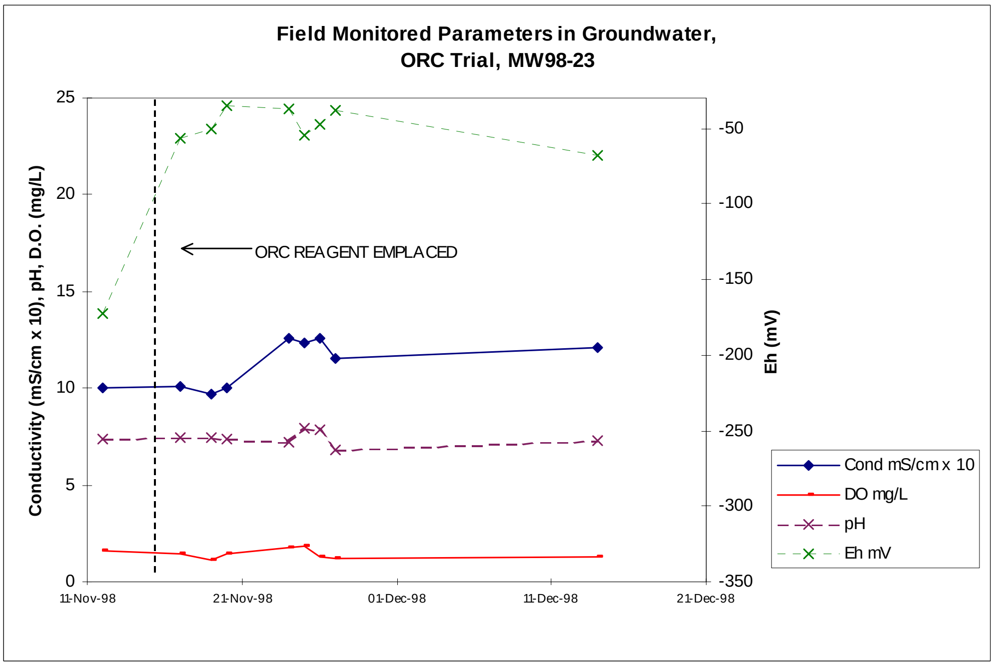
AIR SPARGING TEST 2

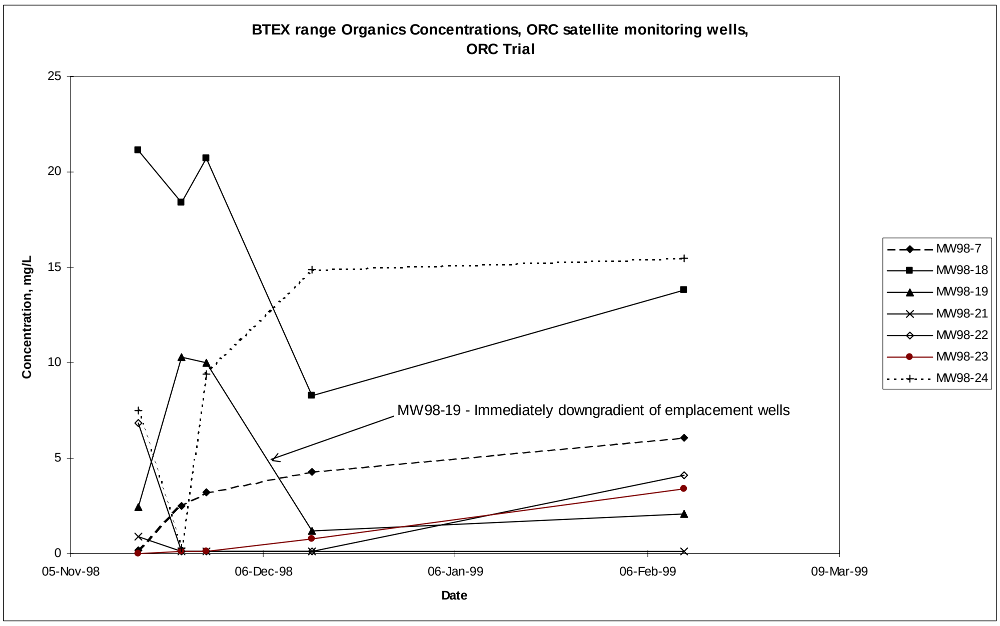


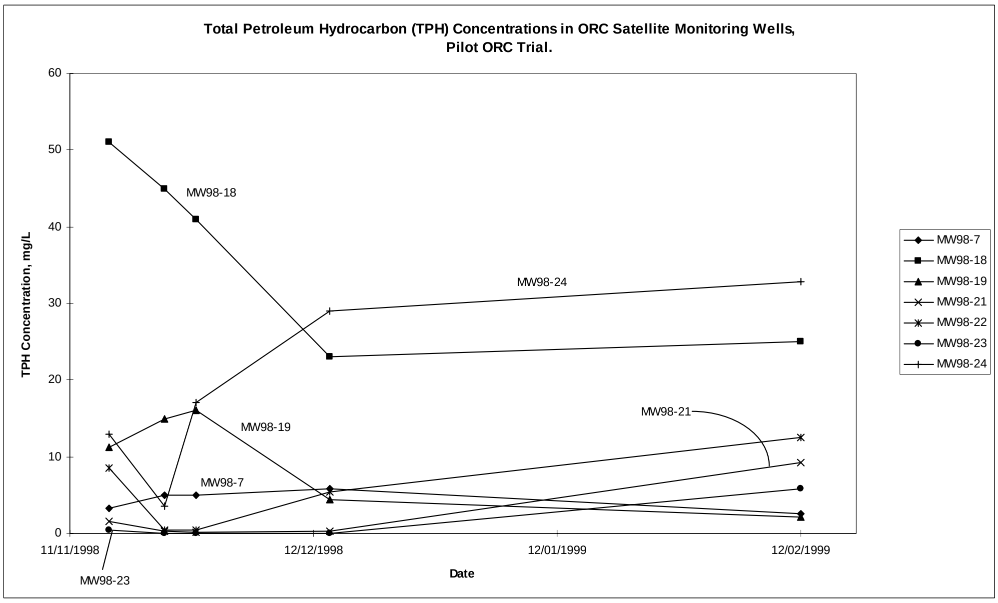


ORC$^{\text{TM}}$ TRIAL






BTEX range Organics Concentrations, ORC satellite monitoring wells, ORC Trial


Total Petroleum Hydrocarbon (TPH) Concentrations in ORC Satellite Monitoring Wells, Pilot ORC Trial.

APPENDIX 4

AIR SPARGING PERFORMANCE DATA – GROUNDWATER AND RESPIRATION TEST RESULTS

Groundwater Analysis Results

Sample I.D. **Screen depth and description**		**MW 98-4** shallow screen, northern plume, downgradient of sparge system										
	Units	13-Jul-99	01-Sep-99	15-Sep-99	05-Nov-99	07-Jan-00	22-Jun-00	29-Nov-00	10-May-01	11-Oct-01	29-Jan-03	27-May-03
Total Dissolved Solids	mg/L	1150	1120	na	na	na	na	na	na	na	na	na
Bicarbonate Alkalinity as CaCO3	mg/L	319	330	319	273	274	262	273	233	155	282	261
Carbonate Alkalinity as CaCO3	mg/L	0	0	0	0	0	0	0	0	0	0	0
pH units	mg/L	7.2	6.8	7.1	6.9	7.0	7.1	7.6	7.4	6.7	7.0	6.8
Conductivity uS/cm @ 25C	mg/L	2440	1910	2060	2000	2660	1750	1420	1220	1190	697	1090
Total Alkalinity as CaCO3	mg/L	319	330	319	273	274	262	273	233	155	282	261
Chloride as Cl	mg/L	505	403	400	298	385	259	186	176	91	107	135
Total Sulphur as SO4 (Total)	mg/L	87.4	82.3	188	211	493	226	132	138	299	64.0	103
Calcium as Ca (Total)	mg/L	97.1	na	112	100	126	80.1	53.1	62.7	126	63.7	64.4
Magnesium as Mg (Total)	mg/L	58.4	na	23.6	24.5	59.9	25.6	16.9	20.7	17.2	22.6	21.3
Sodium as Na (Total)	mg/L	231	na	196	172	199	137	127	105	92.1	87.6	99.1
Potassium as K (Total)	mg/L	11.0	na	5.43	5.38	5.84	4.99	6	4.78	3.9	2.65	2.88
Manganese as Mn (Total)	mg/L	1.89	na	1.52	1.29	1.10	0.47	0.22	0.24	0.6	0.31	0.86
Manganese as Mn (Dissolved)	mg/L	0.63	0.81	0.89	0.84	0.74	0.40	0.18	0.19	0.58	0.29	0.37
Iron as Fe (Total)	mg/L	77.2	na	46.0	12.7	31.1	7.94	10.5	19.8	8.29	4.88	26.1
Iron as Fe (Dissolved)	mg/L	3.57	1.26	1.92	2.12	3.52	4.04	0.87	1.80	0.16	0.32	1.81
Nitrate as N	mg/L	2.7	1.9	3.2	1.3	2.2	<0.1	<0.5	0.6	0.8	0.6	<0.5
Nitrite as N	mg/L	na	na	na	na	na	na	<0.1	<0.1	<0.1	<0.1	<0.1
Ammoniacal Nitrogen as N	mg/L	na	na	na	na	na	na	na	na	na	9.8	2.5
Sulphide (Free) as S	mg/L	2.8	9.2	4.8	0.2	1.0	0.7	4.2	11.5	<0.2	1.5	0.8
Chemical Oxygen Demand	mg/L	46	67	59	70	66	1.0	18	34	74	20	28
Biochemical Oxygen Demand	mg/L	9.5	8.5	9.0	15	8.0	56	7	8.0	<2.0	3.5	<2.0
Total Organic Carbon	mg/L	14	28	na	na	na	10	na	na	na	na	na
TPH GC	mg/L	1.9	1.9	1.5	2.2	1.7	1.5	1.1	1.53	1.7	0.95	1.7
Benzene	mg/L	1.01	<0.001	0.004	2.392	1.836	0.131	<0.001	<0.001	<0.001	<0.001	<0.001
Toluene	mg/L	<0.050	<0.001	<0.001	0.041	<0.010	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Ethyl Benzene	mg/L	0.057	<0.001	0.048	0.036	<0.010	0.002	0.002	<0.001	<0.001	<0.001	0.008
Xylenes	mg/L	<0.050	<0.001	<0.001	<0.010	<0.010	<0.001	0.002	<0.001	<0.001	<0.002	<0.004
Naphthalene	mg/L	0.02	0.01	<0.01	0.01	0.02	0.01	<0.01	<0.01	0.00061	0.00351	0.00269
Acenaphthylene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00100	0.01080	0.00607
Acenaphthene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.00014	0.00514	0.00176
Fluorene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.00057	0.00301	0.0031
Phenanthrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.00009	0.00256	0.00366
Anthracene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.00007	0.00069	0.00124
Fluoranthene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.00029	0.00161	0.00279
Pyrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.00021	0.00151	0.00303
Cyclopenta-cd-pyrene	mg/L	na	na	na	na	na	na	na	na	<0.00100	<0.00010	<0.00010
Benzo(a)Anthracene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00021	0.00032
Chrysene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00004	0.00011
Benzo-e-pyrene	mg/L	na	na	na	na	na	na	na	na	<0.00005	0.00010	<0.00010
Benzo(b)Fluoranthene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00007	0.00015
Benzo(k)Fluoranthene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00003	0.00009
Benzo(a)Pyrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00009	0.00016
Indeno(123-cd)Pyrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00007	0.00016
Dibenzo(ah)Anthracene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Benzo(ghi)Perylene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.00006	0.00006	0.00001
Anthanthrene	mg/L	na	na	na	na	na	na	na	na	<0.00005	0.00001	0.00003
Phenol	mg/L	0.0362	0.2	0.2	0.1	0.3	0.2	0.3	<0.1	<0.1	<0.1	<0.1
Cresols	mg/L	0.0253	0.2	0.2	0.1	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Dimethylphenols	mg/L	0.0940	0.2	0.2	<0.1	0.2	0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Trimethylphenols	mg/L	0.1440	0.3	0.2	<0.1	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

= co-eluted with benzo(b)fluoranthene

na = not analysed

Groundwater Analysis Results

Sample I.D. Screen depth and description		MW 99-2 intermediate screen, northern plume downgradient of sparge system										
	Units	13-Jul-99	01-Sep-99	15-Sep-99	05-Nov-99	07-Jan-00	22-Jun-00	29-Nov-00	10-May-01	11-Oct-01	29-Jan-03	27-May-03
Total Dissolved Solids	mg/L	170	1110	na	na	na	na	na	na	na	na	na
Bicarbonate Alkalinity as CaCO3	mg/L	342	345	338	287	267	238	273	196	274	275	256
Carbonate Alkalinity as CaCO3	mg/L	0	0	0	0	0	0	0	0	0	0	0
pH units	mg/L	8.2	8	8.2	8.3	7.9	7.8	8.2	7.8	8	7.7	6.8
Conductivity uS/cm @ 25C	mg/L	2350	1980	2150	2660	2780	1720	1360	1260	1360	944	897
Total Alkalinity as CaCO3	mg/L	342	345	338	287	267	238	273	196	274	275	256
Chloride as Cl	mg/L	483	428	400	393	416	227	180	175	154	106	106
Total Sulphur as SO4 (Total)	mg/L	114	98.9	112	416	576	259	148	171	85.2	74.9	70.9
Calcium as Ca (Total)	mg/L	60.6	na	73	77.2	145	75.0	56.5	63.9	60.4	64.5	71.2
Magnesium as Mg (Total)	mg/L	46.1	na	39.1	56.9	76.0	23.9	19.6	25.7	26.7	25.5	27.8
Sodium as Na (Total)	mg/L	241	na	303	232	214	136	123	97.9	89.3	78.6	69.5
Potassium as K (Total)	mg/L	6.17	na	5.02	5.44	7.10	5.90	6.16	5.41	5.41	2.68	2.62
Manganese as Mn (Total)	mg/L	0.46	na	0.14	0.13	0.23	0.16	0.07	0.02	0.15	0.45	0.63
Manganese as Mn (Dissolved)	mg/L	0.15	0.09	0.12	0.13	0.22	0.10	0.05	0.04	0.15	0.45	0.60
Iron as Fe (Total)	mg/L	36.4	na	6.63	0.27	0.28	5.24	1.47	0.09	0.22	0.18	2.15
Iron as Fe (Dissolved)	mg/L	0.21	0.18	0.29	0.51	0.25	0.23	0.13	0.04	0.17	0.14	0.11
Nitrate as N	mg/L	1.9	2	2	2	3.3	<0.1	0.8	<0.5	<0.5	0.7	<0.5
Nitrite as N	mg/L	na	na	na	na	na	na	<0.1	<0.1	<0.1	<0.1	0.1
Ammoniacal Nitrogen as N	mg/L	na	na	na	na	na	na	na	na	na	8.7	9.2
Sulphide (Free) as S	mg/L	1.6	12	0.9	1.8	1.6	0.8	1.5	3.1	<0.2	3.0	2.1
Chemical Oxygen Demand	mg/L	22	35	35	41	42	1.6	<5	18	47	22	9
Biochemical Oxygen Demand	mg/L	6.5	9	14	14	7.0	37	6.5	5.5	<2.0	2.5	<2.0
Total Organic Carbon	mg/L	8.6	10	na	na	na	5.5	na	na	na	na	na
TPH GC	mg/L	0.6	0.4	0.33	0.4	0.4	0.21	0.2	<0.1	0.17	0.25	<0.1
Benzene	mg/L	0.696	<0.001	<0.001	<0.005	<0.005	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Toluene	mg/L	<0.005	<0.001	<0.001	<0.005	<0.005	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Ethyl Benzene	mg/L	<0.005	<0.001	<0.001	<0.005	<0.005	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Xylenes	mg/L	<0.005	<0.001	<0.001	<0.005	<0.005	<0.001	<0.001	<0.001	<0.001	<0.002	<0.002
Naphthalene	mg/L	0.02	0.01	0.02	0.01	0.02	<0.01	<0.01	<0.01	<0.0005	<0.00006	<0.00006
Acenaphthylene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00100	<0.00010	<0.00010
Acenaphthene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Fluorene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Phenanthrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00001	0.00002
Anthracene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	0.00001
Fluoranthene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	0.00002
Pyrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	0.00001
Cyclopenta-cd-pyrene	mg/L	na	na	na	na	na	na	na	na	<0.00100	<0.00010	<0.00010
Benzo(a)Anthracene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Chrysene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Benzo-e-pyrene	mg/L	na	na	na	na	na	na	na	na	<0.00005	<0.00001	<0.00001
Benzo(b)Fluoranthene	mg/L	<0.01	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Benzo(k)Fluoranthene	mg/L	<0.01	<0.01	<0.01	#	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Benzo(a)Pyrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Indeno(123-cd)Pyrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Dibenzo(ah)Anthracene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Benzo(ghi)Perylene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Anthanthrene	mg/L	na	na	na	na	na	na	na	na	<0.00005	<0.00001	<0.00001
Phenol	mg/L	0.0656	1	0.9	0.3	0.7	0.4	0.6	0.1	0.3	0.1	<0.1
Cresols	mg/L	0.0770	0.3	0.3	<0.1	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Dimethylphenols	mg/L	0.1650	0.5	0.5	0.2	0.4	0.2	0.2	<0.1	0.1	<0.1	<0.1
Trimethylphenols	mg/L	0.0873	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

= co-eluted with benzo(b)fluoranthene

na = not analysed

Groundwater Analysis Results

Sample I.D.		MW 99-1										
Screen depth and description		deep screen, northern plume, downgradient of sparge system										
	Units	13-Jul-99	01-Sep-99	15-Sep-99	5-Nov-99	07-Jan-00	22-Jun-00	29-Nov-00	10-May-01	11-Oct-01	29-Jan-03	27-May-03
Total Dissolved Solids	mg/L	741	4500	na	na	na	na	na	na	na	na	na
Bicarbonate Alkalinity as CaCO3	mg/L	105	540	539	589	564	527	442	476	368	408	360
Carbonate Alkalinity as CaCO3	mg/L	0	0	0	0	0	0	0	0	0	0	0
pH units	mg/L	7.5	7.7	7.7	7.9	7.6	7.7	7.9	7.8	7.6	7.7	7.7
Conductivity uS/cm @ 25C	mg/L	1350	6320	7000	7630	6120	3890	2970	2730	2630	1890	1760
Total Alkalinity as CaCO3	mg/L	105	540	539	589	564	527	442	476	368	408	360
Chloride as Cl	mg/L	330	2090	2160	2240	1530	907	662	605	498	430	263
Total Sulphur as SO4 (Total)	mg/L	33.2	46.1	60.4	41.1	113	78.6	60.7	60.3	49.5	38.3	44.5
Calcium as Ca (Total)	mg/L	50.8	na	238	269	198	99.9	51.7	55.4	44.4	36.2	37.9
Magnesium as Mg (Total)	mg/L	12.8	na	87.6	99.3	69.3	33.0	24.8	26.4	22.4	20.7	23.7
Sodium as Na (Total)	mg/L	156	na	865	895	681	340	269	273	185	123	102
Potassium as K (Total)	mg/L	4.94	na	12.8	15.3	16.6	17.6	13.6	10.8	11.8	6.87	5.85
Manganese as Mn (Total)	mg/L	0.11	na	0.28	0.27	0.17	0.03	0.04	<0.01	0.07	0.06	0.08
Manganese as Mn (Dissolved)	mg/L	0.09	0.3	0.4	0.28	0.16	0.10	0.04	<0.01	0.07	0.06	0.08
Iron as Fe (Total)	mg/L	1.1	na	1.34	1.11	1.67	1.21	0.46	0.60	0.75	0.81	0.93
Iron as Fe (Dissolved)	mg/L	0.76	0.09	0.5	0.98	0.09	0.43	0.04	0.21	0.07	0.37	0.29
Nitrate as N	mg/L	4.8	12	12	10	10	<0.1	0.8	<0.5	5.9	0.7	1.7
Nitrite as N	mg/L	na	na	na	na	na	na	<0.1	<0.1	7.1	<0.1	0.1
Ammoniacal Nitrogen as N	mg/L	na	na	na	na	na	na	na	na	na	93.9	91.6
Sulphide (Free) as S	mg/L	<0.2	<0.2	<0.2	<0.2	<0.2	0.9	<0.2	<0.2	<0.2	0.2	<0.2
Chemical Oxygen Demand	mg/L	6	620	74	85	146	<0.2	112	66	108	39	21
Biochemical Oxygen Demand	mg/L	<2.0	16	17	16	10	85	<2.0	11	<2.0	5.0	4
Total Organic Carbon	mg/L	4.7	10	na	na	na	4.0	na	na	na	na	na
TPH GC	mg/L	0.5	0.4	0.56	0.3	0.4	0.33	<0.1	<0.1	<0.1	0.27	0.21
Benzene	mg/L	0.003	<0.001	<0.001	1.886	0.767	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Toluene	mg/L	<0.001	<0.001	<0.001	<0.010	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Ethyl Benzene	mg/L	<0.001	<0.001	<0.001	<0.010	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Xylenes	mg/L	<0.001	<0.001	<0.001	<0.010	<0.001	<0.001	<0.001	<0.001	<0.001	<0.002	<0.002
Naphthalene	mg/L	0.03	0.03	0.03	0.04	0.03	<0.01	<0.01	<0.01	<0.0005	<0.00006	<0.00006
Acenaphthylene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00100	<0.00010	<0.00010
Acenaphthene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Fluorene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00005	<0.00001
Phenanthrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00001	<0.00001
Anthracene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Fluoranthene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Pyrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Cyclopenta-cd-pyrene	mg/L	na	na	na	na	na	na	na	na	<0.00100	<0.00010	<0.00010
Benzo(a)Anthracene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Chrysene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Benzo-e-pyrene	mg/L	na	na	na	na	na	na	na	na	<0.00005	<0.00001	<0.00001
Benzo(b)Fluoranthene	mg/L	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Benzo(k)Fluoranthene	mg/L	<0.01	<0.01	#	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Benzo(a)Pyrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Indeno(123-cd)Pyrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Dibenzo(ah)Anthracene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Benzo(ghi)Perylene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Anthanthrene	mg/L	na	na	na	na	na	na	na	na	<0.00005	<0.00001	<0.00001
Phenol	mg/L	0.0380	0.2	0.9	0.3	0.9	0.2	<0.1	0.2	0.2	0.2	0.1
Cresols	mg/L	0.0307	0.2	0.3	<0.1	0.3	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Dimethylphenols	mg/L	0.0307	0.3	0.4	0.3	0.4	0.3	<0.1	<0.1	<0.1	0.1	<0.1
Trimethylphenols	mg/L	0.0098	0.2	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

= co-eluted with benzo(b)fluoranthene

na = not analysed

Groundwater Analysis Results

Sample I.D. **Screen depth and description**		**MW 97-15B** shallow screen, southern plume, downgradient of air sparging system										
	Units	13-Jul-99	01-Sep-99	15-Sep-99	05-Nov-99	07-Jan-00	22-Jun-00	29-Nov-00	10-May-01	11-Oct-01	29-Jan-03	27-May-03
Total Dissolved Solids	mg/L	1740	1650	na	na	na	na	na	na	na	na	na
Bicarbonate Alkalinity as CaCO3	mg/L	80	196	190	110	47	71	272	104	0	197	147
Carbonate Alkalinity as CaCO3	mg/L	0	0	0	0	0	0	0	0	0	0	0
pH units	mg/L	6.4	6.1	6.4	6.2	5.4	5.7	6.8	6.2	4.4	6.3	6.2
Conductivity uS/cm @ 25C	mg/L	1970	1850	1920	2430	1780	1200	1110	1060	1700	793	591
Total Alkalinity as CaCO3	mg/L	80	196	190	110	47	71	272	104	0	197	147
Chloride as Cl	mg/L	69	86	94	55	155	47	68	41	23	13	10
Total Sulphur as SO4 (Total)	mg/L	911	884	695	1320	832	543	215	425	1120	257	173
Calcium as Ca (Total)	mg/L	284	na	215	393	269	178	175	180	279	158	101
Magnesium as Mg (Total)	mg/L	17.6	na	22.6	18.7	12.8	11.5	11.1	10.9	16.5	7.49	6.69
Sodium as Na (Total)	mg/L	85.3	na	122	56.9	75.4	60.6	53	47.9	41.8	21.7	16.6
Potassium as K (Total)	mg/L	9.16	na	8.86	12.9	6.17	5.50	7.59	5.15	7.83	3.24	3.77
Manganese as Mn (Total)	mg/L	0.92	na	1.77	2.66	1.21	0.97	<0.01	0.18	0.93	0.27	0.14
Manganese as Mn (Dissolved)	mg/L	1.01	1.58	1.46	2.51	1.17	0.50	<0.01	0.25	0.95	0.28	0.16
Iron as Fe (Total)	mg/L	97.7	na	68.5	129	77.4	185	1.62	40.7	72.2	18.1	20.8
Iron as Fe (Dissolved)	mg/L	95.5	105	51.4	126	76.4	30.1	0.03	37.7	72.3	16.0	19.1
Nitrate as N	mg/L	<1.0	<1.0	<1.0	<1.0	<1.0	<0.1	5.5	<0.5	<0.5	<0.5	<0.5
Nitrite as N	mg/L	na	na	na	na	na	na	0.3	<0.1	<0.1	<0.1	<0.1
Ammoniacal Nitrogen as N	mg/L	na	na	na	na	na	na	na	na	na	0.8	1.4
Sulphide (Free) as S	mg/L	<0.2	1.2	<0.2	0.6	0.2	0.5	<0.2	0.4	<0.2	0.3	0.3
Chemical Oxygen Demand	mg/L	200	125	180	180	136	0.4	19	100	144	98	113
Biochemical Oxygen Demand	mg/L	40	47	49	90	18	120	<2.0	22	10	7.5	9.0
Total Organic Carbon	mg/L	3.5	52	na	na	na	1	na	na	na	na	na
TPH GC	mg/L	44	28.4	32	22	9.4	13.7	0.93	18.0	7.0	12.1	15.0
Benzene	mg/L	1.326	1.344	2.074	2.176	1.047	0.231	<0.001	0.072	0.013	0.061	0.101
Toluene	mg/L	0.834	0.146	0.1	0.188	0.085	0.046	<0.001	0.043	0.017	0.112	0.055
Ethyl Benzene	mg/L	1.994	0.267	<0.005	0.219	0.199	0.041	<0.001	0.022	0.029	0.036	0.119
Xylenes	mg/L	1.096	1.82	0.841	0.591	0.364	0.173	0.006	0.233	0.037	0.284	0.415
Naphthalene	mg/L	6.7	8.8	6.9	2.9	1.9	2.61	<0.01	2.3	1.57	1.4	2.1
Acenaphthylene	mg/L	0.7	1.1	0.52	0.21	0.11	0.15	<0.01	0.40	0.914	0.881	1.04
Acenaphthene	mg/L	0.16	0.48	0.21	0.19	0.1	0.17	0.02	0.25	0.178	0.44	0.567
Fluorene	mg/L	0.29	0.57	0.18	0.15	0.07	0.10	<0.01	0.20	0.159	0.139	0.133
Phenanthrene	mg/L	0.75	1.6	0.4	0.28	0.07	0.11	<0.01	0.35	0.110	0.177	0.124
Anthracene	mg/L	0.22	0.47	0.1	0.08	<0.04	0.03	<0.01	0.10	0.0205	0.0668	0.0452
Fluoranthene	mg/L	0.21	0.47	0.09	0.06	<0.04	0.02	<0.01	0.10	0.0198	0.0749	0.085
Pyrene	mg/L	0.34	0.74	0.16	0.11	<0.04	0.03	<0.01	0.20	0.0377	0.228	0.137
Cyclopenta-cd-pyrene	mg/L	na	na	na	na	na	na	na	na	0.00423	<0.00500	0.0299
Benzo(a)Anthracene	mg/L	0.08	0.17	0.03	0.02	<0.04	<0.01	<0.01	<0.05	0.00253	0.0325	0.0124
Chrysene	mg/L	0.08	0.18	0.04	0.02	<0.04	<0.01	<0.01	<0.05	0.00094	0.0188	0.00813
Benzo-e-pyrene	mg/L	na	na	na	na	na	na	na	na	0.00022	0.0129	0.0108
Benzo(b)Fluoranthene	mg/L	0.04	#	0.01	0.01	<0.04	<0.01	<0.01	<0.05	0.00026	0.00471	0.00173
Benzo(k)Fluoranthene	mg/L	0.06	<0.2	0.03	0.06	<0.04	<0.01	<0.01	<0.05	0.00017	0.0037	0.00183
Benzo(a)Pyrene	mg/L	0.09	0.18	0.04	0.03	<0.04	<0.01	<0.01	<0.05	0.00065	0.0153	0.00861
Indeno(123-cd)Pyrene	mg/L	0.04	<0.1	0.01	<0.01	<0.04	<0.01	<0.01	<0.05	<0.00005	0.0043	0.0029
Dibenzo(ah)Anthracene	mg/L	0.01	<0.1	<0.01	<0.01	<0.04	<0.01	<0.01	<0.05	0.00009	0.00118	<0.0006
Benzo(ghi)Perylene	mg/L	0.05	<0.1	0.02	<0.01	<0.04	<0.01	<0.01	<0.05	0.00008	0.00705	0.00344
Anthanthrene	mg/L	na	na	na	na	na	na	na	na	<0.00005	0.00282	0.00166
Phenol	mg/L	0.1130	0.5	0.5	0.2	0.2	<0.1	<0.1	<0.1	0.1	<0.1	0.2
Cresols	mg/L	0.1910	0.7	0.5	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Dimethylphenols	mg/L	0.7700	2.7	2.2	0.5	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Trimethylphenols	mg/L	0.1420	1.1	0.9	0.4	0.3	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

= co-eluted with benzo(b)fluoranthene

na = not analysed

Groundwater Analysis Results

Sample I.D. **Screen depth and description**		**MW 99-6** deep screen, southern plume, downgradient of air sparging system										
	Units	13-Jul-99	01-Sep-99	15-Sep-99	05-Nov-99	07-Jan-00	22-Jun-00	29-Nov-00	10-May-01	11-Oct-01	29-Jan-03	27-May-03
Total Dissolved Solids	mg/L	457	1500	na	na	na	na	na	na	na	na	na
Bicarbonate Alkalinity as CaCO3	mg/L	104	282	280	261	257	285	359	336	355	364	337
Carbonate Alkalinity as CaCO3	mg/L	0	0	0	0	0	0	0	0	0	0	0
pH units	mg/L	7.5	8.3	8.2	8.4	7.8	7.8	7.8	7.5	7.7	7.4	7.4
Conductivity uS/cm @ 25C	mg/L	835	2520	2800	2950	2700	2460	1870	1720	1460	753	1400
Total Alkalinity as CaCO3	mg/L	104	282	280	261	257	285	359	336	355	364	337
Chloride as Cl	mg/L	152	543	541	600	564	475	306	309	182	167	218
Total Sulphur as SO4 (Total)	mg/L	74.9	274	306	258	213	212	203	116	98.7	35.0	42.7
Calcium as Ca (Total)	mg/L	34.9	na	37.0	30.8	26.0	44.4	57.5	60.4	75.2	82.2	75.7
Magnesium as Mg (Total)	mg/L	6.09	na	11.6	17.2	14.8	21.5	28	26.6	33.7	28.7	26.7
Sodium as Na (Total)	mg/L	114	na	492	541	514	420	307	290	143	94.9	126
Potassium as K (Total)	mg/L	3.98	na	9.97	12.3	11.6	8.74	10.2	10.1	12.7	14.0	13.1
Manganese as Mn (Total)	mg/L	0.12	na	0.09	0.05	0.04	0.11	0.26	0.26	0.44	0.76	0.70
Manganese as Mn (Dissolved)	mg/L	0.11	0.03	0.04	0.05	0.04	0.09	0.26	0.30	0.44	0.72	0.65
Iron as Fe (Total)	mg/L	3.38	na	2.31	0.14	0.15	0.33	0.32	2.98	0.96	2.93	14.5
Iron as Fe (Dissolved)	mg/L	0.12	0.13	0.06	0.15	0.09	0.07	<0.01	<0.01	0.2	0.14	0.04
Nitrate as N	mg/L	<1.0	3.0	3.9	3.2	3.3	<0.1	<0.5	0.8	<0.5	<0.5	0.6
Nitrite as N	mg/L	na	na	na	na	na	na	0.1	<0.1	<0.1	<0.1	<0.1
Ammoniacal Nitrogen as N	mg/L	na	na	na	na	na	na	na	na	na	16.6	23.8
Sulphide (Free) as S	mg/L	<0.2	<0.2	<0.2	<0.2	<0.2	0.9	<0.2	<0.2	<0.2	<0.2	<0.2
Chemical Oxygen Demand	mg/L	12	36	6	25	34	<0.2	5	9	17	22	13
Biochemical Oxygen Demand	mg/L	2.5	3.5	14	13	4.0	33	2.5	2.0	<2.0	<2.0	<2.0
Total Organic Carbon	mg/L	6.4	7.1	na	na	na	3.5	na	na	na	na	na
TPH GC	mg/L	0.7	0.9	1.4	2.7	2.0	1.9	0.71	<0.1	1.4	0.53	1.0
Benzene	mg/L	<0.001	<0.001	<0.001	<0.005	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Toluene	mg/L	<0.001	<0.001	<0.001	<0.005	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Ethyl Benzene	mg/L	<0.001	<0.001	<0.001	<0.005	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Xylenes	mg/L	<0.001	<0.001	<0.001	<0.005	<0.001	<0.001	<0.001	<0.001	<0.001	<0.002	<0.002
Naphthalene	mg/L	0.05	<0.02	<0.01	0.02	<0.01	<0.01	<0.01	<0.01	0.0100	0.00828	0.00394
Acenaphthylene	mg/L	0.03	<0.02	0.1	0.15	0.11	0.09	0.05	<0.01	0.134	0.01690	0.05010
Acenaphthene	mg/L	<0.01	<0.02	<0.01	0.01	0.02	0.01	<0.01	<0.01	0.296	0.01230	0.04070
Fluorene	mg/L	<0.01	<0.02	0.03	0.05	0.04	0.04	0.01	<0.01	0.113	0.00071	0.04890
Phenanthrene	mg/L	<0.01	<0.02	<0.01	0.03	<0.01	0.03	<0.01	<0.01	0.0304	<0.00001	0.02210
Anthracene	mg/L	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.0111	0.00023	0.01320
Fluoranthene	mg/L	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.00921	0.00169	0.01120
Pyrene	mg/L	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.0155	0.00280	0.01660
Cyclopenta-cd-pyrene	mg/L	na	na	na	na	na	na	na	na	<0.00100	<0.00010	<0.00100
Benzo(a)Anthracene	mg/L	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00048	0.00020
Chrysene	mg/L	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00004	0.00008
Benzo-e-pyrene	mg/L	na	na	na	na	na	na	na	na	<0.00005	0.00008	<0.00006
Benzo(b)Fluoranthene	mg/L	<0.01	<0.02	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00003	<0.00006
Benzo(k)Fluoranthene	mg/L	<0.01	<0.02	<0.01	#	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00002	<0.00006
Benzo(a)Pyrene	mg/L	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00008	<0.00006
Indeno(123-cd)Pyrene	mg/L	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00006	<0.00006
Dibenzo(ah)Anthracene	mg/L	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00006
Benzo(ghi)Perylene	mg/L	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00006	<0.00006
Anthanthrene	mg/L	na	na	na	na	na	na	na	na	<0.00005	0.00001	<0.00006
Phenol	mg/L	0.0166	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Cresols	mg/L	0.0227	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Dimethylphenols	mg/L	0.0044	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Trimethylphenols	mg/L	0.0028	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

= co-eluted with benzo(b)fluoranthene

na = not analysed

Groundwater Analysis Results

Sample I.D. Screen depth and description		MW 99-7 intermediate screen, southern plume, downgradient of air sparging system										
	Units	13-Jul-99	01-Sep-99	15-Sep-99	05-Nov-99	07-Jan-00	22-Jun-00	29-Nov-00	10-May-01	11-Oct-01	29-Jan-03	27-May-03
Total Dissolved Solids	mg/L	559	983	na	na	na	na	na	na	na	na	na
Bicarbonate Alkalinity as CaCO3	mg/L	138	228	228	226	194	320	345	342	299	364	388
Carbonate Alkalinity as CaCO3	mg/L	0	0	0	0	0	0	0	0	0	0	0
pH units	mg/L	7.3	6.8	7.1	7.3	6.6	7.6	7.2	7.6	7.4	7.2	7.1
Conductivity uS/cm @ 25C	mg/L	954	1510	1670	1790	1740	1490	1420	1260	1280	1080	1080
Total Alkalinity as CaCO3	mg/L	138	228	228	226	194	320	345	342	299	364	388
Chloride as Cl	mg/L	154	303	302	230	196	223	160	158	132	137	109
Total Sulphur as SO4 (Total)	mg/L	104	149	168	292	392	155	209	84.4	114	38.0	22.8
Calcium as Ca (Total)	mg/L	54.2	na	74.8	118	148	99.7	142	99.4	104	107	105
Magnesium as Mg (Total)	mg/L	11.6	na	20.8	32.6	27.0	26.5	38.6	29.8	29	19.8	18.5
Sodium as Na (Total)	mg/L	111	na	286	192	146	175	95.7	108	98.1	82.2	68.4
Potassium as K (Total)	mg/L	5.64	na	9.13	10.0	11.9	9.06	15.1	16.6	16.2	10.3	8.76
Manganese as Mn (Total)	mg/L	0.77	na	2.14	4.13	2.79	1.67	1.79	1.12	1.14	1.30	1.26
Manganese as Mn (Dissolved)	mg/L	0.70	1.98	1.93	3.06	2.61	1.66	1.73	1.19	1.15	1.31	1.26
Iron as Fe (Total)	mg/L	5.00	na	5.93	16.7	26.6	1.62	9.35	4.61	0.32	4.11	5.10
Iron as Fe (Dissolved)	mg/L	0.66	2.54	3.77	0.15	12.8	0.02	0.32	<0.01	0.04	0.26	0.06
Nitrate as N	mg/L	<1.0	1.2	1.4	<1.0	<1.0	<0.1	<0.5	<0.5	9	<0.5	<0.5
Nitrite as N	mg/L	na	na	na	na	na	na	<0.1	<0.1	0.9	<0.1	0.1
Ammoniacal Nitrogen as N	mg/L	na	na	na	na	na	na	na	na	na	12.0	13.6
Sulphide (Free) as S	mg/L	0.4	2.4	<0.2	<0.2	<0.2	0.8	<0.2	<0.2	<0.2	<0.2	<0.2
Chemical Oxygen Demand	mg/L	11	13	8	25	54	<0.2	<5	19	9	15	13
Biochemical Oxygen Demand	mg/L	<2.0	1	18	8.5	9.0	29	3	3.0	<2.0	<2.0	<2.0
Total Organic Carbon	mg/L	6.1	5.1	na	na	na	3.5	na	na	na	na	na
TPH GC	mg/L	1.0	3.2	2.6	2.0	3.2	0.15	1	<0.1	<0.1	0.29	<0.1
Benzene	mg/L	<0.001	<0.001	<0.001	<0.005	0.645	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Toluene	mg/L	<0.001	<0.001	<0.001	0.01	0.029	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Ethyl Benzene	mg/L	<0.001	<0.001	<0.001	<0.005	0.128	<0.001	<0.001	<0.001	<0.001	<0.001	0.001
Xylenes	mg/L	<0.001	<0.001	<0.001	<0.005	0.203	<0.001	<0.001	<0.001	<0.001	<0.002	<0.004
Naphthalene	mg/L	0.09	<0.02	0.59	0.01	0.56	<0.01	0.14	<0.01	0.0144	0.00389	0.00242
Acenaphthylene	mg/L	0.02	<0.02	0.04	<0.01	0.01	<0.01	<0.01	<0.01	0.00368	0.00809	0.00514
Acenaphthene	mg/L	<0.01	0.02	0.04	0.01	0.05	<0.01	0.01	<0.01	0.00978	0.00561	0.00448
Fluorene	mg/L	0.01	<0.02	0.02	<0.01	0.02	<0.01	<0.01	<0.01	0.00179	0.00145	0.00167
Phenanthrene	mg/L	<0.01	<0.02	0.02	<0.01	0.02	<0.01	<0.01	<0.01	0.00097	0.00093	0.00118
Anthracene	mg/L	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.00044	0.00022	0.00037
Fluoranthene	mg/L	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.00038	0.00014	0.00019
Pyrene	mg/L	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.00060	0.00020	0.00088
Cyclopenta-cd-pyrene	mg/L	na	na	na	na	na	na	na	na	<0.00100	<0.00010	0.00013
Benzo(a)Anthracene	mg/L	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.00023	0.00010	0.00010
Chrysene	mg/L	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00003	0.00007
Benzo-e-pyrene	mg/L	na	na	na	na	na	na	na	na	<0.00005	0.00003	0.00007
Benzo(b)Fluoranthene	mg/L	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00001	0.00001
Benzo(k)Fluoranthene	mg/L	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	0.00001
Benzo(a)Pyrene	mg/L	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00003	0.00003
Indeno(123-cd)Pyrene	mg/L	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00006
Dibenzo(ah)Anthracene	mg/L	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00006
Benzo(ghi)Perylene	mg/L	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00006
Anthanthrene	mg/L	na	na	na	na	na	na	na	na	<0.00005	<0.00001	<0.00006
Phenol	mg/L	0.0157	<0.1	<0.1	<0.1	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Cresols	mg/L	0.0174	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Dimethylphenols	mg/L	0.0210	<0.1	0.1	<0.1	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Trimethylphenols	mg/L	0.0239	<0.1	<0.1	<0.1	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

= co-eluted with benzo(b)fluoranthene

na = not analysed

Groundwater Analysis Results

Sample I.D. **Screen depth and description**		**SW 99-2** northern plume, within zone of air sparging										
	Units	13-Jul-99	01-Sep-99	15-Sep-99	05-Nov-99	07-Jan-00	22-Jun-00	29-Nov-00	10-May-01	11-Oct-01	29-Jan-03	27-May-03
Total Dissolved Solids	mg/L	582	959	na	na	na	na	na	na	na	na	na
Bicarbonate Alkalinity as CaCO3	mg/L	323	171	77	36	8	5	0	9	25	33	53
Carbonate Alkalinity as CaCO3	mg/L	0	0	0	0	0	0	0	0	0	0	0
pH units	mg/L	8.2	7.1	6.9	6.7	5.6	4.4	6.1	4.5	7.2	6.8	6.9
Conductivity uS/cm @ 25C	mg/L	1250	1460	2410	3620	3380	2470	1530	1790	2040	1470	1350
Total Alkalinity as CaCO3	mg/L	323	171	77	36	8	5	0	9	25	33	53
Chloride as Cl	mg/L	157	195	158	168	134	117	105	107	104	90	90
Total Sulphur as SO4 (Total)	mg/L	134	376	921	1970	1970	1420	593	1060	1180	625	490
Calcium as Ca (Total)	mg/L	449	na	286	506	481	489	225	358	379	237	189
Magnesium as Mg (Total)	mg/L	313	na	37.1	74.5	91.9	57.0	30.3	46.4	61	41.3	31.7
Sodium as Na (Total)	mg/L	43	na	61.4	94.6	104	76.1	73.5	62.5	69.5	62.4	55.0
Potassium as K (Total)	mg/L	23.4	na	6.33	11.3	11.0	7.60	5.99	3.60	4.63	6.79	3.90
Manganese as Mn (Total)	mg/L	15.6	na	6.29	7.16	9.47	5.24	3.8	3.06	2.11	1.85	1.72
Manganese as Mn (Dissolved)	mg/L	0.42	1.18	3.58	6.18	9.40	5.17	1.73	3.31	1.79	0.20	2.01
Iron as Fe (Total)	mg/L	500	na	1.78	96.6	59.4	1.22	52.4	<0.01	13	3.36	0.54
Iron as Fe (Dissolved)	mg/L	0.18	2.31	0.23	0.38	1.45	0.16	<0.01	<0.01	0.01	0.07	0.04
Nitrate as N	mg/L	<1.0	<1.0	<1.0	<1.0	11	<0.1	23	7.5	4.9	16.0	10.5
Nitrite as N	mg/L	na	na	na	na	na	na	0.4	0.3	<0.1	0.9	<0.1
Ammoniacal Nitrogen as N	mg/L	na	na	na	na	na	na	na	na	na	0.3	0.2
Sulphide (Free) as S	mg/L	2.6	20	1.8	0.6	0.6	27.1	<0.2	<0.2	<0.2	<0.2	<0.2
Chemical Oxygen Demand	mg/L	37	14	26	22	24	<0.2	<5	9	<5	5	8
Biochemical Oxygen Demand	mg/L	4.5	<2.0	3	2	<2.0	62	<2.0	<2.0	<2.0	3.0	<2.0
Total Organic Carbon	mg/L	12	12	na	na	na	<2.0	na	na	na	na	na
TPH GC	mg/L	2.8	0.3	0.5	<0.1	0.12	<0.1	<0.1	<0.1	<0.1	<0.13	<0.1
Benzene	mg/L	1.708	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Toluene	mg/L	<0.020	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Ethyl Benzene	mg/L	0.12	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Xylenes	mg/L	0.301	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.002	<0.002
Naphthalene	mg/L	0.28	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.0005	0.0002	<0.00006
Acenaphthylene	mg/L	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00100	<0.00010	<0.00010
Acenaphthene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Fluorene	mg/L	0.03	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Phenanthrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00001	<0.00001
Anthracene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Fluoranthene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Pyrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Cyclopenta-cd-pyrene	mg/L	na	na	na	na	na	na	na	na	<0.00100	<0.00010	<0.00010
Benzo(a)Anthracene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00001	<0.00001
Chrysene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Benzo-e-pyrene	mg/L	na	na	na	na	na	na	na	na	<0.00005	<0.00001	<0.00001
Benzo(b)Fluoranthene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Benzo(k)Fluoranthene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Benzo(a)Pyrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Indeno(123-cd)Pyrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Dibenzo(ah)Anthracene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Benzo(ghi)Perylene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Anthanthrene	mg/L	na	na	na	na	na	na	na	na	<0.00005	<0.00001	<0.00001
Phenol	mg/L	0.0601	<0.01	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Cresols	mg/L	0.0295	<0.01	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Dimethylphenols	mg/L	0.1301	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Trimethylphenols	mg/L	0.3660	0.4	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

\# = co-eluted with benzo(b)fluoranthene

na = not analysed

Groundwater Analysis Results

Sample I.D. **Screen depth and description**		**SW 99-3** northern plume, within zone of air sparging										
	Units	13-Jul-99	01-Sep-99	15-Sep-99	05-Nov-99	07-Jan-00	22-Jun-00	29-Nov-00	10-May-01	11-Oct-01	29-Jan-03	27-May-03
Total Dissolved Solids	mg/L	760	1180	na	na	na	na	na	na	na	na	na
Bicarbonate Alkalinity as CaCO3	mg/L	348	74	87	5	<2	<2	0	2	0	2	23
Carbonate Alkalinity as CaCO3	mg/L	0	0	0	0	0	0	0	0	0	0	0
pH units	mg/L	8.3	7.1	7.4	6.0	4.5	4.5	4.6	3.6	3.5	4.8	5.8
Conductivity uS/cm @ 25C	mg/L	1610	1910	2530	4030	4090	2280	2160	1750	1810	1020	1030
Total Alkalinity as CaCO3	mg/L	348	74	87	5	<2	<2	0	<2	0	<2	23
Chloride as Cl	mg/L	114	186	198	212	226	187	147	121	124	120	115
Total Sulphur as SO4 (Total)	mg/L	266	628	983	2080	2250	1010	1080	939	739	309	322
Calcium as Ca (Total)	mg/L	321	na	193	449	509	271	348	289	184	83.2	92.9
Magnesium as Mg (Total)	mg/L	277	na	30.5	77.4	71.9	39.6	57.9	51.2	31.7	24.7	25.8
Sodium as Na (Total)	mg/L	183	na	156	182	182	137	107	83.4	75.5	81.6	77.6
Potassium as K (Total)	mg/L	24.6	na	7.55	10.0	9.97	6.25	86	5.51	3.87	2.81	2.84
Manganese as Mn (Total)	mg/L	12.3	na	0.71	5.29	6.10	5.08	6.67	3.86	3.15	0.63	1.21
Manganese as Mn (Dissolved)	mg/L	0.15	0.40	0.60	5.16	5.94	4.96	6.15	3.92	3.16	0.68	1.25
Iron as Fe (Total)	mg/L	512	na	9.87	0.99	8.70	7.72	254	34.8	2.8	0.59	9.20
Iron as Fe (Dissolved)	mg/L	0.38	0.03	0.10	0.26	0.19	0.05	0.09	<0.01	2.26	0.23	2.51
Nitrate as N	mg/L	<1	<1	<1	2.0	11	<0.1	31.6	7.6	1.8	6.6	2.2
Nitrite as N	mg/L	na	na	na	na	na	na	<0.1	<0.1	<0.1	<0.1	<0.1
Ammoniacal Nitrogen as N	mg/L	na	na	na	na	na	na	na	na	na	2.5	1.0
Sulphide (Free) as S	mg/L	4.0	2.8	<0.2	<0.2	<0.2	24.0	2.6	<0.2	<0.2	4.5	<0.2
Chemical Oxygen Demand	mg/L	26	29	13	35	30	<0.2	<5	<5	6	<5	<5
Biochemical Oxygen Demand	mg/L	12	<2.0	<2.0	2.0	<2.0	19	<2.0	<2.0	<2.0	2.0	<2.0
Total Organic Carbon	mg/L	9.7	7.0	na	na	na	<2.0	na	na	na	na	na
TPH GC	mg/L	1.1	0.9	0.17	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Benzene	mg/L	6.189	<0.001	<0.001	0.005	0.011	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Toluene	mg/L	0.011	<0.001	<0.001	0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Ethyl Benzene	mg/L	0.037	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Xylenes	mg/L	0.32	<0.001	<0.001	0.002	0.003	<0.001	<0.001	<0.001	<0.001	<0.002	<0.002
Naphthalene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.0005	<0.00006	<0.00006
Acenaphthylene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00100	<0.00010	<0.00010
Acenaphthene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Fluorene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Phenanthrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00001	<0.00001
Anthracene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Fluoranthene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Pyrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Cyclopenta-cd-pyrene	mg/L	na	na	na	na	na	na	na	na	<0.00100	<0.00010	<0.00010
Benzo(a)Anthracene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Chrysene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Benzo-e-pyrene	mg/L	na	na	na	na	na	na	na	na	<0.00005	<0.00001	<0.00001
Benzo(b)Fluoranthene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Benzo(k)Fluoranthene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Benzo(a)Pyrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Indeno(123-cd)Pyrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Dibenzo(ah)Anthracene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Benzo(ghi)Perylene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Anthanthrene	mg/L	na	na	na	na	na	na	na	na	<0.00005	<0.00001	<0.00001
Phenol	mg/L	0.0484	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Cresols	mg/L	0.0017	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Dimethylphenols	mg/L	0.3	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Trimethylphenols	mg/L	0.1580	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

= co-eluted with benzo(b)fluoranthene

na = not analysed

Groundwater Analysis Results

Sample I.D. Screen depth and description	Units	SW 99-4 northern plume, within zone of air sparging										
		13-Jul-99	01-Sep-99	15-Sep-99	05-Nov-99	07-Jan-00	22-Jun-00	29-Nov-00	10-May-01	11-Oct-01	29-Jan-03	27-May-03
Total Dissolved Solids	mg/L	411	902	na	na	na	na	na	na	na	na	na
Bicarbonate Alkalinity as CaCO3	mg/L	269	82	121	32	3	0	0	0	66	2	50
Carbonate Alkalinity as CaCO3	mg/L	0	0	0	0	0	0	0	0	0	0	0
pH units	mg/L	8.2	6.9	7.2	6.8	4.6	3.6	3.9	4.1	7.2	4.8	6.0
Conductivity uS/cm @ 25C	mg/L	1120	1670	2440	5280	4940	2260	1500	1430	1350	933	902
Total Alkalinity as CaCO3	mg/L	269	82	121	32	3	0	0	0	66	<2	50
Chloride as Cl	mg/L	121	144	196	282	268	214	188	173	153	109	119
Total Sulphur as SO4 (Total)	mg/L	107	498	854	2750	2800	949	474	509	306	245	217
Calcium as Ca (Total)	mg/L	35.6	na	144	527	646	250	128	140	98.8	66.9	65.8
Magnesium as Mg (Total)	mg/L	14.4	na	32.3	174	222	41.4	28.2	37.7	29	20.4	21.6
Sodium as Na (Total)	mg/L	83.4	na	148	127	103	144	112	101	106	81.5	79.8
Potassium as K (Total)	mg/L	4.62	na	7.07	10.5	10.4	4.57	3.85	3.40	4.88	6.48	5.83
Manganese as Mn (Total)	mg/L	0.32	na	1.52	6.23	13.4	3.63	1.99	1.94	0.78	0.39	0.41
Manganese as Mn (Dissolved)	mg/L	0.07	0.38	1.49	6.72	13.2	3.72	1.98	2.17	0.78	0.39	0.41
Iron as Fe (Total)	mg/L	12.6	na	9.67	0.88	10.3	13.9	12.3	11.1	0.27	0.16	18.4
Iron as Fe (Dissolved)	mg/L	0.11	0.10	0.08	0.20	0.35	0.62	1.09	0.46	0.01	0.09	0.09
Nitrate as N	mg/L	<1.0	<1.0	<1.0	2.7	11	3.3	7.2	7.5	14.1	9.0	0.7
Nitrite as N	mg/L	na	na	na	na	na	na	2.3	<0.1	0.4	<0.1	<0.1
Ammoniacal Nitrogen as N	mg/L	na	na	na	na	na	na	na	na	na	3.1	2.2
Sulphide (Free) as S	mg/L	1.8	0.8	<0.2	<0.2	<0.2	10.1	<0.2	<0.2	<0.2	<0.2	<0.2
Chemical Oxygen Demand	mg/L	16	19	<5	14	45	<0.2	<5	<5	15	5	11
Biochemical Oxygen Demand	mg/L	15	<2.0	2.5	6.5	<2.0	24	<2.0	<2.0	<2.0	<2.0	<2.0
Total Organic Carbon	mg/L	6.3	7.2	na	na	na	3.0	na	na	na	na	na
TPH GC	mg/L	0.4	0.2	0.13	<0.1	<0.1	0.23	<0.1	<0.1	<0.1	<0.1	<0.1
Benzene	mg/L	3.059	<0.001	0.001	0.002	0.053	0.077	0.03	<0.001	<0.001	<0.001	<0.001
Toluene	mg/L	<0.010	<0.001	0.001	<0.001	0.002	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Ethyl Benzene	mg/L	<0.010	<0.001	0.001	<0.001	0.003	0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Xylenes	mg/L	0.036	<0.001	0.001	<0.001	0.043	0.007	<0.001	<0.001	<0.001	<0.002	<0.002
Naphthalene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.0005	<0.00006	<0.00006
Acenaphthylene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00100	<0.00010	<0.00010
Acenaphthene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Fluorene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Phenanthrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00001	<0.00001
Anthracene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Fluoranthene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Pyrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Cyclopenta-cd-pyrene	mg/L	na	na	na	na	na	na	na	na	<0.00100	<0.00010	<0.00010
Benzo(a)Anthracene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Chrysene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Benzo-e-pyrene	mg/L	na	na	na	na	na	na	na	na	<0.00005	<0.00001	<0.00001
Benzo(b)Fluoranthene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Benzo(k)Fluoranthene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Benzo(a)Pyrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Indeno(123-cd)Pyrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Dibenzo(ah)Anthracene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Benzo(ghi)Perylene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Anthanthrene	mg/L	na	na	na	na	na	na	na	na	<0.00005	<0.00001	<0.00001
Phenol	mg/L	0.0456	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Cresols	mg/L	0.0047	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Dimethylphenols	mg/L	0.1200	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Trimethylphenols	mg/L	0.0869	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

= co-eluted with benzo(b)fluoranthene

na = not analysed

Groundwater Analysis Results

Sample I.D. Screen depth and description	Units	SW 99-5 northern plume, within zone of air sparging										
		13-Jul-99	01-Sep-99	15-Sep-99	05-Nov-99	07-Jan-00	22-Jun-00	29-Nov-00	10-May-01	11-Oct-01	29-Jan-03	27-May-03
Total Dissolved Solids	mg/L	718	1360	na	na	na	na	na	na	na	na	na
Bicarbonate Alkalinity as CaCO3	mg/L	262	107	139	50	30	<2	0	2	38	193	231
Carbonate Alkalinity as CaCO3	mg/L	0	0	0	0	0	0	0	0	0	0	0
pH units	mg/L	8.0	7.2	7.5	7.6	6.6	5.2	4.5	7.7	6.7	6.6	6.8
Conductivity uS/cm @ 25C	mg/L	1300	1740	1910	2380	1670	2020	1320	1310	1210	897	979
Total Alkalinity as CaCO3	mg/L	262	107	139	50	30	<2	0	<2	38	193	231
Chloride as Cl	mg/L	206	223	194	176	142	357	197	276	177	124	133
Total Sulphur as SO4 (Total)	mg/L	134	546	712	1030	666	272	188	118	139	60.6	62.1
Calcium as Ca (Total)	mg/L	90.5	na	121	181	138	163	71.7	72.5	37.7	51.1	55.1
Magnesium as Mg (Total)	mg/L	108	na	91.5	133	79.3	61.7	26	28.1	28.5	27.3	29.4
Sodium as Na (Total)	mg/L	123	na	157	177	126	101	145	145	153	88.2	102
Potassium as K (Total)	mg/L	10.2	na	5.54	3.37	3.35	10.3	6.02	7.63	4.69	5.31	4.96
Manganese as Mn (Total)	mg/L	3.03	na	1.73	1.94	9.75	3.36	1.77	1.41	0.64	0.22	0.65
Manganese as Mn (Dissolved)	mg/L	0.27	1.00	1.16	2.00	1.73	3.24	1.55	1.56	0.55	0.33	0.64
Iron as Fe (Total)	mg/L	138	na	44.6	14.9	59.7	10.5	26.4	7.35	7.74	0.05	4.86
Iron as Fe (Dissolved)	mg/L	0.35	0.04	0.09	0.21	0.40	0.04	0.02	0.09	0.05	0.03	0.36
Nitrate as N	mg/L	<1.0	<1.0	<1.0	18	13	<0.1	47	42.1	31.4	8.4	4.8
Nitrite as N	mg/L	na	na	na	na	na	na	<0.1	<0.1	0.4	4.7	0.3
Ammoniacal Nitrogen as N	mg/L	na	na	na	na	na	na	na	na	na	5.7	4.8
Sulphide (Free) as S	mg/L	1.4	0.6	<0.2	<0.2	<0.2	60.6	<0.2	<0.2	<0.2	<0.2	<0.2
Chemical Oxygen Demand	mg/L	<5	16	10	11	6	3.8	<5	<56	<5	24	16
Biochemical Oxygen Demand	mg/L	3.5	<2.0	<2.0	2.5	<2.0	26	<2.0	<2.0	<2.0	5.0	2
Total Organic Carbon	mg/L	4.4	5.0	na	na	na	<2.0	na	na	na	na	na
TPH GC	mg/L	0.2	0.1	0.11	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Benzene	mg/L	1.065	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Toluene	mg/L	<0.005	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Ethyl Benzene	mg/L	0.005	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Xylenes	mg/L	<0.005	<0.001	<0.001	<0.001	<0.001	0.006	<0.001	<0.001	<0.001	<0.002	<0.002
Naphthalene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.00161	<0.00006	<0.00006
Acenaphthylene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00100	<0.00010	<0.00010
Acenaphthene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Fluorene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Phenanthrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	0.00001
Anthracene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Fluoranthene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Pyrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Cyclopenta-cd-pyrene	mg/L	na	na	na	na	na	na	na	na	<0.00100	<0.00010	<0.00010
Benzo(a)Anthracene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Chrysene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Benzo-e-pyrene	mg/L	na	na	na	na	na	na	na	na	<0.00005	<0.00001	<0.00001
Benzo(b)Fluoranthene	mg/L	<0.01	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Benzo(k)Fluoranthene	mg/L	<0.01	<0.01	<0.01	#	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Benzo(a)Pyrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Indeno(123-cd)Pyrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Dibenzo(ah)Anthracene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Benzo(ghi)Perylene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Anthanthrene	mg/L	na	na	na	na	na	na	na	na	<0.00005	<0.00001	<0.00001
Phenol	mg/L	0.0116	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Cresols	mg/L	0.0160	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Dimethylphenols	mg/L	0.0034	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Trimethylphenols	mg/L	0.0254	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

= co-eluted with benzo(b)fluoranthene

na = not analysed

Groundwater Analysis Results

Sample I.D. **Screen depth and description**		**SW 99-16** southern plume, within zone of air sparging										
	Units	13-Jul-99	01-Sep-99	15-Sep-99	05-Nov-99	07-Jan-00	22-Jun-00	29-Nov-00	10-May-01	11-Oct-01	29-Jan-03	27-May-03
Total Dissolved Solids	mg/L	163	583	na	na	na	na	na	na	na	na	na
Bicarbonate Alkalinity as CaCO3	mg/L	338	415	374	103	12	42	12	15	138	16	531
Carbonate Alkalinity as CaCO3	mg/L	0	0	0	0	0	0	0	0	0	0	0
pH units	mg/L	8.1	7.7	7.5	7.0	5.6	6.6	5.5	6.0	6.9	4.7	7.0
Conductivity uS/cm @ 25C	mg/L	962	1770	1760	1890	1830	1390	1560	1280	1620	1250	1460
Total Alkalinity as CaCO3	mg/L	338	415	374	103	12	42	12	15	138	16	531
Chloride as Cl	mg/L	69	80	70	71	79	76	126	80	246	34	27
Total Sulphur as SO4 (Total)	mg/L	21.8	329	340	432	552	216	183	142	142	262	141
Calcium as Ca (Total)	mg/L	14.6	na	71.7	114	145	39.6	50.6	52.4	162	90.7	80.2
Magnesium as Mg (Total)	mg/L	6.76	na	20.2	14.5	17.5	5.43	8.72	8.27	17	11.9	10.6
Sodium as Na (Total)	mg/L	41.7	na	76.9	64.0	75.2	43.2	78.3	45.8	146	28.2	25.9
Potassium as K (Total)	mg/L	3.61	na	5.47	5.02	5.63	3.90	5.43	5.11	6.19	3.98	4.15
Manganese as Mn (Total)	mg/L	0.22	na	0.76	2.16	2.66	0.94	0.69	0.48	0.91	0.70	0.48
Manganese as Mn (Dissolved)	mg/L	0.07	0.10	0.33	2.17	2.47	0.37	0.69	0.49	0.95	0.67	0.47
Iron as Fe (Total)	mg/L	12.7	na	9.78	4.53	10.7	3.71	5.34	6.23	2.05	2.47	8.74
Iron as Fe (Dissolved)	mg/L	0.37	0.15	0.21	0.16	0.23	0.10	0.08	0.30	0.09	0.09	1.55
Nitrate as N	mg/L	<1.0	<1.0	<1.0	47	29	44.0	5490	4.3	32.5	29.1	<0.5
Nitrite as N	mg/L	na	na	na	na	na	na	2210	83.9	1.3	61.4	<0.1
Ammoniacal Nitrogen as N	mg/L	na	na	na	na	na	na	na	na	na	73.2	106
Sulphide (Free) as S	mg/L	1.8	5.4	<0.2	<0.2	<0.2	12.5	<0.2	<0.2	<0.2	<0.2	0.2
Chemical Oxygen Demand	mg/L	39	96	40	41	75	0.8	104	111	39	114	70
Biochemical Oxygen Demand	mg/L	6.5	9.0	7.0	4.5	5.0	101	2.5	7.0	<2.0	<2.0	35
Total Organic Carbon	mg/L	16	19	na	na	na	3.5	na	na	na	na	na
TPH GC	mg/L	0.8	2.2	0.7	0.3	1.3	0.13	0.53	0.48	0.41	0.54	10.0
Benzene	mg/L	0.01	0.021	<0.001	<0.001	0.015	0.005	0.079	0.002	0.24	0.05	0.011
Toluene	mg/L	<0.010	<0.001	<0.001	0.006	<0.001	<0.001	<0.001	<0.001	<0.050	<0.001	<0.250
Ethyl Benzene	mg/L	<0.010	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.050	<0.001	<0.250
Xylenes	mg/L	<0.010	0.013	<0.001	<0.001	0.001	0.004	<0.001	<0.001	0.056	0.004	1.111
Naphthalene	mg/L	0.02	0.04	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.00132	0.00085	0.0724
Acenaphthylene	mg/L	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00100	<0.00010	0.0341
Acenaphthene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00006
Fluorene	mg/L	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00006
Phenanthrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00006
Anthracene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00006
Fluoranthene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00006
Pyrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00006
Cyclopenta-cd-pyrene	mg/L	na	na	na	na	na	na	na	na	<0.00100	<0.00010	<0.00100
Benzo(a)Anthracene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00006
Chrysene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00006
Benzo-e-pyrene	mg/L	na	na	na	na	na	na	na	na	<0.00005	<0.00001	<0.00006
Benzo(b)Fluoranthene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00006
Benzo(k)Fluoranthene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00006
Benzo(a)Pyrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00006
Indeno(123-cd)Pyrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00006
Dibenzo(ah)Anthracene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00006
Benzo(ghi)Perylene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00006
Anthanthrene	mg/L	na	na	na	na	na	na	na	na	<0.00005	<0.00001	<0.00006
Phenol	mg/L	0.3	0.1	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	1.0
Cresols	mg/L	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Dimethylphenols	mg/L	0.3	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	3.4
Trimethylphenols	mg/L	0.1140	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	2.1

= co-eluted with benzo(b)fluoranthene

na = not analysed

Groundwater Analysis Results

Sample I.D. **Screen depth and description**		**SW 99-17** southern plume, within zone of air sparging										
	Units	13-Jul-99	01-Sep-99	15-Sep-99	05-Nov-99	07-Jan-00	22-Jun-00	29-Nov-00	10-May-01	11-Oct-01	29-Jan-03	27-May-03
Total Dissolved Solids	mg/L	833	1000	na	na	na	na	na	na	na	na	na
Bicarbonate Alkalinity as CaCO3	mg/L	380	91	175	130	37	10	20	119	22	130	565
Carbonate Alkalinity as CaCO3	mg/L	0	0	0	0	0	0	0	0	0	0	0
pH units	mg/L	6.8	6.7	7.0	6.9	6.0	6.0	6	6.8	6.1	7.0	7.0
Conductivity uS/cm @ 25C	mg/L	1660	1540	1510	1670	1480	1990	1340	1170	1460	1180	1380
Total Alkalinity as CaCO3	mg/L	380	91	175	130	37	10	20	119	22	130	565
Chloride as Cl	mg/L	140	99	96	103	129	336	140	107	69	145	68
Total Sulphur as SO4 (Total)	mg/L	98.8	536	383	422	417	331	352	232	155	152	58.6
Calcium as Ca (Total)	mg/L	111	na	103	136	151	174	139	140	153	123	112
Magnesium as Mg (Total)	mg/L	50.6	na	12.1	10.4	11.8	17.2	13	18.2	16	13.2	19.5
Sodium as Na (Total)	mg/L	51.9	na	70.6	78.3	70.7	189	125	97.2	129	112	68.1
Potassium as K (Total)	mg/L	9.35	na	5.02	4.52	3.00	3.43	2.82	4.39	6.04	3.68	7.31
Manganese as Mn (Total)	mg/L	2.35	na	1.33	1.30	1.58	1.63	1.02	0.76	0.94	0.61	0.74
Manganese as Mn (Dissolved)	mg/L	1.90	1.45	0.84	1.38	1.56	1.61	1.01	0.78	0.91	0.62	0.74
Iron as Fe (Total)	mg/L	104	na	12.9	8.39	3.81	10.0	8.44	6.40	5.13	0.65	4.68
Iron as Fe (Dissolved)	mg/L	9.14	3.23	0.81	0.14	0.55	0.06	0.09	0.11	0.14	0.10	1.98
Nitrate as N	mg/L	<1.0	<1.0	<1.0	3.5	8.7	21.1	16.2	31.5	15	30.4	<0.5
Nitrite as N	mg/L	na	na	na	na	na	na	14	7.6	66.7	0.2	<0.1
Ammoniacal Nitrogen as N	mg/L	na	na	na	na	na	na	na	na	na	0.6	50.4
Sulphide (Free) as S	mg/L	1.1	4.8	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	0.8
Chemical Oxygen Demand	mg/L	49	107	76	87	69	85	52	61	93	52	53
Biochemical Oxygen Demand	mg/L	23	2	10	16	<2.0	<2.0	2.5	6.0	<2.0	<2.0	10
Total Organic Carbon	mg/L	38	25	na	na	na	na	na	na	na	na	na
TPH GC	mg/L	13.0	6.2	2.4	1.2	2.2	1.2	2.3	0.94	0.38	2.58	4.4
Benzene	mg/L	5.269	1.194	<0.001	<0.001	0.002	0.01	<0.001	0.014	<0.001	<0.001	0.006
Toluene	mg/L	0.02	0.021	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.250
Ethyl Benzene	mg/L	0.02	<0.020	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.250
Xylenes	mg/L	0.34	0.075	<0.001	<0.001	<0.001	0.002	<0.001	<0.001	<0.001	0.002	<0.500
Naphthalene	mg/L	0.45	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.0005	0.00025	0.03510
Acenaphthylene	mg/L	0.07	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00100	<0.00010	0.03120
Acenaphthene	mg/L	0.05	0.05	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	0.02260
Fluorene	mg/L	0.06	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00001	0.00452
Phenanthrene	mg/L	0.09	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	0.00139
Anthracene	mg/L	0.02	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	0.00014
Fluoranthene	mg/L	0.03	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00002	0.00030
Pyrene	mg/L	0.03	0.04	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00003	0.00045
Cyclopenta-cd-pyrene	mg/L	na	na	na	na	na	na	na	na	<0.00100	<0.00010	<0.00100
Benzo(a)Anthracene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00005	0.00014
Chrysene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00002	<0.00006
Benzo-e-pyrene	mg/L	na	na	na	na	na	na	na	na	0.00014	0.00008	0.00006
Benzo(b)Fluoranthene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.00006	0.00001	<0.00006
Benzo(k)Fluoranthene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00001	<0.00006
Benzo(a)Pyrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.00014	0.00006	<0.00006
Indeno(123-cd)Pyrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.00009	0.00004	<0.00006
Dibenzo(ah)Anthracene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00006
Benzo(ghi)Perylene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.00015	0.00007	<0.00006
Anthanthrene	mg/L	na	na	na	na	na	na	na	na	<0.00005	<0.00001	<0.00006
Phenol	mg/L	0.4	1.2	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.2
Cresols	mg/L	0.2	1.4	<0.1	<0.1	<0.1	<0.1	<0.1	1.2	<0.1	<0.1	<0.1
Dimethylphenols	mg/L	3.4	8.0	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	1.2
Trimethylphenols	mg/L	2.2	3.4	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	1.2

= co-eluted with benzo(b)fluoranthene

na = not analysed

Groundwater Analysis Results

Sample I.D. **Screen depth and description**		**SW 99-18** southern plume, within zone of air sparging										
	Units	13-Jul-99	01-Sep-99	15-Sep-99	05-Nov-99	07-Jan-00	22-Jun-00	29-Nov-00	10-May-01	11-Oct-01	29-Jan-03	27-May-03
Total Dissolved Solids	mg/L	479	691	na	na	na	na	na	na	na	na	na
Bicarbonate Alkalinity as CaCO3	mg/L	371	532	534	604	562	307	674	657	374	602	634
Carbonate Alkalinity as CaCO3	mg/L	0	0	0	0	0	0	0	0	0	0	0
pH units	mg/L	7.3	7.0	7.2	7.1	6.7	7.3	6.9	7.5	6.9	7.0	7.0
Conductivity uS/cm @ 25C	mg/L	1220	1660	1790	1910	1940	1830	1760	1690	1890	1600	1750
Total Alkalinity as CaCO3	mg/L	371	532	534	604	562	607	674	657	374	602	634
Chloride as Cl	mg/L	115	130	132	126	137	134	89	127	90	122	143
Total Sulphur as SO4 (Total)	mg/L	307	154	181	126	198	123	610	2400	319	157	149
Calcium as Ca (Total)	mg/L	257	na	118	137	156	136	172	150	95.2	181	132
Magnesium as Mg (Total)	mg/L	125	na	13.4	14.2	13.7	12.0	15.7	14.9	17.1	17.0	16.6
Sodium as Na (Total)	mg/L	80.1	na	83.6	62.9	53.1	55.3	63.5	72.1	66.1	67.9	86.8
Potassium as K (Total)	mg/L	16.4	na	4.62	5.52	5.00	4.97	4.6	3.93	6.03	4.62	6.87
Manganese as Mn (Total)	mg/L	6.84	na	1.34	1.75	1.92	0.94	0.88	0.18	0.85	0.67	0.54
Manganese as Mn (Dissolved)	mg/L	0.74	0.98	1.26	1.80	1.63	0.99	0.83	0.52	0.7	0.70	0.48
Iron as Fe (Total)	mg/L	221	na	8.40	40.3	4.83	3.72	25.9	3.86	29.4	0.95	1.28
Iron as Fe (Dissolved)	mg/L	0.80	0.69	1.57	2.84	3.71	3.61	0.09	<0.01	4.22	0.08	0.08
Nitrate as N	mg/L	<1.0	<1.0	<1.0	<1.0	<1.0	0.1	<0.5	1.7	<0.5	<0.5	1.9
Nitrite as N	mg/L	na	na	na	na	na	na	0.2	0.1	0.1	<0.1	<0.1
Ammoniacal Nitrogen as N	mg/L	na	na	na	na	na	na	na	na	na	41.8	59.8
Sulphide (Free) as S	mg/L	1.9	11.0	1.2	0.6	1.2	9.6	29.2	23.1	2	11.0	1.4
Chemical Oxygen Demand	mg/L	285	88	46	72	55	70	101	93	41	58	23
Biochemical Oxygen Demand	mg/L	31	1	33	34	<2.0	1	40	85	1	55	135
Total Organic Carbon	mg/L	18	25	na	na	na	na	na	na	na	na	na
TPH GC	mg/L	7.7	9.5	3.4	2.4	1.0	1.4	4.4	7.6	2.2	3.7	3.7
Benzene	mg/L	6.412	>3.212	0.539	3.042	<0.001	<0.001	6.685	5.721	<0.001	5.284	0.572
Toluene	mg/L	<0.020	0.012	<0.001	0.006	<0.001	<0.001	0.082	0.033	<0.001	<0.050	<0.250
Ethyl Benzene	mg/L	0.077	0.01	<0.001	0.011	<0.001	<0.001	<0.050	0.146	<0.001	0.076	<0.250
Xylenes	mg/L	1.305	0.721	0.292	0.213	<0.001	<0.001	0.22	0.442	<0.001	<0.100	<0.250
Naphthalene	mg/L	0.17	0.31	0.06	0.01	0.01	0.03	0.13	0.35	0.0391	0.0515	0.0574
Acenaphthylene	mg/L	0.03	<0.1	<0.01	<0.01	<0.01	<0.01	0.02	<0.05	0.0153	0.0491	0.0283
Acenaphthene	mg/L	<0.01	<0.1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.05	0.0017	0.111	0.0023
Fluorene	mg/L	<0.01	<0.1	<0.01	<0.01	<0.01	0.01	0.06	<0.05	0.00080	0.00297	0.00046
Phenanthrene	mg/L	<0.01	<0.1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.05	0.00039	0.00182	0.00075
Anthracene	mg/L	0.02	<0.1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.05	<0.00005	0.00007	0.00008
Fluoranthene	mg/L	<0.01	<0.1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.05	0.00005	0.00007	<0.00006
Pyrene	mg/L	<0.01	<0.1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.05	<0.00005	0.00009	0.00007
Cyclopenta-cd-pyrene	mg/L	na	na	na	na	na	na	na	na	<0.00100	<0.00010	<0.00010
Benzo(a)Anthracene	mg/L	<0.01	<0.1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.05	<0.00005	0.00004	<0.00006
Chrysene	mg/L	<0.01	<0.1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.05	<0.00005	<0.00001	<0.00006
Benzo-e-pyrene	mg/L	na	na	na	na	na	na	na	na	<0.00005	<0.00001	<0.00006
Benzo(b)Fluoranthene	mg/L	<0.01	<0.1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.05	<0.00005	<0.00001	<0.00006
Benzo(k)Fluoranthene	mg/L	<0.01	<0.1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.05	<0.00005	<0.00001	<0.00006
Benzo(a)Pyrene	mg/L	<0.01	<0.1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.05	<0.00005	0.00001	<0.00006
Indeno(123-cd)Pyrene	mg/L	<0.01	<0.1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.05	<0.00005	<0.00001	<0.00006
Dibenzo(ah)Anthracene	mg/L	<0.01	<0.1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.05	<0.00005	<0.00001	<0.00006
Benzo(ghi)Perylene	mg/L	<0.01	<0.1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.05	<0.00005	<0.00001	<0.00006
Anthanthrene	mg/L	na	na	na	na	na	na	na	na	<0.00005	<0.00001	<0.00006
Phenol	mg/L	0.7	0.4	1.1	0.6	0.1	0.4	1	8.5	0.6	0.1	0.7
Cresols	mg/L	0.2	0.1	1.2	0.4	<0.1	<0.1	<0.1	<0.1	<0.1	0.7	<0.1
Dimethylphenols	mg/L	2.4	0.4	4.1	3.9	0.5	1.0	3.2	4.0	1.3	1.7	2.3
Trimethylphenols	mg/L	1.8	0.9	2.1	1.7	0.4	0.7	0.7	1.0	0.8	1.2	1.2

= co-eluted with benzo(b)fluoranthene

na = not analysed

Groundwater Analysis Results

Sample I.D. **Screen depth and description**		**SW 99-19** southern plume, within zone of air sparging										
	Units	13-Jul-99	01-Sep-99	15-Sep-99	05-Nov-99	07-Jan-00	22-Jun-00	29-Nov-00	10-May-01	11-Oct-01	29-Jan-03	27-May-03
Total Dissolved Solids	mg/L	967	1960	na	na	na	na	na	na	na	na	na
Bicarbonate Alkalinity as CaCO3	mg/L	452	90	264	46	98	143	257	110	130	217	559
Carbonate Alkalinity as CaCO3	mg/L	0	0	0	0	0	0	0	0	0	0	0
pH units	mg/L	7.3	6.9	7.4	7.0	6.9	7.1	7.4	6.9	7	7.8	7.0
Conductivity uS/cm @ 25C	mg/L	1720	2180	1840	1930	1710	1500	1310	1350	1310	1140	1470
Total Alkalinity as CaCO3	mg/L	452	90	264	46	98	143	257	110	130	217	559
Chloride as Cl	mg/L	133	138	144	141	108	100	94	74	83	104	110
Total Sulphur as SO4 (Total)	mg/L	331	1110	458	488	479	401	184	488	319	131	71.8
Calcium as Ca (Total)	mg/L	230	na	173	265	250	229	168	231	168	129	136
Magnesium as Mg (Total)	mg/L	131	na	19.7	23.2	20.1	18.5	16.4	21.2	16.7	21.4	22.4
Sodium as Na (Total)	mg/L	118	na	128	116	97.4	93.0	91.2	73.1	93.4	86.6	78.5
Potassium as K (Total)	mg/L	15.5	na	5.42	3.49	4.96	2.74	1.79	2.62	3.18	3.64	3.91
Manganese as Mn (Total)	mg/L	5.55	na	1.35	2.14	2.72	1.89	1.22	0.65	0.99	2.29	2.15
Manganese as Mn (Dissolved)	mg/L	1.79	1.94	1.11	2.25	2.35	1.30	0.58	1.42	0.37	2.42	1.82
Iron as Fe (Total)	mg/L	207	na	22.0	2.93	28.2	33.1	38.5	1.94	18	0.81	35.4
Iron as Fe (Dissolved)	mg/L	1.14	1.53	0.31	0.18	0.29	0.08	0.09	<0.01	0.09	0.08	1.62
Nitrate as N	mg/L	<1.0	<1.0	<1.0	70	50	0.1	43.7	39.0	30.7	37.6	0.9
Nitrite as N	mg/L	na	na	na	na	na	na	<0.1	0.4	<0.1	<0.1	<0.1
Ammoniacal Nitrogen as N	mg/L	na	na	na	na	na	na	na	na	na	0.2	41.1
Sulphide (Free) as S	mg/L	1.5	0.3	<0.2	<0.2	<0.2	2.0	<0.2	0.4	<0.2	4.5	10.0
Chemical Oxygen Demand	mg/L	62	43	38	35	27	46	10	29	9	23	46
Biochemical Oxygen Demand	mg/L	10	2.5	<2.0	6.0	<2.0	<2.0	<2.0	<2.0	<2.0	2.5	2.5
Total Organic Carbon	mg/L	23	18	na	na	na	na	na	na	na	na	na
TPH GC	mg/L	6.3	0.7	0.22	0.1	0.17	<0.1	0.15	<0.1	<0.1	0.24	2.5
Benzene	mg/L	2.409	0.013	<0.001	0.002	<0.001	<0.001	<0.001	0.018	<0.001	<0.001	<0.001
Toluene	mg/L	<0.020	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Ethyl Benzene	mg/L	<0.020	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Xylenes	mg/L	0.895	<0.001	<0.001	0.002	<0.001	<0.001	<0.001	<0.001	<0.001	<0.002	<0.003
Naphthalene	mg/L	0.37	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.0005	0.00017	0.0092
Acenaphthylene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00100	<0.00010	0.00253
Acenaphthene	mg/L	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00009	0.0118
Fluorene	mg/L	<0.01	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00002	0.00087
Phenanthrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00003	0.00011
Anthracene	mg/L	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	0.00001
Fluoranthene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00001	0.00001
Pyrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00002	0.00001
Cyclopenta-cd-pyrene	mg/L	na	na	na	na	na	na	na	na	<0.00100	<0.00010	<0.00011
Benzo(a)Anthracene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00002	0.00001
Chrysene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Benzo-e-pyrene	mg/L	na	na	na	na	na	na	na	na	<0.00005	0.00003	0.00001
Benzo(b)Fluoranthene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00002	<0.00001
Benzo(k)Fluoranthene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00001	<0.00001
Benzo(a)Pyrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00003	0.00001
Indeno(123-cd)Pyrene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00002	0.00001
Dibenzo(ah)Anthracene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	<0.00001	0.00001
Benzo(ghi)Perylene	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.00005	0.00004	0.00001
Anthanthrene	mg/L	na	na	na	na	na	na	na	na	<0.00005	<0.00001	<0.00001
Phenol	mg/L	0.1540	0.4	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.4
Cresols	mg/L	0.3090	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Dimethylphenols	mg/L	0.7750	1.7	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.8
Trimethylphenols	mg/L	1.4400	0.9	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.6

= co-eluted with benzo(b)fluoranthene

na = not analysed

Groundwater Analysis Results

Sample I.D. Screen depth and description		MW98-5 shallow screen, northern plume, upgradient of air sparging system					MW99-4 Intermendiate screen, northern plume, upgradient of air sparging system				
	Units	13-Jul-99	22-Jun-00	11-Oct-01	29-Jan-03	27-May-03	13-Jul-99	22-Jun-00	11-Oct-01	29-Jan-03	27-May-03
Total Dissolved Solids	mg/L	786	na	na	na	na	798	na	na	na	na
Bicarbonate Alkalinity as CaCO3	mg/L	392	388	170	488	210	248	282	123	252	257
Carbonate Alkalinity as CaCO3	mg/L	0	0	0	0	0	0	0	0	0	0
pH units	mg/L	7.7	7.1	7.1	7.0	6.9	7.8	7.9	7.6	6.8	6.9
Conductivity uS/cm @ 25C	mg/L	1230	966	446	940	490	1650	1320	1140	927	978
Total Alkalinity as CaCO3	mg/L	392	388	170	488	210	248	282	123	252	257
Chloride as Cl	mg/L	76	63	2	30	21	283	188	163	119	119
Total Sulphur as SO4 (Total)	mg/L	191	108	28.6	31.0	25.1	126	120	92.2	80.2	82.7
Calcium as Ca (Total)	mg/L	164	121	78.1	145	65.7	67.2	71.4	69.1	74.6	74.9
Magnesium as Mg (Total)	mg/L	38.5	21.5	2.22	20.7	9.04	24.7	30.0	30.2	28.2	27.5
Sodium as Na (Total)	mg/L	81.2	52.6	2.9	27.2	18.4	130	101	84.8	63.6	65.6
Potassium as K (Total)	mg/L	6.93	6.13	1.17	6.07	4.29	7.05	5.66	7.31	5.92	6.03
Manganese as Mn (Total)	mg/L	1.19	0.79	0.33	1.53	0.33	0.18	0.11	0.15	0.19	0.19
Manganese as Mn (Dissolved)	mg/L	0.75	0.72	0.05	1.12	0.29	0.18	0.10	0.13	0.18	0.19
Iron as Fe (Total)	mg/L	36.3	17.6	36.1	22.0	6.12	1	0.83	2.17	2.15	1.34
Iron as Fe (Dissolved)	mg/L	0.28	1.00	0.01	0.18	0.66	0.27	0.07	0.04	0.08	0.06
Nitrate as N	mg/L	<1.0	<0.1	<0.5	<0.5	<0.5	1.8	0.1	9.1	20.0	0.5
Nitrite as N	mg/L	na	na	<0.1	<0.1	<0.1	na	na	0.5	<0.1	0.2
Ammoniacal Nitrogen as N	mg/L	na	na	na	8.4	4.4	na	na	na	<0.1	15.5
Sulphide (Free) as S	mg/L	2.3	0.5	0.2	12.0	4.9	<0.2	32.0	<0.2	<0.2	<0.2
Chemical Oxygen Demand	mg/L	36	6.0	<5	51	14	11	22	9	<5	6
Biochemical Oxygen Demand	mg/L	15	44	<2.0	8.0	8.0	<2.0	<2.0	<2.0	<2.0	<2.0
Total Organic Carbon	mg/L	14	10	na	na	na	6.4	na	na	na	na
TPH GC	mg/L	3.8	na	<0.1	3.61	11.0	<0.1	<0.1	<0.1	0.1	<0.1
Benzene	mg/L	1.394	0.0028	<0.001	0.008	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Toluene	mg/L	<0.050	<0.001	<0.001	0.003	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Ethyl Benzene	mg/L	<0.050	<0.001	<0.001	0.004	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Xylenes	mg/L	0.271	0.036	<0.001	0.095	<0.002	<0.001	<0.001	<0.001	<0.002	<0.002
Naphthalene	mg/L	0.53	135	0.00098	0.313	0.00677	<0.01	<0.01	<0.0005	<0.00006	0.000877
Acenaphthylene	mg/L	<0.01	0.37	<0.00100	0.21	0.0197	<0.01	<0.01	<0.00100	<0.00010	0.00028
Acenaphthene	mg/L	0.01	<0.01	<0.00005	0.109	0.0127	<0.01	<0.01	<0.00005	<0.00001	0.000107
Fluorene	mg/L	0.02	0.01	<0.00005	0.0139	0.0055	<0.01	<0.01	<0.00005	<0.00001	0.00002
Phenanthrene	mg/L	<0.01	<0.01	<0.00005	0.00782	0.00372	<0.01	<0.01	<0.00005	<0.00001	0.00004
Anthracene	mg/L	<0.01	<0.01	<0.00005	0.00143	0.0013	<0.01	<0.01	<0.00005	<0.00001	0.00001
Fluoranthene	mg/L	<0.01	<0.01	<0.00005	0.00426	0.00216	<0.01	<0.01	<0.00005	<0.00001	0.00001
Pyrene	mg/L	<0.01	<0.01	<0.00005	0.00574	0.00249	<0.01	<0.01	<0.00005	<0.00001	0.00002
Cyclopenta-cd-pyrene	mg/L	na	na	<0.00100	<0.00010	<0.00010	na	na	<0.00100	<0.00010	<0.00010
Benzo(a)Anthracene	mg/L	<0.01	<0.01	<0.00005	0.000131	0.00013	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Chrysene	mg/L	<0.01	<0.01	<0.00005	0.00002	0.00003	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Benzo-e-pyrene	mg/L	na	na	<0.00005	0.00009	0.0001	na	na	<0.00005	<0.00001	<0.00001
Benzo(b)Fluoranthene	mg/L	<0.01	<0.01	<0.00005	0.00005	0.00004	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Benzo(k)Fluoranthene	mg/L	<0.01	<0.01	<0.00005	0.00002	0.00003	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Benzo(a)Pyrene	mg/L	<0.01	<0.01	<0.00005	0.00008	0.00009	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Indeno(123-cd)Pyrene	mg/L	<0.01	<0.01	<0.00005	<0.00001	0.00004	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Dibenzo(ah)Anthracene	mg/L	<0.01	<0.01	<0.00005	<0.00001	<0.00001	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Benzo(ghi)Perylene	mg/L	<0.01	<0.01	<0.00005	0.00003	0.00005	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Anthanthrene	mg/L	na	na	<0.00005	<0.00001	0.00001	na	na	<0.00005	<0.00001	<0.00001
Phenol	mg/L	0.0549	<0.01	<0.1	0.1	<0.1	0.0124	<0.1	<0.1	<0.1	<0.1
Cresols	mg/L	0.0338	0.2	<0.1	0.2	<0.1	0.0271	<0.1	<0.1	<0.1	<0.1
Dimethylphenols	mg/L	0.1190	<0.1	<0.1	0.3	<0.1	0.0334	<0.1	<0.1	<0.1	<0.1
Trimethylphenols	mg/L	0.3250	0.2	<0.1	0.5	<0.1	0.0101	<0.1	<0.1	<0.1	<0.1

= co-eluted with benzo(b)fluoranthene

na = not analysed

Groundwater Analysis Results

Sample I.D. **Screen depth and description**		**MW99-5** deep screen, northern plume, upgradient of air sparging system					**MW98-7** shallow screen, southern plume, upgradient of air sparging system				
	Units	13-Jul-99	22-Jun-00	11-Oct-01	29-Jan-03	27-May-03	13-Jul-99	22-Jun-00	11/10/01	29-Jan-03	27-May-03
Total Dissolved Solids	mg/L	541	na	na	na	na	278	na	na	na	na
Bicarbonate Alkalinity as CaCO3	mg/L	274	292	247	299	282	385	343	603	545	479
Carbonate Alkalinity as CaCO3	mg/L	0	0	0	0	0	0	0	0	0	0
pH units	mg/L	7.7	7.5	7.7	7.1	6.9	7.9	6.8	7.2	6.9	6.9
Conductivity uS/cm @ 25C	mg/L	1330	1190	1060	840	860	1170	1700	1890	1290	1210
Total Alkalinity as CaCO3	mg/L	274	292	247	299	282	385	343	603	545	479
Chloride as Cl	mg/L	155	135	104	80	84	97	198	124	42	31
Total Sulphur as SO4 (Total)	mg/L	128	105	52.4	38.6	37.4	31.1	191	103	62.1	77.3
Calcium as Ca (Total)	mg/L	64.8	58.7	59.6	57.9	56.2	30.2	93.9	56	74.8	78.9
Magnesium as Mg (Total)	mg/L	42.4	20.3	19.1	17.6	17.0	8.98	8.52	8.77	9.17	10.7
Sodium as Na (Total)	mg/L	66.6	57.0	56.6	45.4	45.2	45.2	145	85	38.0	39.0
Potassium as K (Total)	mg/L	12.2	8.22	6.48	7.17	7.07	4.65	3.98	5.78	3.79	2.88
Manganese as Mn (Total)	mg/L	1.63	0.18	0.33	0.20	0.20	0.36	0.32	0.24	0.35	0.41
Manganese as Mn (Dissolved)	mg/L	0.42	0.19	0.2	0.18	0.19	0.10	0.21	0.21	0.33	0.36
Iron as Fe (Total)	mg/L	67.5	1.00	7.48	2.42	0.51	21.6	28.4	20.2	17.2	10.0
Iron as Fe (Dissolved)	mg/L	0.15	0.08	0.16	0.26	0.03	0.43	0.34	4.18	11.2	0.32
Nitrate as N	mg/L	<1.0	0.1	0.8	<0.5	1.4	<1.0	1.4	0.6	<0.5	<0.5
Nitrite as N	mg/L	na	0.5	<0.1	<0.1	0.2	na	11.0	<0.1	<0.1	<0.1
Ammoniacal Nitrogen as N	mg/L	na	na	na	20.3	31.7	na	na	na	69.8	64.0
Sulphide (Free) as S	mg/L	1.5	0.6	<0.2	2.4	1.4	1.5	<0.2	0.8	5.2	6.8
Chemical Oxygen Demand	mg/L	42	41	13	23	19	60	56	106	100	77
Biochemical Oxygen Demand	mg/L	15	11	<2.0	3.5	3.0	29	<2.0	30	54	55
Total Organic Carbon	mg/L	12	na	na	na	na	20	na	na	na	na
TPH GC	mg/L	1.1	0.68	0.45	0.46	6.4	4.0	0.98	2.5	8.71	15.0
Benzene	mg/L	4.595	<0.001	<0.001	<0.001	<0.001	2.662	<0.001	0.972	14.527	1.876
Toluene	mg/L	<0.010	0.032	<0.001	<0.001	<0.001	<0.020	<0.001	<0.050	<0.001	0.162
Ethyl Benzene	mg/L	0.013	<0.001	<0.001	<0.001	<0.001	<0.020	<0.001	<0.050	<0.001	0.17
Xylenes	mg/L	0.214	0.003	<0.001	<0.002	<0.002	0.539	<0.001	0.296	<0.002	1.061
Naphthalene	mg/L	0.14	0.03	0.0144	0.00397	0.00558	0.06	<0.01	0.0303	0.0282	0.0836
Acenaphthylene	mg/L	<0.01	<0.01	0.0118	0.0262	0.019	<0.01	<0.01	<0.00100	0.0064	0.0112
Acenaphthene	mg/L	<0.01	<0.01	0.00175	0.0108	0.00711	<0.01	<0.01	<0.00005	0.00451	0.00041
Fluorene	mg/L	<0.01	<0.01	0.00050	0.00082	0.00083	<0.01	<0.01	0.00012	0.000187	0.0001
Phenanthrene	mg/L	<0.01	<0.01	0.00023	0.00016	0.00019	<0.01	<0.01	<0.00005	0.00122	0.00007
Anthracene	mg/L	<0.01	<0.01	<0.00005	0.00006	0.0001	<0.01	<0.01	<0.00005	0.000607	<0.00006
Fluoranthene	mg/L	<0.01	<0.01	0.00007	0.00009	0.00013	<0.01	<0.01	<0.00005	0.00219	0.00034
Pyrene	mg/L	<0.01	<0.01	0.00007	0.00007	0.00015	<0.01	<0.01	<0.00005	0.00308	0.0003
Cyclopenta-cd-pyrene	mg/L	na	na	<0.00100	<0.00010	<0.00010	na	na	<0.00100	<0.00010	<0.00100
Benzo(a)Anthracene	mg/L	<0.01	<0.01	<0.00005	0.00006	0.00006	<0.01	<0.01	<0.00005	<0.00001	0.00008
Chrysene	mg/L	<0.01	<0.01	<0.00005	0.00002	0.00005	<0.01	<0.01	<0.00005	<0.00001	<0.00006
Benzo-e-pyrene	mg/L	na	na	<0.00005	0.00002	0.00003	na	na	<0.00005	<0.00001	<0.00006
Benzo(b)Fluoranthene	mg/L	<0.01	<0.01	<0.00005	0.00002	0.00001	<0.01	<0.01	<0.00005	0.00008	<0.00006
Benzo(k)Fluoranthene	mg/L	<0.01	<0.01	<0.00005	0.00001	0.00001	<0.01	<0.01	<0.00005	0.00006	<0.00006
Benzo(a)Pyrene	mg/L	<0.01	<0.01	<0.00005	0.00002	0.00002	<0.01	<0.01	<0.00005	<0.00001	<0.00006
Indeno(123-cd)Pyrene	mg/L	<0.01	<0.01	<0.00005	<0.00001	0.00001	<0.01	<0.01	<0.00005	0.000117	<0.00006
Dibenzo(ah)Anthracene	mg/L	<0.01	<0.01	<0.00005	<0.00001	<0.00001	<0.01	<0.01	<0.00005	0.00002	<0.00006
Benzo(ghi)Perylene	mg/L	<0.01	<0.01	<0.00005	<0.00001	0.00001	<0.01	<0.01	<0.00005	0.000117	<0.00006
Anthanthrene	mg/L	na	na	<0.00005	<0.00001	<0.00001	na	na	<0.00005	0.00006	<0.00006
Phenol	mg/L	0.0426	0.3	0.1	<0.1	<0.1	0.3330	<0.1	1.6	0.7	1.0
Cresols	mg/L	0.0293	<0.1	<0.1	<0.1	<0.1	0.1780	0.2	<0.1	1.5	<0.1
Dimethylphenols	mg/L	0.0101	0.1	<0.1	<0.1	<0.1	0.8100	0.3	7.2	7.1	7.0
Trimethylphenols	mg/L	0.1570	<0.1	<0.1	<0.1	<0.1	0.7070	0.2	2.7	2.4	2.4

\# = co-eluted with benzo(b)fluoranthene

na = not analysed

Groundwater Analysis Results

Sample I.D. **Screen depth and description**		**MW99-8** intermediate screen, southern plume, upgradient of air sparging system					**MW99-9** deep screen, southern plume, upgradient of air sparging system				
	Units	13-Jul-99	22-Jun-00	11-Oct-01	29-Jan-03	27-May-03	13-Jul-99	22-Jun-00	11-Oct-01	29-Jan-03	27-May-03
Total Dissolved Solids	mg/L	407	na	na	na	na	465	na	na	na	na
Bicarbonate Alkalinity as CaCO3	mg/L	131	74	268	311	254	322	74	32	386	369
Carbonate Alkalinity as CaCO3	mg/L	0	0	0	0	0	0	0	0	0	0
pH units	mg/L	7.4	6.2	7.4	7.4	6.9	7.4	6.2	6.5	7.1	7.1
Conductivity uS/cm @ 25C	mg/L	758	1420	1330	3950	967	910	1420	1190	953	997
Total Alkalinity as CaCO3	mg/L	131	74	268	311	254	322	74	32	386	369
Chloride as Cl	mg/L	130	193	187	107	128	71	193	114	68	100
Total Sulphur as SO4 (Total)	mg/L	45.6	188	108	47.9	59.1	50.4	188	221	41.1	11.1
Calcium as Ca (Total)	mg/L	45.5	109	87.8	76.7	74.2	78.8	109	110	86.0	86.8
Magnesium as Mg (Total)	mg/L	8.36	26.4	21.4	23.2	21.2	18.9	26.4	22.7	19.5	23.0
Sodium as Na (Total)	mg/L	82.5	106	122	92.5	92.4	43.7	106	72.2	60.8	66.8
Potassium as K (Total)	mg/L	5.57	11.3	9.94	10.4	10.8	10.8	11.3	10.4	6.86	10.1
Manganese as Mn (Total)	mg/L	0.34	1.63	1.09	1.96	1.37	0.54	1.63	0.81	0.57	0.50
Manganese as Mn (Dissolved)	mg/L	0.35	1.52	1.07	1.90	1.46	0.59	1.52	0.82	0.57	0.72
Iron as Fe (Total)	mg/L	0.67	0.83	0.16	0.35	0.14	1.61	0.83	2.47	1.83	3.77
Iron as Fe (Dissolved)	mg/L	0.21	0.13	0.05	0.25	0.07	0.39	0.13	0.03	0.08	0.22
Nitrate as N	mg/L	<1.0	0.2	<0.5	0.7	<0.5	<1.0	0.2	10	<0.5	<0.5
Nitrite as N	mg/L	na	74.2	<0.1	<0.1	<0.1	na	74.2	0.7	<0.1	<0.1
Ammoniacal Nitrogen as N	mg/L	na	na	na	0.5	5.7	na	na	na	17.3	14.8
Sulphide (Free) as S	mg/L	<0.2	<0.2	<0.2	<0.2	0.2	<0.2	<0.2	<0.2	<0.2	0.3
Chemical Oxygen Demand	mg/L	<5	23	11	7	7	36	23	12	37	20
Biochemical Oxygen Demand	mg/L	5.5	<2.0	6.5	<2.0	<2.0	4.0	<2.0	<2.0	5.5	3
Total Organic Carbon	mg/L	5.0	na	na	na	na	13	na	na	na	na
TPH GC	mg/L	2.1	0.16	0.38	<0.1	<0.1	2.8	0.16	<0.1	0.98	1.5
Benzene	mg/L	0.329	<0.001	<0.001	<0.001	<0.001	4.136	<0.001	<0.001	<0.001	<0.001
Toluene	mg/L	<0.005	<0.001	<0.001	<0.001	<0.001	<0.010	<0.001	<0.001	<0.001	<0.001
Ethyl Benzene	mg/L	<0.005	<0.001	<0.001	<0.001	<0.001	0.039	<0.001	<0.001	<0.001	<0.001
Xylenes	mg/L	0.084	<0.001	<0.001	<0.002	<0.002	0.376	<0.001	<0.001	<0.002	<0.002
Naphthalene	mg/L	0.08	<0.01	0.00235	0.00008	<0.00006	0.09	<0.01	0.00139	0.00791	0.0125
Acenaphthylene	mg/L	<0.01	<0.01	<0.00100	<0.00010	<0.00010	<0.01	<0.01	<0.00100	0.00137	0.00427
Acenaphthene	mg/L	<0.01	<0.01	0.00110	0.00001	0.00002	<0.01	<0.01	<0.00005	0.002	<0.00001
Fluorene	mg/L	0.01	<0.01	<0.00005	0.00001	<0.00001	<0.01	<0.01	0.00009	0.00006	0.00001
Phenanthrene	mg/L	<0.01	<0.01	<0.00005	0.00002	<0.00001	<0.01	<0.01	<0.00005	<0.00001	0.00001
Anthracene	mg/L	<0.01	<0.01	<0.00005	<0.00001	<0.00001	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Fluoranthene	mg/L	<0.01	<0.01	<0.00005	<0.00001	<0.00001	<0.01	<0.01	<0.00005	<0.00001	0.00001
Pyrene	mg/L	<0.01	<0.01	<0.00005	<0.00001	<0.00001	<0.01	<0.01	<0.00005	<0.00001	0.00001
Cyclopenta-cd-pyrene	mg/L	na	na	<0.00100	<0.00010	<0.00010	na	na	<0.00100	<0.00010	<0.00010
Benzo(a)Anthracene	mg/L	<0.01	<0.01	<0.00005	<0.00001	<0.00001	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Chrysene	mg/L	<0.01	<0.01	<0.00005	<0.00001	<0.00001	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Benzo-e-pyrene	mg/L	na	na	<0.00005	<0.00001	<0.00001	na	na	<0.00005	<0.00001	<0.00001
Benzo(b)Fluoranthene	mg/L	<0.01	<0.01	<0.00005	<0.00001	<0.00001	0.01	<0.01	<0.00005	<0.00001	<0.00001
Benzo(k)Fluoranthene	mg/L	<0.01	<0.01	<0.00005	<0.00001	<0.00001	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Benzo(a)Pyrene	mg/L	<0.01	<0.01	<0.00005	<0.00001	<0.00001	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Indeno(123-cd)Pyrene	mg/L	<0.01	<0.01	<0.00005	<0.00001	<0.00001	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Dibenzo(ah)Anthracene	mg/L	<0.01	<0.01	<0.00005	<0.00001	<0.00001	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Benzo(ghi)Perylene	mg/L	<0.01	<0.01	<0.00005	<0.00001	<0.00001	<0.01	<0.01	<0.00005	<0.00001	<0.00001
Anthanthrene	mg/L	na	na	<0.00005	<0.00001	<0.00001	na	na	<0.00005	0.00000	<0.00001
Phenol	mg/L	0.0953	<0.1	0.2	<0.1	<0.1	0.3	<0.1	<0.1	0.2	0.1
Cresols	mg/L	0.1070	<0.1	<0.1	<0.1	<0.1	0.2	<0.1	<0.1	<0.1	<0.1
Dimethylphenols	mg/L	1.0707	<0.1	0.4	<0.1	<0.1	0.9	<0.1	<0.1	0.4	0.4
Trimethylphenols	mg/L	0.5620	<0.1	0.3	<0.1	<0.1	1.0	<0.1	<0.1	0.4	0.3

= co-eluted with benzo(b)fluoranthene

na = not analysed

Note:

PAH (polyaromatic hydrocarbon) analysis was carried out by GC-FID (gas chromatograph - flame ion detection) up to June 2000. From July 2000 onwards PAH analysis was carried out by HPLC (high performance liquid chromatography)

Summary of Dissolved Oxygen Decay Rates and Interpreted Biodegradation Rates, Calculated from Respiration Tests

Well	Date	Time interval for decay rate measurement			D.O. at time 1 mg/L	D.O. at time 2 mg/L	Change in D.O. mg/L	D.O.Decay Rate mg/L/hr	Benzene biodegradation rate, mg/L/hr	Naphthalene biodegradarion rate, mg/L/hr
		Start time (time 1)	Stop time (time 2)	Time elapsed hours						
SW99-3	20-Jul-99	13:18	13:37	0.32	10.76	6.41	4.35	13.74	4.46	4.58
SW99-4	19-Jul-99	15:15	15:45	0.50	9.29	3.02	6.27	12.54	4.08	4.18
	23-Jul-99	14:58	15:38	0.67	11.42	3.72	7.70	11.55	3.75	3.85
	23-Aug-99	11:38	12:10	0.53	8.92	3.87	5.05	9.47	3.08	3.16
SW99-5	20-Jul-99	10:04	10:41	0.62	10.98	3.05	7.93	12.86	4.18	4.29
SW99-12	17-Jul_99	16:51	17:09	0.30	8.60	1.89	6.71	22.37	7.27	7.46
SW99-14	19-Jul-99	11:47	12:02	0.25	9.06	4.44	4.62	18.48	6.01	6.16
SW99-15	21-Jul-99	14:33	15:00	0.45	7.06	3.78	3.28	7.29	2.37	2.43
SW99-16	22-Jul-99	10:42	11:49	1.12	9.59	1.51	8.08	7.24	2.35	2.41
SW99-17	26-Jul-99	16:37	16:53	0.27	11.37	1.34	10.03	37.61	12.22	12.54
	23-Aug-99	14:21	14:46	0.42	7.06	2.11	4.95	11.88	3.86	3.96
SW99-20	27-Jul-99	10:18	11:24	1.10	9.02	1.07	7.95	7.23	2.35	2.41